Wearable skin sensors for in vitro diagnostics

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Wearable skin sensors can monitor body signals with high sensitivity and wide dynamic range, enabling in vitro diagnostics and the use of therapeutic devices.

Recent advances in in vitro diagnostics on human skin or organ surfaces rely on the use of sensors, LEDs, and signal transmitters. Having wearable diagnostic and therapeutic devices with high sensitivity and wide range is key to ‘ubiquitous’ health care, where technology can monitor and improve a patient’s condition.

Skin-attachable sensors comprise two major components: an adhesive patch for stable fixation on the human skin or organ surface, and a biosignal detection or wiring component for in vitro diagnostics. A biomedical patch acts as a supporting layer, allowing a reliable transfer of vital or mechano-signals (e.g., blood pressure or heart rate) to the sensor matrix. An electric active layer monitors various dynamic biosignals with high sensitivity and wide dynamic range. In this article, we describe our recent achievements in bioinspired design to fabricate a dry adhesive skin patch and a layered strain gauge sensor for in vitro diagnostics.

To create the patch, we used structural characteristics based on gecko foot hair to produce high-density micropillars with a bulged tip. These maximize normal and shear adhesion on a rough skin surface: see Figure 1(A). Such mushroom-shaped pillars, made of soft polydimethylsiloxane (PDMS), are less affected than conventional acrylate-based adhesives by surface contamination, oxidation, and other environmental factors. Also, the micropillars provide better long-term biocompatibility because of increased ventilation.
We then produced composite micropillars made of stiff and soft PDMS materials: see Figure 1(A). These composite, mushroom-tipped micropillars can be fabricated by direct replica molding of rigid-bottom versions and selective inking of the soft tip layer. The integrated composite micropillars showed a normal adhesion force of up to \( \sim 1.8 \text{Ncm}^{-2} \) (maximum: \( \sim 2 \text{Ncm}^{-2} \)) on human skin, as well as high durability (\( \sim 30 \) cycles) without notable degradation.

We further demonstrated the adhesive's use as a fixative unit to monitor an electrocardiogram for 48 hours at two locations on a volunteer's skin (chest and wrist): see Figure 1(B). Although such a skin patch is still difficult to use under highly dynamic conditions—say, running—we observed no side effects such as allergy, redness, or skin damage during most daily activities (e.g., walking, sitting, and sleeping).

To enable detection of biosignals, we developed a layered strain gauge sensor based on nanoscale mechanical interlocking between metal-coated, high-aspect-ratio nanofibers: see Figure 2(A). This van der Waals force-assisted interlocking is modeled on the wing-locking device of a beetle, where densely populated microhairs on the cuticular surface are brought together to enhance the lateral shear force. Specifically, in contrast with other detection systems, our nanointerlocking mechanism does not involve any complex, integrated nanomaterial assemblies or layered arrays, allowing for a simple, cheap, yet robust sensing platform for highly sensitive, large-area strain gauge sensors.

The flexible sensors can measure and distinguish three different mechanical loads in the form of normal pressure, shear, and torsion with high sensitivity and wide dynamic range by interpreting each gauge factor (\( \sim 11.5 \) for pressure, \( \sim 0.75 \) for shear, and \( \sim 8.53 \) for torsion) with high repeatability (<8000 cycles).
Figure 2. (A) Schematic illustration for the assembly of a flexible strain gauge sensor based on reversible interlocking of nanofibers. The scanning electron microscopy image shows platinum-coated polymer nanofibers. (B) Operation of a the sensitive and wearable sensor. (C) Measurement of a heartbeat under normal (∼60 beats per minute with an average intensity of ∼100Pa) and exercise conditions (∼100bpm with an average intensity of 300∼400Pa). PDMS: Polydimethylsiloxane. $R_{\text{off}}$, $R_{\text{on}}$: Resistance (ohms) of the sensor system when switched on and off.

We measured the physical force of a heartbeat in real time by attaching the sensor over the artery of a volunteer's wrist with the aid of a medical adhesive: see Figure 2(B). We monitored the heartbeats under two conditions: normal (∼60 beats per minute with an average intensity of ∼100Pa) and exercise conditions (∼100bpm with an average intensity of 300∼400Pa): see Figure 2(C). We could differentiate the signals by discernible magnitudes and frequencies, suggesting that the sensor could be used as a diagnostic device to measure, among other things, unique patterns of beating frequency and levels of blood pressure.6

We are currently investigating the development of a ‘theranostic’ medical patch incorporating dual functions of biosignal monitoring and drug delivery. Our research could aid the development of more biocompatible, long-term skin-attachable devices for use in wearable sensors, electronic skin, and implantable medical devices.

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