Supplementary Materials for

Biomimetic temperature-sensing layer for artificial skins

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Published 1 February 2017, Sci. Robot. 2, eaa9251 (2017)
DOI: 10.1126/scirobotics.eaa9251

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Methods

Pectin film

Current-voltage characteristic

Figure S1 shows the current-voltage characteristic of a typical pectin film. The characteristic is linear and does not contain major bumps, steps or discontinuities. This is generally a sign of absence of major electrical defects in the bulk of the material or contacts’ defects.

Fig. S1. Pectin film. Current vs. voltage characteristic of a pectin film. Each circle represents a measurement point.
Control experiments

Figure S2 shows the conductivity as a function of temperature of three different samples: \( \text{Ca}^{2+} \) crosslinked pectin films, pectin films with water but without crosslinking ions, and 32mM CaCl2 solution.

**Fig. S2. Conductivity variation as a function of temperature in control experiments.** Red dots \( \text{Ca}^{2+} \) crosslinked pectin. Dark orange dots: pectin. Blue dots: pure water. Black dots: 32mM CaCl2 solution.
Current-temperature characteristics

Figure S3a shows the temperature and current measurements as a function of time for a typical pectin film. The experiment was performed by increasing the temperature of the film from 8 to 30°C and then from 30 to 39°C using a hotplate. Temperature was monitored using a thermal camera (FLIR A655sc) directly pointing to the film. The current across the device was monitored using a source meter (Keithley model 2635) and followed the temperature profile measured by the thermal camera. The temperature-current relation is exponential.

![Temperature vs. Time](image1)

**Fig. S3. Current-temperature characteristics of a pectin film and corresponding Arrhenius plot.** (a) Temperature and current on a pectin film as a function of time. The blue line reports the current measured in the film. The red line represents the temperature of the film measured by the thermal camera. (b) Arrhenius plot of electrical conductivity derived from Fig. S3a.

Figure S3b shows the Arrhenius plot of the conductivity of the pectin film. The activation energy can be derived from the slope of the line in the Arrhenius plot, multiplying it by the gas constant, as follows:

$$E_a = \text{Slope} \times R = 9.85 \text{ K} \times 8.31 \text{ J K}^{-1}\text{ mol}^{-1} = 81.9 \text{ kJ mol}^{-1}$$

Bending

Figure S4 shows the bending positions corresponding to experiment in Fig. 3A.
Fig. S4. Bending positions corresponding to experiment in Fig. 3A.
**Temperature mapping skins**

Figure S5 shows the setup for the temperature measurement of films with multiple electrical contacts (herein referred to as “skins”). Figure S5a shows a 4-pixel configuration. The architecture of the skin is reported in Fig. 3C. The bottom insulator is made of silicon dioxide thermally grown on a silicon wafer, while the top insulator is a PDMS layer or acetate sheet. Chromium/gold contacts were sputtered on the bottom insulator. The same configuration was used for the 16-pixel skin, shown in Fig. S5b.

![Fig. S5. Setup for the electrical measurements performed on skins. (a), 4-pixel skin. (b), 16-pixel skin.](image)
Read out circuit

Figure S6 shows the schematic of the read out circuit used for the 4-pixels skin. Figure S6a shows a diagram of the working principle: when temperature increases in correspondence of the pixel P11, the electrical resistance decreases locally. Thanks to the high sensitivity, the variation of resistance affects the series of resistances of the entire row and column as in Fig. S6a. This principle is similar to the one showed in Movie S1. Thus the local change in resistance is conveniently measurable interrogating each row and column in a separate time interval. This is done by allowing current to circulate in the row or column by switching on each CMOS couple. Only one row or column is on at any given time. Figure S6c shows an example of row 1 being read. Figure S6d shows the signals used to enable the reading. A buffer and an amplifier are used to condition and transfer the signals from the skin to the DAQ board. The DAQ read-out occurs when the enabling signal reaches its maximum value.
As responsivity and sensitivity are intrinsic characteristics of the material the only non-uniformity between rows columns is in their absolute current level. This is due to a non-perfectly uniform thickness of deposition of the material on its substrate. Prior to performing the experiments reported in Fig. 3D,E the absolute current levels of each row and column were leveled at room temperature, via the external resistors of the readout circuit in Fig. S6c.
Fig. S7. Voltage at the readout circuit for every row and column in a 4-pixel skin. Light blue: signals from row 1. Red: signals from row 2. Violet: signals from column 1. Green: signals from column 2. All the time scales in the panels are between 0 and 10 sec. All amplitudes are between -1 and 4.3 except for P22, column 2, which is between -1 and 7 (as indicated in the corresponding panel). All signals for each finger position are acquired synchronously. The panels indicated by the letter “H” represent the highest signals for each row and column.
Figure S8 shows the current as a function of time in row 1 when P11 is touched for ~1 sec. The noise level was undetectable, confirming that noise in the measurements of Fig. S7 was due to the readout circuit.

**Fig. S8. Current versus time when the film is touched with a finger.** The black dots report the current measurements. The blue shadowed region represents the finger’s contact time on the skin.
Figure S9 shows the thermal fingerprint on the film, as acquired by the thermal camera. The image was taken immediately after lifting the finger that was in touch with the skin for ~1 sec. The temperature increase caused by the finger was less than 1 K, compared to temperature of the rest of the skin.

**Fig. S9. Thermal image of the skin just after being touched with a finger.** The image shows the temperature map obtained with the thermal camera after a finger touched the skin in position P11 (light green area). All values in the color intensity bar are expressed in °C.
To prove that the sensitivity of the skin is due to temperature changes and not pressure, we pressed the skin with a rounded metal part for ca. 5 sec, as shown in Fig. S10 (red panel). The skin was then touched with a finger, for the same length of time (green panel). When the skin was in contact with the metal tip, which was approximately at the same temperature of the skin, its effect on the current-time plot was negligible. However, when the skin was in contact with the finger, which was warmer than the skin, a current increase was evident.

Fig. S10. Effect of pressure and temperature on a 4-pixel skin.
Measurement results on a 16-pixel temperature mapping skin

We tested a 16-pixel skin, as shown in Fig. S5b, placing a warm (26°C) aluminum square in contact with the skin. Figure S11 shows the thermal image of the skin, obtained after 0.8 sec. This image corresponds to the pixelated picture in Fig. 3F. Table S2 shows the values obtained from the skin, reported in Fig. 3E. To obtain these values, the acquisition rate used was 10 samples/sec, which corresponds to 1.25 samples/sec/channel.

![Fig. S11. Aluminum square in contact with the 16-pixel skin.](image-url)
Figure S12 shows a typical thermal response measured at three different frequencies on a pectin film samples. The current is reported in arbitrary units since it was measured as the RMS value of the voltage drop on a resistor (50 kΩ) in series with the sample (see inset of Fig S12). No responsivity difference between measurements at different frequencies and d.c. measurements was found.

Fig. S12. Alternating current measurements on the pectin films.
Measurement results on a 4-pixel temperature mapping skin

We report in Tab. S1 and Fig. S7 the results obtained from measurements on a 4-pixel temperature mapping skin. To obtain these measurements and locally increase the temperature on each pixel, we position a finger for ~2 sec on a different quadrant of the skin. Table S1 shows the values representing the product of the signals in Fig. S7, when the finger is in each of the 4 positions (P11, P12, P21, P22). The table is obtained considering only the maximum voltage variation for each row and column (R1, R2, C1, C2). These values are multiplied as follows: R1C1, R1C2, R2C1, R2C2, the results are normalized for each experiment and reported in the schematics of Tab. S1. The sampling rate was 100 s\(^{-1}\) and the averaging was 5 points per channel.

Table S1. Values corresponding to the block diagrams, with color map shown in Fig. 3D.
Table S2. Values corresponding to the block diagram, with color map shown in Fig. 3E.

|    | C1   | C2   | C3   | C4   |
|----|------|------|------|------|
| R1 | 0.45 | 0.49 | 0.59 | 0.59 |
| R2 | 0.59 | 0.63 | 0.76 | 0.76 |
| R3 | 0.77 | 0.82 | 1.00 | 0.99 |
| R4 | 0.74 | 0.79 | 0.96 | 0.95 |

a.c. measurements
Large area sensors

Supplementary Movie 1 shows an experiment with a large area sensor. A cup of coffee (covering less than a ninth of the film’s surface area) was placed in the middle of the film while electrical current was monitored as a function of time, in parallel to the acquisition by a thermal camera and an optical video. To explain the current measurements, we associated a lumped element model to the sensor area. The resistance of the uniform film is concentrated into nine resistors (3 branches of 3 resistors in series, as shown in the white schematic diagram superimposed to the digital images in the video) connecting the two electrodes (cyan lines in the video). We assumed that only the resistor under the cup is contributing to the current increase, in proportion to the area under the cup and to its temperature variation (see thermal images in the video). We also assumed that the resistance change under the cup corresponds to the measurements reported in Fig. S3a, from which we derived that $R(30^\circ C) = 0.36 \times R(22^\circ C)$. We measured a current change across the large area of $\Delta I = 6.6\%$ between 22 and 30°C. This value agrees with the assumption that the material has the same sensitivity as the one measured in the small films (Fig. 1A,E). The high responsivity of the pectin hydrogels is responsible for the ability to capture local events in large films, though without identifying the precise location and spatial dimension of the temperature source.

**Movie S1. Large-area film testing.** Results of an experiment performed on a sample A4 paper size with carbon tape electrodes, supported by a glass substrate and covered with an acetate sheet. In the movie, at time frame, $t = 1$ sec, we show on the left a flexible film sample, and on the right the same sample deposited on a glass slide for testing. At time $t = 14$ sec, we show imaginary lines dividing the sensor in 9 areas and the corresponding lumped elements model composed of 3 parallel branches of 3 resistors in series. At time $t = 19$ sec, we show that the resistor associated to the area heated by the cup changes color, to represent its dependence on temperature. At time $t = 30$ sec, we show in parallel a thermal camera video (on the top left corner), the current measured across the sensor (in the top right corner), and the corresponding optical video with superimposed schematic of the electrical model (bottom left corner). At time $t = 52$ sec we show the change in resistance estimated from Fig. S3a, which explains the change in current measured across the film, highlighted in cyan in the current-time plot.