



Self-Powered Analogue Smart Skin

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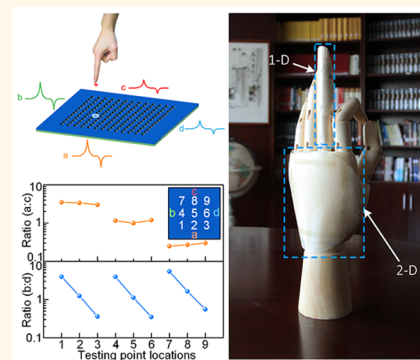
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S Supporting Information

ABSTRACT: The progress of smart skin technology presents unprecedented opportunities for artificial intelligence. Resolution enhancement and energy conservation are critical to improve the perception and standby time of robots. Here, we present a self-powered analogue smart skin for detecting contact location and velocity of the object, based on a single-electrode contact electrification effect and planar electrostatic induction. Using an analogue localizing method, the resolution of this two-dimensional smart skin can be achieved at 1.9 mm with only four terminals, which notably decreases the terminal number of smart skins. The sensitivity of this smart skin is remarkable, which can even perceive the perturbation of a honey bee. Meanwhile, benefiting from the triboelectric mechanism, extra power supply is unnecessary for this smart skin. Therefore, it solves the problems of batteries and connecting wires for smart skins. With microstructured poly(dimethylsiloxane) films and silver nanowire electrodes, it can be covered on the skin with transparency, flexibility, and high sensitivity.

KEYWORDS: smart skin, position sensors, analogue, self-powered, flexible electronics



Smart skin is a critical element that helps robots sense the world. Plenty of smart skins that can measure various physical quantities such as location, pressure, temperature, and humidity using different strategies are presented to emulate the functions of human skin in the past.^{1–19} Thin-film transistors,¹ piezoresistive composite polymers,² ionic conductors,³ silicon nanoribbons,⁵ Ge/Si nanowire arrays,⁶ carbon nanotubes,⁷ and even self-healing composites⁹ are used to make smart skins flexible, stretchable, and multifunctional. Nevertheless, resolution enhancement and energy conservation are still critical to improve the perception and standby time of the smart skin. In the previous works, a digital method based on pixels is extensively utilized to realize high-resolution location.⁷ However, for digital smart skins, higher resolution, the significant target for location, usually means increasing the number of sensing units and electrodes, which will cause a noteworthy cost increase and extra difficulties on electrode extraction, signal interference, and data processing. An analogue method provides a fully new strategy, especially in terms of reducing the number of sensing units and electrodes.¹⁵

The improvement of a self-powered system provides a promising solution to make smart skins portable and battery-free.^{20–33} In self-powered systems, mechanical energy in the surrounding environment is collected through a triboelectric effect or piezoelectric effect and then used to drive the whole system. In recent years, self-powered systems have been applied as sensors to measure the movement,²² posture,²³ and pressure.²⁵ Many effective processes and theoretical analyses

have been developed to make the self-powered system perform better.^{26–32}

Here, we present a self-powered analogue smart skin to detect location as well as contact velocity, based on a single-electrode contact electrification effect and planar electrostatic induction. Silver nanowires (Ag NWs) are used to fabricate the flexible and transparent electrodes, and only four electrodes are necessary for the two-dimensional analogue smart skin, which notably decreases the terminal number of smart skins. Based on the voltage ratios of opposite electrodes, the touch stimulus is located with millimeter precision resolution and high sensitivity. The overall peak voltages can be applied to measure the touching velocity. Furthermore, the triboelectric mechanism enables this smart skin to be totally self-powered without any external battery, which is very beneficial for portable devices.

RESULTS AND DISCUSSION

The Ag NW electrodes were placed on a thin polyethylene terephthalate (PET) substrate with a thickness of 12.5 μm . The microstructured poly(dimethylsiloxane) (PDMS) film was directly covered on the PET substrate with electrodes, as a friction surface to enhance the triboelectric charge density

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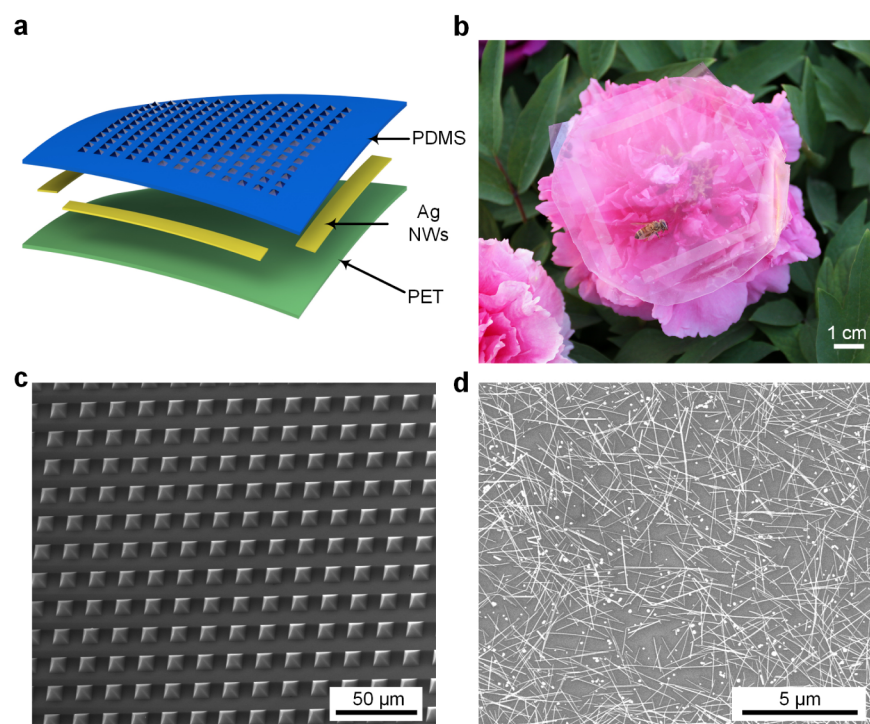


Figure 1. Structure of analogue smart skins. (a) Schematic diagram of an analogue smart skin. (b) Optical image of the transparent, flexible, and lightweight smart skin. The smart skin with a honey bee landing on it will not deform the peony. (c) SEM image of microstructures on the PDMS film. (d) SEM image of the Ag NW electrodes.

between the smart skin and the object (Figure 1a). Due to the remarkable transparency (shown in Figure S1) and flexibility of both PDMS film and the Ag NW electrodes, the object (a pink peony in Figure 1b) can be covered and clearly observed through the smart skin. The PDMS film was fabricated with a prepared Si mold and spin-coating method to form the microstructure and was then treated with C_4F_8 plasma²⁸ to form a surface with an electron affinity higher than that of the untreated plain PDMS film (Figure 1c). The flexible Ag NW electrodes were fabricated with good uniformity and conductivity, which is shown in Figure 1d and Figure S2.

The operating mode begins with one contact between the object (finger) and the surface of smart skins (Figure 2a). There are positive and negative charges on the surface of the finger and the PDMS film, respectively. At this time, the electrical field is confined to the space between the finger surface and the PDMS film, so that the electrode voltage will not be affected by the charges. When the finger separates and moves far away from the PDMS film, the negative charges on the surface of the PDMS film induces opposite charges on the electrodes. Due to the different distance between negative charges and electrodes, the amount of induced charges on opposite electrodes will be different. Therefore, different currents from the ground to each electrode will be formed as the finger moves away. When the finger is far enough away, we can conclude that the maximum charge on the electrodes is reached eventually. When the finger approaches the PDMS film again, the charges on the electrodes will be repelled and flow into the ground. Therefore, the negative current will be formed. Based on the different current and voltage (ground potential set to 0 V) of opposite electrodes, the location of the applied force can be defined. Considering the structure in Figure 1a, which contains two pairs of opposite electrodes orthogonally, a two-dimensional location can be defined on the surface. More

specifically, the pressure can be located by analyzing the ratio of opposite electrode voltages.

Electrostatic theory is used to analyze the working mechanism of analogue smart skins. Figure 2b shows the simplified model that considers each electrode as a point, as well as the area of surface electric charges on the finger and PDMS film. With this point charge simplification, the working mechanism can be presented straightforward and the output can be predicted. Due to the contact electrification effect, the finger and PDMS film will be charged with heterogeneous charges after contact. Both charges on the PDMS film and finger will set up an electric field. Setting infinity to 0 V and ground, the open circuit voltages of electrodes are determined by two point charges, $+Q$ and $-Q$ on finger and PDMS film. The open circuit voltage of the left electrode (U_1) and the right electrode (U_2) can be expressed as³⁴

$$U_1 = -k\frac{Q}{x} + k\frac{Q}{\sqrt{x^2 + h^2}}$$

$$= kQ\left(-\frac{1}{x} + \frac{1}{\sqrt{x^2 + h(v, t)^2}}\right) \quad (1)$$

$$U_2 = -k\frac{Q}{L-x} + k\frac{Q}{\sqrt{(L-x)^2 + h(v, t)^2}}$$

$$= kQ\left(-\frac{1}{L-x} + \frac{1}{\sqrt{(L-x)^2 + h(v, t)^2}}\right) \quad (2)$$

where k is the electrostatic force constant and L is the distance between two electrodes; v and t , in turn, are the contact velocity of applied force and time, respectively. Electrode voltages are profoundly affected by location of charge (x) and the distance

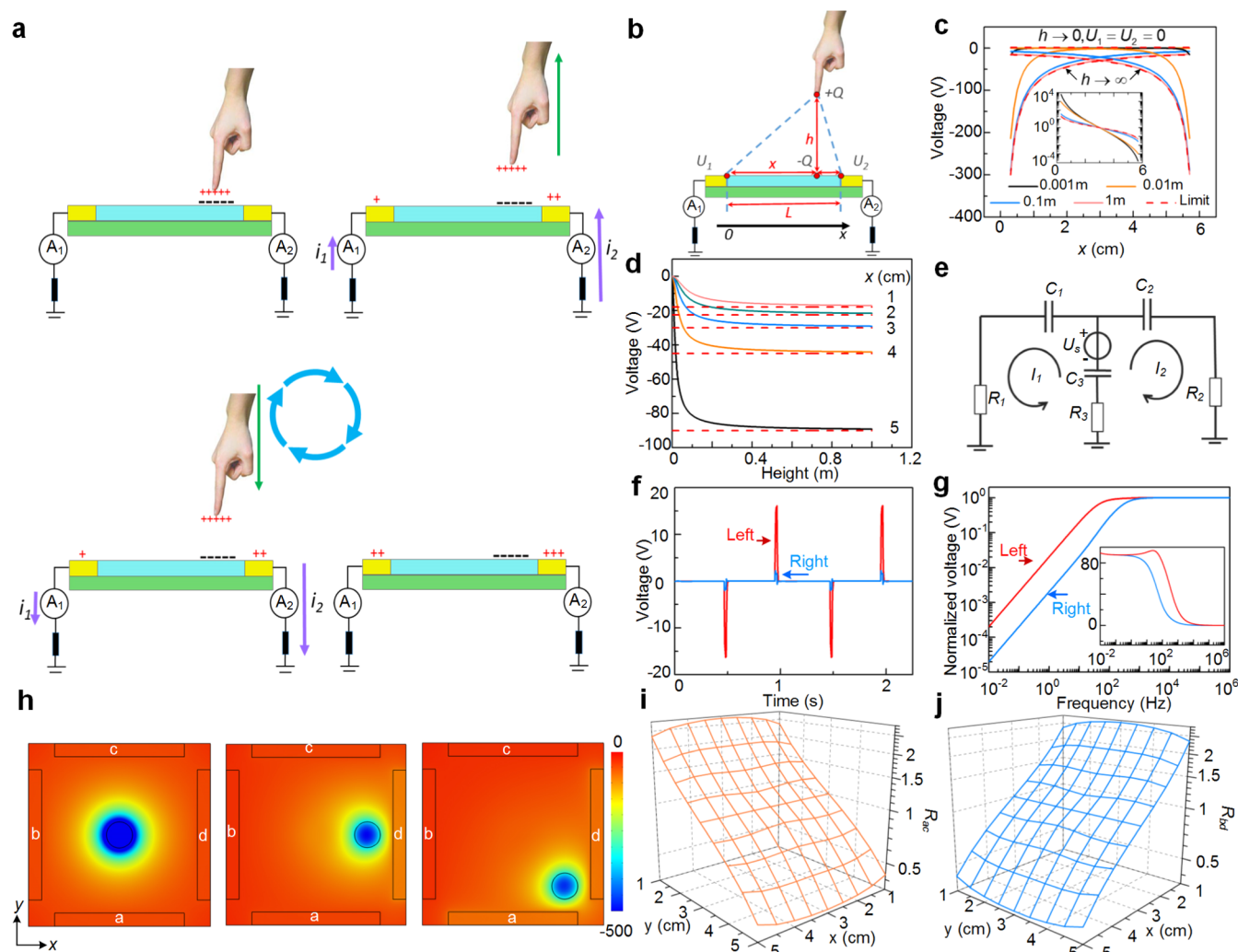


Figure 2. Working principle of analogue smart skins. (a) Charge distributions and currents in different working stages. (b) Electrostatic theory analysis of analogue smart skins. (c) Relationship between the electrode voltage and horizontal position. The inset shows the voltage ratio between the left electrode and the right electrode. (d) Relationship between the electrode voltage and horizontal position. (e) Equivalent circuit model of analogue smart skins. (f) Real-time voltage outputs of the right and left electrodes using the circuit diagram in (e) and SPICE. (g) Frequency domain analysis of analogue smart skins reveals that, at low frequency, the ratio of the electrode voltage is determined by ratio of C_1 and C_2 . At high frequency, the ratio tends to be 1. The inset of the phase frequency characteristic curve shows the phase shift at different frequencies. (h) Voltage distribution with different charge locations. The unit of voltage is volt. (i) Voltage ratio of electrode a and electrode c with the location of charges changing. (j) Voltage ratio of electrode b and electrode d with the location of charges changing.

between point charges (h). Figure 2c,d shows the trends when x and h change. When h is 0, $U_1 = U_2 = 0$ because the electrical field is located between the finger and the PDMS film as previously mentioned. When h increases (Figure 2d), the electrode voltage approaches $U_1 = -k\frac{Q}{x}$ and $U_2 = -k\frac{Q}{L-x}$. The limits depend on the horizontal positions of charges, which are apparent (red dashed line). Because of the structural symmetry, only the left electrode voltage is present in Figure 2d, and the right electrode voltage has similar trends. The voltage change will cause the current in the corresponding resistor when the resistance is finite. On the other hand, these trends also suggest that the final relative position of the finger and the PDMS film will affect the output voltage while the distance (h) is not large enough. Figure 2c reveals that the voltages of the left and right electrodes are influenced by the horizontal position of the negative charge on the PDMS film. The change of horizontal position can result in opposite monotonous trends of two electrode voltages. When the location of the charges moves

from the left side to the right side (x increases), the voltage ratio between the opposite electrode decreases monotonically (inset of Figure 2c). In addition, the ratio of U_1 and U_2 remains unaffected when Q changes because Q affects both U_1 and U_2 equally. This suggests that the voltage ratios have high stability and will not be disturbed by some condition changes such as humidity and temperature, which will affect triboelectric charges. Based on the monotonous continuous voltage ratio, analogue smart skins can attain infinite resolution in theory.

The equivalent circuit model presented in Figure 2e indicates that the distances between each electrode and finger can be replaced by capacitors. The horizontal position affects the capacitance of C_1 and C_2 . If the distance is farther, the capacitance will be smaller. Based on a human body model (HBM),³⁵ the human body is equal to a capacitor of 100 pF and a resistor of 1.5 k Ω connected in series (C_3 and R_3). To know the relationship between C_1 , C_2 , and electrode voltages,

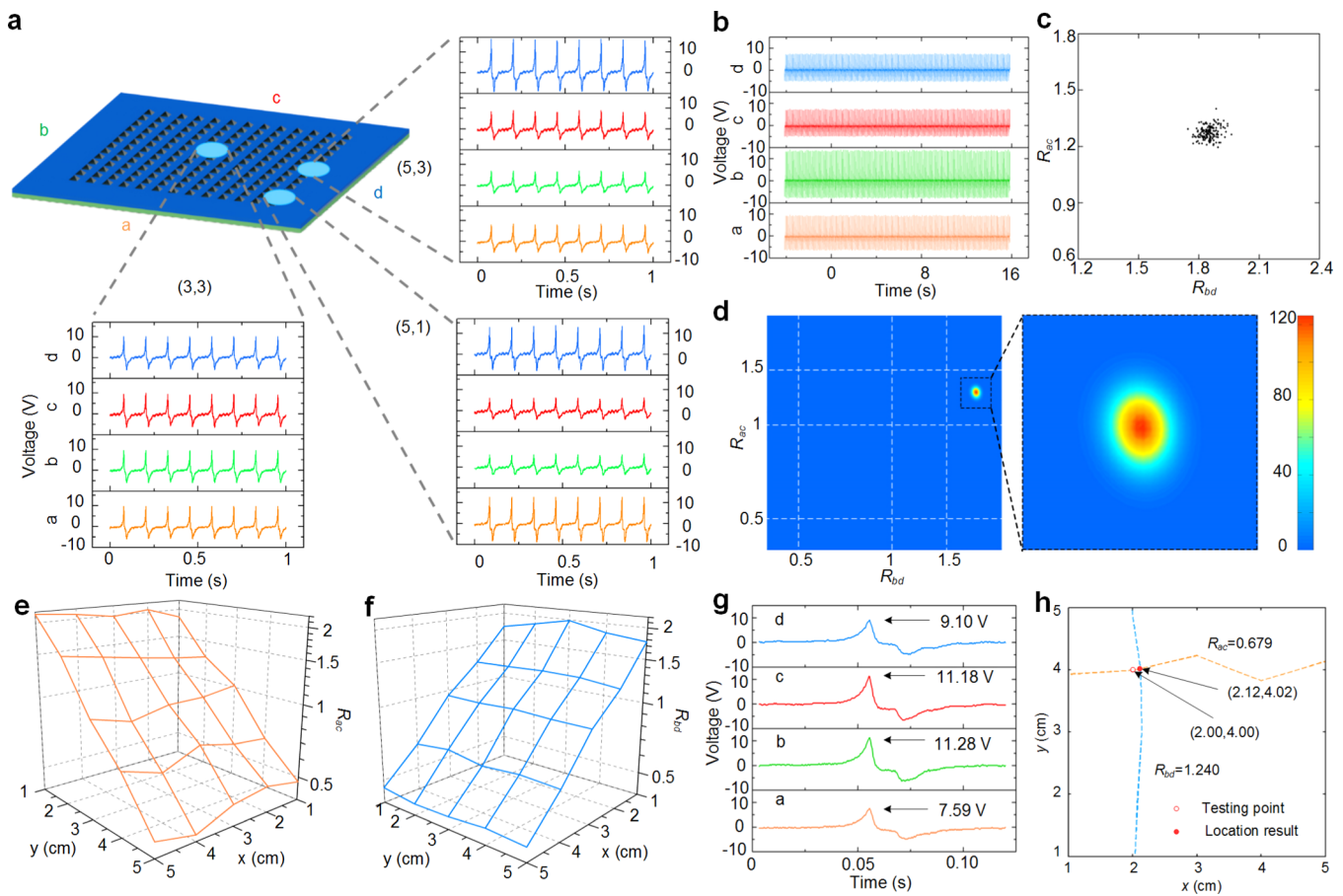


Figure 3. Measurement of the analogue smart skins on a plain surface. (a) Voltage outputs of four electrodes at feature points (3,3), (5,1), and (5,3). (b) Voltage outputs of four electrodes at point (1,2) (160 tests at 8 Hz). (c) 160 tests of voltage ratios of opposite electrodes at (1,2) show good centrality. (d) Statistical distribution of ratios in (c) with double logarithmic coordinates and two-dimensional normal distribution model. (e) Voltage ratio of electrode a and electrode c with 25 testing points, changing from (1,1) to (5,5). (f) Voltage ratio of electrode b and electrode d with 25 testing points, changing from (1,1) to (5,5). (g) Voltage output when one extra test was applied at (2.00, 4.00). The voltage ratios are $R_{ac} = 0.679$ and $R_{bd} = 1.240$. (h) Bottom surface projections of two contour lines in panel e at $R_{ac} = 0.679$ and in panel f at $R_{bd} = 1.240$ have one intersection point at (2.12, 4.02), which is the location result of the analogue smart skin.

eq 3 is derived by Kirchhoff's law and phasor method as follows:

It can be solved as follows:

$$\begin{cases} \dot{U}_s = \dot{U}_1 + \dot{U}_{C_1} + \dot{U}_{R_3} + \dot{U}_{C_3} \\ \dot{U}_s = \dot{U}_2 + \dot{U}_{C_2} + \dot{U}_{R_3} + \dot{U}_{C_3} \end{cases} \quad (3)$$

$$\begin{cases} \dot{U}_1 = \dot{U}_s \frac{j\omega^2 R_1 R_2 + \omega \frac{R_1}{C_2}}{j\omega^2 (R_1 R_2 + R_2 R_3 + R_1 R_3) + \omega \left(\frac{R_2}{C_1} + \frac{R_1}{C_2} + \frac{R_2}{C_3} + \frac{R_3}{C_2} + \frac{R_1}{C_3} + \frac{R_3}{C_1} \right) - j \left(\frac{C_1 + C_2 + C_3}{C_1 C_2 C_3} \right)} \\ \dot{U}_2 = \dot{U}_s \frac{j\omega^2 R_1 R_2 + \omega \frac{R_2}{C_1}}{j\omega^2 (R_1 R_2 + R_2 R_3 + R_1 R_3) + \omega \left(\frac{R_2}{C_1} + \frac{R_1}{C_2} + \frac{R_2}{C_3} + \frac{R_3}{C_2} + \frac{R_1}{C_3} + \frac{R_3}{C_1} \right) - j \left(\frac{C_1 + C_2 + C_3}{C_1 C_2 C_3} \right)} \end{cases} \quad (4)$$

The voltage ratio of the opposite electrodes is

$$\frac{\dot{U}_1}{\dot{U}_2} = \frac{j\omega C_1 C_2 R_1 R_2 + C_1 R_1}{j\omega C_1 C_2 R_1 R_2 + C_2 R_2} \quad (5)$$

Here, $\dot{U}_1$ and $\dot{U}_2$ are the phasor form of U_1 and U_2 and j is the imaginary unit. In eq 5, we find that the ratio of electrode voltages only depends on C_1 , C_2 , load resistance (R_1 and R_2), and frequency ω . Figure 2f presents the real-time voltages of the left and right electrodes, which are like pulse signals, using a circuit diagram in Figure 2e and simulation program with

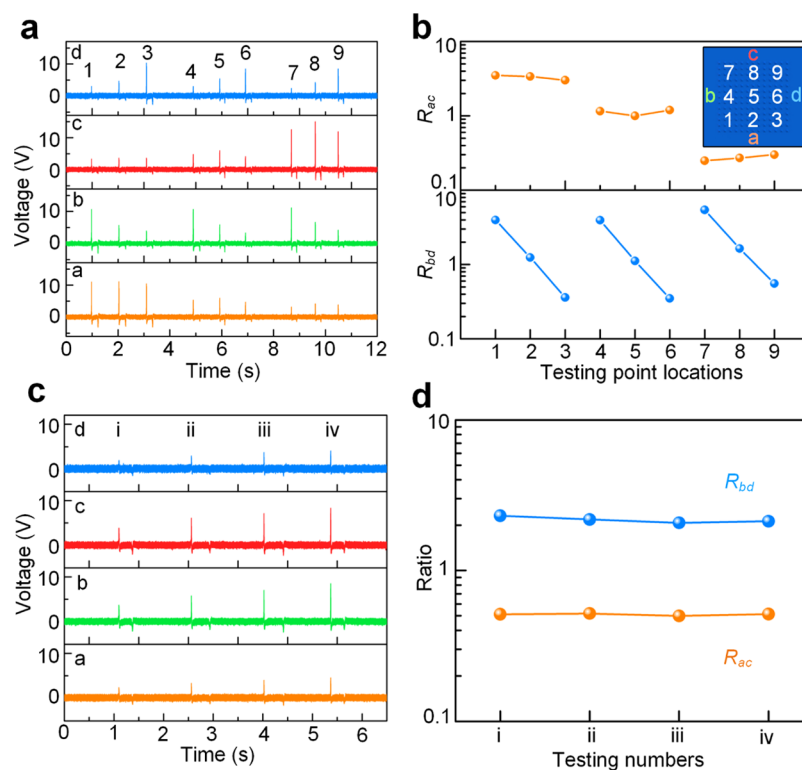


Figure 4. Influence of location and velocity on the output of analogue smart skins. (a) Voltage output and (b) voltage ratio of opposite electrodes when the smart skin is tested with a bare finger at nine different points shown in the inset of (b). (c) Voltage output and (d) voltage ratio of opposite electrodes when contact velocity successively increases from the first test to the fourth test. The tests are performed at the same point with a bare finger.

integrated circuit emphasis (SPICE). SPICE is a analog electronic circuit simulator used to predict circuit behavior.³⁶ The resistances of R_1 and R_2 are finite and set to 100 M Ω . The input of the circuit (U_s) is square wave (1 Hz, 100 V); C_1 is set to 50 pF, and C_2 is set to 5 pF. In Figure 2f, the pulse peak voltage of U_2 is 1.6 V, and U_1 is 16.3 V, about 10 times that of U_2 . It matches eq 5 because the ratio between C_1 and C_2 is 10. When C_1 and C_2 are very small, eq 5 can be simplified as $\dot{U}_1/\dot{U}_2 = C_1/C_2$. Frequency domain analysis of analogue smart skins is presented in Figure 2g. Amplitude frequency characteristics and phase frequency characteristics of two opposite electrodes are provided. In the low-frequency region (less than 30 Hz), the voltage ratio between the left electrode and the right electrode stabilizes at 10 because of the different capacitances between the contact point and two electrodes (C_1 and C_2). The input signal includes components of high frequency and low frequency, and the real response of it will be slightly less than 10, which is the weighted average of a response at all frequencies. Frequency domain analysis of typical actual signals can be found in Figure S3. The inset of Figure 2g demonstrates that the phase shifts of both electrodes, which depend on C_1 and C_2 , are $\sim 90^\circ$ when the frequency is less than 30 Hz. With increasing frequency, the phase shifts become different. It reveals that when the frequency is relatively high (~ 100 Hz), the different capacitances will result in a different signal delay in the left and right electrodes.

Using finite element analysis, we obtain the voltage distributions with different charge locations (Figure 2h and Figure S4). The voltages of electrodes a–d (denoted by E-a, E-b, E-c, and E-d) will change with the movement of applied force location, which causes negative charges and low potential on

the surface. In Figure 2h, the voltages of electrodes a and d decrease while the negative triboelectric charges approach these electrodes. The change rule of the electrode voltage of E-a with the movement of triboelectric charges is shown in Figure S5. Obviously, with the surface charges moving away from E-a, y increases, and the open circuit voltage (absolute value) of E-a will decrease. The change of x will slightly influence the voltage of the electrode. In this simulation, the height of positive charges (h) is identically equal to 50 cm. Due to the symmetry, the open voltage will follow the similar rule in every electrode when the applied force moves. Figure 2i,j shows the ratio of the top electrode voltage and bottom electrode voltage (a:c) and the ratio of the left electrode voltage and right electrode voltage (b:d), respectively, while the charge location changes. They show good monotonicity, which is especially significant for confirming the location of pressure. To locate the pressure, the voltage ratios of opposite electrodes (a:c and b:d) should be measured, denoted by R_{ac} and R_{bd} . The planes where $R_{ac} = \text{constant}$ and $R_{bd} = \text{constant}$ from two intersection lines with the curved surfaces are shown in Figure 2i,j, respectively. Then, the projection of the two lines on the bottom surface ($R_{ac} = R_{bd} = 0$) will have an intersection point, from which the location of the applied pressure can be determined.

The analogue smart skin shows good stability on the plain glass surface when a vibration of 8 Hz is applied and the amplitude is kept at 11 mm with a vibration generator system. The contact surface of the vibrator is a round PET film that is 1 cm in diameter, and the load resistance between each electrode and a reference ground is 100 M Ω . Figure 3a presents the voltages of four electrodes at feature points (3,3) (center of smart skin), (5,1) (corner of smart skin), and (5,3) (close to

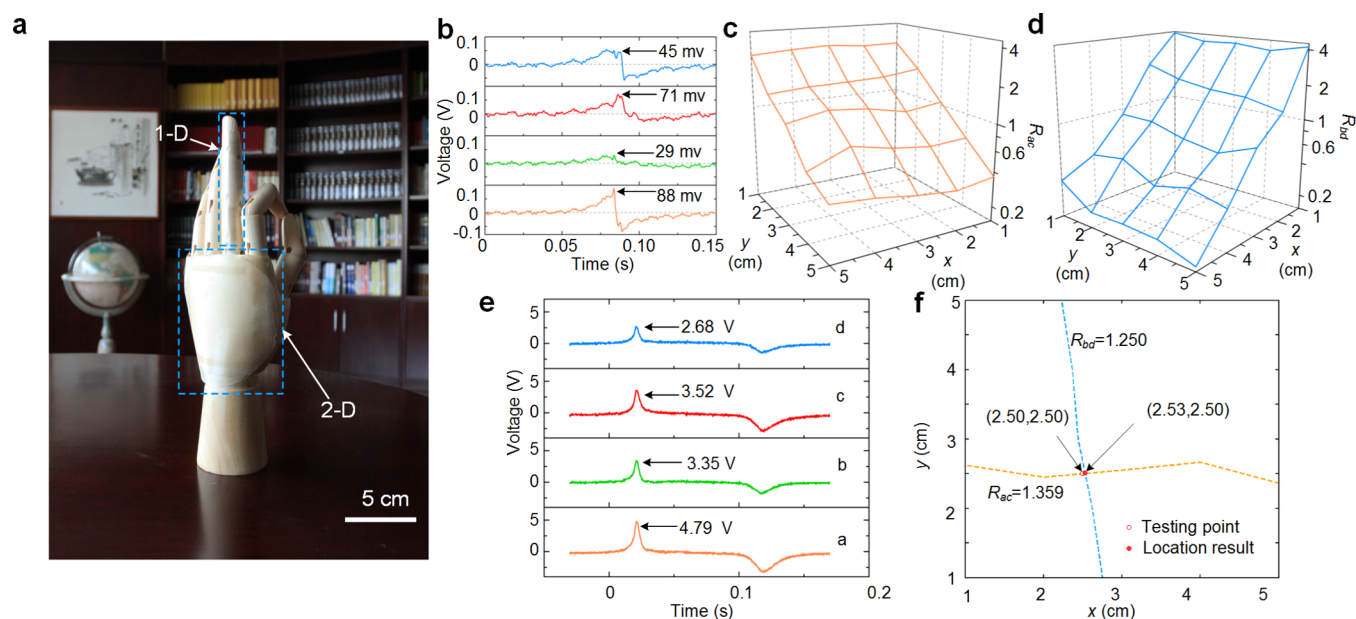


Figure 5. Use of smart skin on an artificial hand. (a) Photograph of an artificial hand covered by two-dimensional analogue smart skins on the curved back of the hand and one-dimensional analogue smart skins on the middle finger. (b) Voltage output when a honey bee approaches and leaves the two-dimensional smart skin swiftly. (c,d) Voltage ratios of electrodes a–d. (e) Voltage output when the two-dimensional smart skin on the artificial hand is touched. (f) Location result of analogue smart skins. The testing point is (2.50, 2.50), and the result is (2.53, 2.50), with a slight deviation of only 0.3 mm.

the middle of one electrode). At point (3,3), the peak voltages can get up to 10 V, with similar voltages on the four electrodes. However, at point (5,1), voltage on E-a and E-d is larger than that on the other two electrodes because the test point is closer. The test point is closest to E-d at point (5,3), so the voltage of E-d is the largest. At every point of integer location from (1,1) to (5,5), 160 tests were applied, with a total of 25 points. As a representative of a common situation, we show the 160 testing results in Figure 3b at point (1,2). In 160 tests, we obtained stable outputs, and the voltage ratios also show notable aggregation within the ratio range of 0.2 in Figure 3c. Figure 3d shows the probability density distribution of testing results with a two-dimensional normal distribution model. The oval-shaped distribution instead of a circular form shows that aggregation in the x direction is a little better than that in the y direction. Positive peak voltages are used to calculate the voltage ratio because they are more stable and notable than negative peaks. In most instances, the changing rate of touching velocity is larger than that of leaving velocity. It causes notable output enhancement of the positive peak voltage. Parameter estimations are performed in this step to obtain the voltage ratio expectation (denoted by μ , which is 1.27 in the a:c direction and 1.85 in the b:d direction), variance (0.033 in the a:c direction and 0.038 in the b:d direction), and correlation coefficient (0.045). The half width at half-maximum (hwhm) is 0.039 and 0.045 on the R_{ac} and R_{bd} axes, respectively. The entire distribution of 25 testing points can be found in Figure S6. When considering adjacent point (1,3), at which the voltage ratio expectation and hwhm in the R_{ac} direction is 1.02 and 0.041, respectively, the resolution from point (1,2) to point (1,3) can be estimated using $(\text{hwhm}_{ac,12} + \text{hwhm}_{ac,13})/(\mu_{ac,12} - \mu_{ac,13})$ in the R_{ac} direction (y direction). In this estimate method, we consider that the distance between (1,2) and (1,3) is 1 cm, which corresponds to the ratio changes from 1.27 to 1.02, and the solution is defined using a concept similar to that of the Rayleigh criterion. The resolution in the R_{ac} direction at

the region from (1,2) to (1,3) is ~ 3.1 mm. The solution in all regions can be found in Tables S1 and S2. The average resolution on the whole surface is 1.9 mm. A experimental verification of millimeter resolution is provided in Figure S7. In this verification, two points that are 2 mm apart are pressed successively. The location result proved that these two points are distinguishable with this analogue smart skin.

Specific monotonous trends of voltage ratio between opposite electrodes are presented in Figure 3e,f, while the test point changes. When the test point approaches E-a, R_{ac} increases almost inversely proportional. Meanwhile, R_{bd} increases when the test point approaches E-b. The voltage ratio of the opposite electrode ranges from 0.4 to 2, with good resolution. To determine the location of applied force using the method mentioned earlier, two voltage ratios are necessary. One location test was applied at (2,4), with the voltage output in Figure 3g. Based on the peak voltage, we can conclude that R_{ac} is 0.679 and R_{bd} is 1.240. According to the intersection of the two projections shown in Figure 3h, the location result is (2.12, 4.02), which presents excellent accuracy with the distance deviation of 1.2 mm. Figure 4a,b shows the output of nine tests at different points with a bare finger (Video S1). With the movement of testing points that are shown in the inset of Figure 4b, the voltages of four electrodes change regularly. When the testing point moves from left to right in one row, R_{bd} decreases and R_{ac} remains the same. R_{bd} decreases with the location change from the bottom row up. Different contact velocities affect the output at the same location (Figure 4c). With the increasing of contact velocity, the outputs of all electrodes evidently rise. However, the change of contact velocity has no influence on the ratio of opposite electrodes (Figure 4d), so it does not affect the location result. This property suggests the ability to detect the location and contact velocity at the same time. Figure S8 presents the effect of testing frequency (thus velocity) on output voltage with a vibration generator system. When the frequency decreases from

5 to 2 Hz, the output drops from ~ 9 to ~ 5 V. It demonstrates the ability to use this smart skin on the measurement of touch velocity. The analogue smart skins are very stable, which maintains the same output in 30 000 cycles (see Figure S9).

Self-powered analogue smart skin are powerful tools to help a robot feel the environment without any power supply. The smart skin shows remarkable location ability on the artificial hand (Figure 5). Before using the smart skin on an artificial hand, one-dimensional and two-dimensional analogue smart skins are prepared. They are fixed on the curved hand back and the middle finger (Figure 5a). The one-dimensional smart skin only needs two electrodes which are placed at the two opposite ends of the smart skin (Figure S10). It uses the same material and manufacturing process with the two-dimensional smart skin. In the one-dimensional location, we only need the voltage ratio in one direction, so the applied pressure can be accurately located by two electrodes. The demonstration of a one-dimensional smart skin is shown in Video S2 and Figure S11. Using a two-dimensional analogue smart skin, we can even test the disturbance of a honey bee, which is only 0.16 g (Figure 5b). In addition, the landing point of a jumping gryllus is conformed with this analogue smart skin, shown in Figure S12 and Video S3. The voltages of all the electrodes increase with the honey bee approaching it. When the honey bee flies away, electrodes present the negative peaks shown in Figure 5b. The different peak voltages reveal that the contacting point is near E-a in the x direction and E-d in the y direction (more specifically, based on the voltage ratio distribution in Figure 5c,d, the location result is (3.44, 2.85)). Figure 5c,d shows the voltage ratio distribution of the two-dimensional smart skin on the back on an artificial hand. Similarly, 25 points were tested, and at each point, we applied 160 tests. The voltage output and ratio distributions on the artificial hand were different from the distribution on the plain surface because the spatial locations of electrodes change and the metal components in the artificial hand slightly impact the distribution of the electric field. The solution of the smart skin on an artificial hand is calculated, and it can be found in Tables S3 and S4. The average resolution in all regions is 1.9 mm, which shows extraordinary stability compared with the smart skin on a plain surface.

After determining the voltage ratio distributions, we can use the distribution to test the location of pressure. In one demonstration, point (2.50, 2.50) was touched with a bare finger. The output is shown in Figure 5e. Peak voltages are in the range from 2.68 to 4.79 V. Voltage ratios are 1.359 in the x direction and 1.250 in the y direction. Therefore, the intersection of two projection lines shown in Figure 5f is the location result of analogue smart skins. In this test, the result is (2.53, 2.50) and it is in close proximity to the actual testing point with a slight deviation of ~ 0.3 mm.

CONCLUSIONS

The analogue smart skins, which are flexible, transparent, and lightweight, present a self-powered method to realize one-dimensional and two-dimensional locations fleetly with high resolution up to 1.9 mm, and the distance deviation can reach 1.2 mm at the plain surface test and 0.3 mm on the artificial hand. Additional functions can be integrated into analogue smart skin, such as contact velocity measurement. In the future, analogue smart skins show great potential to increase detection resolution and sensitivity with low cost because the theoretical estimation of resolution and sensitivity is much higher. In many

fields, such as artificial intelligence and bionics, the self-powered analogue smart skin shows bright prospects.

MATERIALS AND METHODS

Fabrication of a Si Mold. The (100)-oriented silicon wafer with thermally grown SiO_2 was prepared. Using lithography, a square window (10 μm length and 10 μm gap between each other) was left on the SiO_2 layer. Then a reactive ion etching process was performed to etch out the SiO_2 with SF_6 and to expose the silicon. The residual photoresist was cleaned with acetone. Using the SiO_2 with square windows as the hard mask, KOH solution (together with isopropyl and deionized water) etching was applied and Si molds with pyramid structures were prepared. The mold was treated with trimethylchlorosilane (J&K Scientific) by gas phase for 30 min to change the surface property and make it easier to remove the PDMS film.

Fabrication of the Microstructured PDMS Film. Elastomer and the cross-linker (Sylgard 184, Dow Corning) were prepared in the ratio of 10:1 (w/w). The mixture was placed on the Si mold by the spin-coating method at 500 rpm for 120 s and was heated at 100 $^\circ\text{C}$ for 10 min. The Si mold was removed carefully, and the PDMS film was microstructured. Then the PDMS film was treated with C_4F_8 plasma to make the surface better for charge transfer.

Preparation of a Silver Nanowire solution. The commercial Ag NW ethanol solution (5 mg/mL, LEADERNANO) was first diluted 10 times and then centrifuged at 6000 rpm for 10 min to remove polyvinylpyrrolidone. After supernatant was removed and commensurable ethanol was added, the solution was centrifuged at 6000 rpm for 10 min again. Second, after supernatant was removed, moderate ethanol was added to dilute the concentration of the solution to 1 mg mL^{-1} .

Fabrication of Silver Nanowire Electrodes. Silver nanowire solution was dropped on the PET film and then spin-coated at 1500 rpm for 30 s. This step was repeated 10 times. The sample was then placed on the hot plate at 100 $^\circ\text{C}$ for 30 min to anneal. Lithography was used to pattern the electrode. After exposure and removal of the photoresist by acetone, the sample was developed in $\text{Fe}(\text{NO}_3)_3$ aqueous solution (10 wt %) for 5 min to remove the extra Ag NWs. The sample was rinsed with deionized water, and then the remaining photoresist was removed with acetone. After being washed with deionized water and dried, the film with Ag NW electrodes was ready.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.nano.5b07074.

Detailed supporting figures and tables of the resolution, simulation, and detailed measurement of one-dimensional smart skin (PDF)

Real-time live view when the two-dimensional smart skin is tested at nine different points (AVI)

Real-time live view when the testing point moves from left to right on the one-dimensional smart skin (AVI)

Real-time live view of a gryllus landing on the smart skin with obvious voltage outputs (AVI)

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Notes

The authors declare no competing financial interest.

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