FLEXIBLE ELECTRONICS

Sophisticated skin

Advances in materials science and layout design have enabled the realization of flexible and multifunctional electronic devices. Two demonstrations of electronic skins, which combine temperature and pressure sensing with integrated thermal actuators and organic displays, unveil the potential of these devices for robotics and clinical applications.

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Skin is a large, flexible and robust organ that covers and protects the body from external damage. At the same time it has an important sensory role, it is the attachment site for touch, pain and thermoreceptors. This multifunctional biological model is inspiring the development of electronic equivalents — referred to as 'electronic skin' — consisting of large-area networks of sensors that detect pressure, temperature and other environmental stimuli, and are usually realized on pliable or stretchable substrates. These devices have been proposed as advanced biomimetic prostheses and diagnostic tools, as well as a means to provide robots with sensory perceptions, an ambitious technological goal that brings to mind the 'machine-human' in the science-fiction movie *Metropolis* or the sentient android Data in *Star Trek*. Engineers and materials scientists are working on the functional complexity of these sensors — adding data processing and actuation capabilities — and on their mechanical properties, aiming to realize devices that conformably adapt to the skin and ensure a reduced risk of tissue reaction or alteration of the normal biological functions. Writing in *Nature Materials*, two independent groups now report the fabrication of electronic skins that complement sensing tasks with added functionalities: Ali Javey and co-workers report a flexible touch sensor with integrated output capabilities[1] and John Rogers and colleagues describe an array of thermal sensors and heaters that enable full thermal characterization of human skin with an accuracy that is unavailable with other methods at present[2].

Javey and collaborators[1] developed a sophisticated electronic skin that is able to detect pressure stimuli, the intensity of which are simultaneously displayed on an integrated array of organic light-emitting diodes (OLEDs). Each pixel of this electronic skin consists of a pressure sensor and a thin-film transistor that controls the current driving a coloured OLED. It is noteworthy that this complex architecture, comprising materials rather unconventional for the electronics industry, such as carbon nanotubes, organic semiconductors and carbon nanoparticles, can be attained on large areas and with high yield using conventional microfabrication processes. Arrays of 16 × 16 coloured pixels were realized on a polyimide substrate, resulting in a free-standing, flexible electronic display whose brightness can be locally tuned by the touch of a finger (Fig. 1; right inset). Pressure sensing is of course only one example of the possible integrated systems that can be enabled by the fabrication strategy demonstrated by these researchers; it is easy to imagine analogous mapping and direct visualization of other detectable events, such as temperature variations, exposure to chemicals or bonding to biological molecules, achieved by simply modifying the sensing element of each pixel. Immediate applications may be foreseen in interactive input–output devices, for example in autonomous, reusable touch panels that can be adapted to any curved surface and allow the user to directly see the intensity of their touch on it.

Rogers and colleagues[2] demonstrated an electronic skin that enables precise measurements of temperature variations on human skin. The system uses thin metal films or thin nanoscale silicon membranes to realize temperature-sensitive arrays of resistors or diodes, respectively; these components are embedded between two polyimide layers that have a thickness of just 1 μm, which electrically insulate the devices and provide an effective barrier to moisture. The vertical symmetry of this membrane configuration places the electronic parts in the neutral mechanical plane (the horizontal section where the stress is minimized during mechanical deformations) making the electronic skin remarkably robust against bending. The ultrathin membrane can be directly laminated on the epidermis, which has a comparable elastic modulus: this similarity allows an enhanced conformal contact between the two surfaces (as shown by the laminated array withstanding

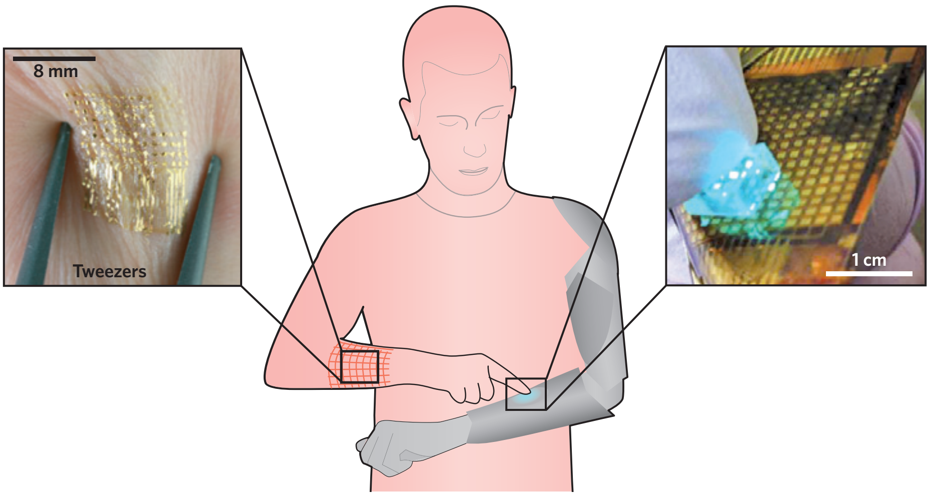

Figure 1 | Humanoid robots in science fiction inspired the development of electronic skin with a sensory perception similar to that of humans. Left: Ultrathin conformal electronic films on elastomeric substrates gently adhere to human skin, and follow the pinching of the skin in a twisting motion. Such films enable precision thermometry of the skin[2]. Right: Local light emission from the touched array illustrates a user-interactive touch panel[1].

pinching and twisting in the left inset of Fig. 1), and reduces discomfort to the user, who eventually will not feel the presence of the device on the skin. The researchers also show that the arrays can be mounted on microperforated elastomeric substrates, enabling perspiration of the tissues and allowing temperature measurements to be made with an accuracy of a few millikelvin, even during intense sweating. Importantly, they take advantage of the dual functionality, as sensors and actuators, of the thin metal films to release known amounts of heat and measure the resulting temperature increase, thus assessing the local thermal conductivity and water content of the skin. These compliant devices could therefore be used as wearable health-monitoring tools, collecting clinically relevant information on blood flow and tissue hydration outside hospital settings.

The various constraints — resistance to mechanical stress, high flexibility, stability of the electronic and sensing performance under repeated bending and flexing, and ageing — imposed by the applications envisaged for these devices pose non-trivial problems[3] that must be addressed by proper design and a careful combination of materials with different mechanical properties[4]. Building on the proof of concepts reported by Javey[1] and Rogers[2], the implementation of a bendable OLED display that is responsive to temperature for robotic applications, where relatively bulky device configurations can be tolerated, may be straightforward. However, complying with the additional constraints of biomedical applications, such as a conformal contact with the epidermis[5] and minimized discomfort to the user, will definitely need more technological effort. Recent demonstrations of imperceptible electronic devices have shown a high degree of integration between sensors, actuators and transistors[6]; further, these devices are 'mechanically invisible' (which means that the elastic properties of the devices match those of the surface onto which they are applied). However, at this stage, the possibility of including ultrathin OLEDs that demonstrate stable performance when put in contact with skin or exposed to air has not yet been proven.

Fully autonomous systems will also require an independent power supply, therefore highly flexible and even mechanically stretchable batteries[7,8], supercapacitors[9] or other energy-storage elements will need to be integrated. Furthermore, electronic skin will benefit from energy-efficient and adaptable computation systems on board, which are able to filter, elaborate and react to the received stimuli. In this sense, other biological models, such as bees, which have a body mass of less than a gram and are able to perform extremely complex flying skills with a brain that dissipates less than 10 μW of power (ref. 10), may inspire the next steps in this research field. Although, at present, we are far from achieving this state of the art found in nature, looking at the speed of new developments in electronics there is no doubt that there will be rapid progress towards fully integrated electronic skins in the future. ❐

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