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Dual-mode tactile sensors for body movement recognition and physiological signal detection

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Abstract
The emergence of multi-responsive flexible devices signifies a revolutionary era in human-machine interfaces, aiming for more realistic and diverse interaction modes. This paper develops an ultra-sensitive polyurethane (TPU) / multi-walled carbon nanotube (MWCNT) electronic skin (e-skin) which can precisely detect both pressure, strain, or their combinations at different levels in real time without signal overlap. The proposed e-skin integrates a flexible, biomimetic PDMS microcone structure with a cracked TPU/MWCNT conductive network, exhibiting exceptional sensitivity by a positive resistance response to strain (630, 70%) and a negative resistance response to pressure (-0.14004 kPa^{-1}, 0~2.5kPa), as well as a wide pressure detection range (200kPa) and strain detection range (70%). Furthermore, the e-skin's durability was confirmed through repeated mechanical loading cycles (>10,000 cycles), highlighting its potential for long-term wearable applications. Extensive tests have confirmed that the proposed e-skin is capable of accurately distinguishing a series of precise physiological signals and joint movements such as pulse, heartbeat, breathing, blink and maintain reliable performance among multiple activities including bending, stretching, and pressing. This research contributes to the growing field of wearable electronics by providing a robust, skin-friendly interface capable of enhancing the efficiency and diversity of human-machine communication.

Dual-mode tactile sensor, piezoresistive sensor, PDMS microstructure, cracked TPU/MWCNT conductive network

1. Introduction

The development of electronic skin (e-skin) that mimics the multifunctional properties of human skin and overcomes the limitations associated with traditional sensors using rigid substrates [1,2], has gained significant attention in various applications [3-7], such as intelligent robotics, wearable medical devices, and motion detection, driving innovations in human-machine interfaces.

The emergence of multi-responsive flexible devices signifies a revolutionary era in human-machine interfaces, aiming for more realistic and diverse interaction modes. Sensing technologies based on mechanisms such as thermoresistive, pyroelectric, piezoresistive, triboelectric, capacitive, and piezoelectric have been integrated in hybrid configurations to achieve collecting data in different types for multi-modal e-skin by creating multiple sensing units and connecting each unit smoothly. However, incorporation of multiple sensing units in e-skin increases the complexity of fabrication, often leading to issues with interfacial stability between materials. Furthermore, the wide range of materials needed for the production of individual sensors reduces the overall cost-effectiveness of the manufacturing process [8-10]. Therefore, a wearable device with solo sensing unit capable of detecting multiple stimuli is considered crucial for simplifying processing and exploring further miniaturization and integration towards an intelligent future.

This study proposes an advanced e-skin sensor utilizing the piezoresistive effect, which provides both dynamic and static detection capabilities essential for finger behavior recognition. By leveraging electrospinning and coating deposition process to fabricate a flexible, three-dimensional nanofiber conductive network composed of thermoplastic polyurethane (TPU) and multi-walled carbon nanotubes (MWCNTs), the sensor achieves superior mechanical flexibility and performance. The pre-stretched "island-bridge" microstructure, formed via controlled cracking, enables detection of pressure and strain through distinct, non-overlapping signals. While cracks are typically seen as defects to avoid, they can be beneficial when introduced in a controlled manner. Additionally, a bio-inspired polydimethylsiloxane (PDMS) membrane, designed with micro-nano structures, improves the dynamic response of the sensor. This design not only enhances the sensor's sensitivity across a wide detection range but also maintains its durability under repetitive mechanical loads. Furthermore, the proposed e-skin was thoroughly characterized in terms of morphology and electrical properties, confirming its performance and underlying mechanisms. A series of tests demonstrated the e-skin's capability to reliably monitor physiological signals and joint movements.

2. Design and preparation of dual-mode e-skin

2.1. Preparation of the electrospun TPU membrane

Electrospinning technique was introduced to fabricate the TPU nanofiber membrane. TPU pellets were initially dried in a vacuum oven at 80°C for 24 hours and then dissolved at a 20 wt% concentration in a solvent mixture of DMF and EAC (2:1 volume ratio). The solution was magnetically stirred at 80°C for 8 hours to achieve complete dissolution. The electrospinning process was carried out at a room temperature of 25-30°C with 60% humidity, an applied voltage of 15 kV, a working distance of 15 cm between the needle tip and the collector, a roller speed of 100 rpm, and a solution flow rate of 2 mL/h. The electrostatic force caused the solvent to evaporate rapidly, resulting in the formation of a continuous nanofiber membrane on the collector. Finally, the resultant TPU nanofiber membrane was vacuum dried at room temperature for 12 hours to eliminate as much of the remaining solvent as possible, shown as Step 1 in Fig.1.

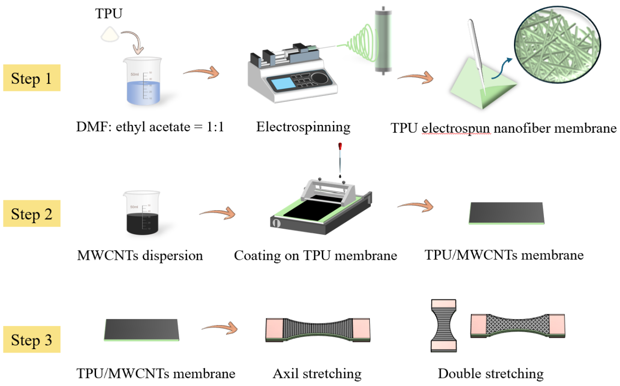

Figure 1. The preparation process of sensing layer. Step 1: Electrospun TPU nanofiber membrane, Step 2: MWCNTs coated on the TPU nanofiber membrane, Step 3: TPU/MWCNTs membranes in uniaxial and biaxial tension, respectively.

2.2. Preparation of the micrometer-scale cracked TPU/MWCNTs Membrane

Coating techniques and stretching methods were introduced to prepare the micrometer-scale cracked TPU/MWCNTs membrane. The TPU fiber membrane was pre-cut to a size of 30 mm × 100 mm and 0.5 mL of MWCNTs aqueous dispersion was uniformly applied onto the TPU nanofiber membrane at a travel speed of 5 mm/s. Subsequently, the membrane was affixed to a flat surface and dried in a low-humidity, well-ventilated environment at room temperature for 3 hours. Once dried, the membrane was sectioned into 30 mm × 30 mm samples and mounted onto a tensile machine to stretch at strain of 100% with a rate of 2 mm/s. The samples will be divided into two groups in uniaxial and biaxial tension, respectively. The desired micrometer-scale cracked structure can be effectively created within the membrane through the above stretching. This entire process has been illustrated in Step 2 & 3 in Fig.1.

2.3. Preparation of PDMS layer with biomimetic microcone structures

The dual-template method was employed to fabricate PDMS layer featuring micro-conical structures that mimic the surface of Broussonetia papyrifera leaves, as illustrated in Fig.2. Fresh Broussonetia papyrifera leaves were thoroughly rinsed with deionized water, air-dried at room temperature for 20-30 minutes, cut into 25 mm × 25 mm sections and secured inside a culture dish. Then, degassed PDMS (5:1 mixing ratio of base and curing agent) was poured over the leaf template and cured in a vacuum oven at 65°C for 4 hours. After curing, the PDMS negative mold was carefully removed, and any residual leaf material was ultrasonically cleaned with 70% ethanol until all remnants were eliminated. To prevent the formation of strong chemical bonds between the negative mold and the substrate, a thin gold film was applied to the surface of the negative microstructure via a magnetron sputtering device for 120 seconds. Finally, the prepared PDMS (10:1 mixing ratio of base and curing agent) was poured onto the negative mold and cured again in a vacuum oven at 65°C for 4 hours. Upon completion of the curing process, the PDMS layer with micro-conical structures replicating the surface of the Broussonetia papyrifera leaf was carefully peeled off, yielding the desired biomimetic structures.

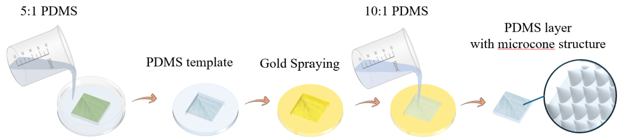

Figure 2. The preparation process of the PDMS layer.

2.4. Assembly of the dual-mode E-skin

The flexible, high-performance, and durable e-skin is constructed using a combination of micrometer-scale cracked TPU/MWCNTs membrane, biomimetic PDMS layer, PU layer, and copper foil, presented in Fig.3. The copper foil attached to both ends of the micrometer-scale cracked TPU/MWCNTs membrane is served as electrodes, with copper wires used as leads. Next, a smooth PDMS membrane with a thickness of 0.5 mm is applied to the exposed MWCNTs side, while a PDMS membrane featuring a biomimetic micro-cone structure is applied to the exposed TPU side. The entire assembly is then encapsulated within a high-elasticity medical-grade PU layer, resulting in a sandwich-structured sensor with the micrometer-scale cracked TPU/MWCNTs membrane positioned at its core.

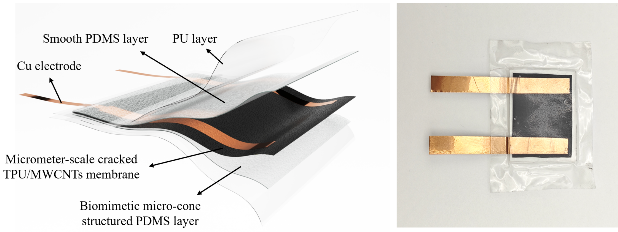

Figure 3. Encapsulation structure and appearance of the sensor.

3. Characterizations and tests of dual-mode e-skin

3.1. Surface characterization of membranes and e-skin

As shown in Fig.4 (a), the TPU fiber network displays a well-organized structure with fiber diameter observable at the microscopic scale ranging from 0.6 to 1.3 micrometers, ensuring consistent mechanical performance of the nanofiber membrane. The presence of these thicker fibers establishes favorable conditions for integrating a larger number of conductive CNT particles onto the fiber network in the following procedure, thereby enhancing the creation of extra conductive pathways. The TPU electrospun fiber membrane, upon coating with a high-concentration MWCNTs solution, exhibits a uniform deposition of MWCNTs across its surface. As shown in Fig.4 (b) a smooth and uniform layer of MWCNTs has been coated on the surface of the unstretched TPU nanofiber membrane.

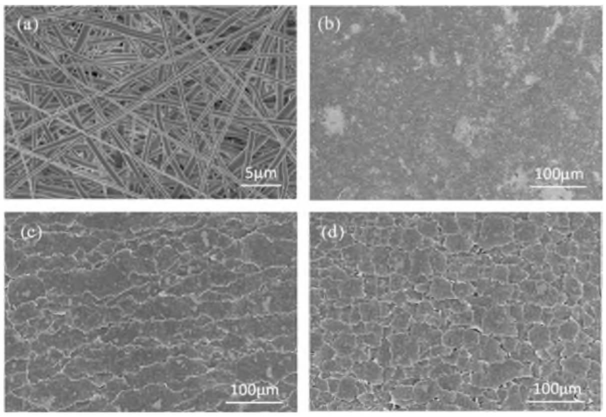

Figure 4. (a) Electrospun TPU fiber membrane. SEM images showing the pre-stretching process of the MWCNT layer: (b) unstretched, (c) uniaxially stretched, and (d) biaxially stretched.

After uniaxial and biaxial stretching, numerous lateral and perpendicular cracks formed on the surface as presented in Fig.4 (c) and (d), resulting in stripe and grid-like patterns of cracks across the entire fiber membrane surface, respectively. To evaluate the advantages of the cracks, we adopted TEM to closely observe the cracks in Fig.5 (a) and (b), and found that the conductive network, which maintains electrical continuity between electrodes, primarily consists of these MWCNTs conductive islands ("islands") and the MWCNTs attached to the surface fibers of the TPU ("bridges"). When the membrane is subjected to compressive forces, a rapid increase in the number of contact points between the "bridges". facilitating the quick connection of the "islands," while the tunneling resistance between adjacent conductive fillers within the layer decreases, resulting in a significant decrease in resistance between the electrodes.

We further demonstrated the successful replication of the microcone structures on PDMS layer, as shown in Fig.5 (c) and (d). These images demonstrate that the microcone structures are relatively uniformly distributed. The sizes of the micro-cones align with expectations, with the majority exhibiting a base diameter ranging from approximately 100 to 150 µm and a height distribution between 60 and 120 µm. The introduction of micro-cone patterned PDMS into the sensors effectively enhancing the sensor's performance in pressure detection, which is primarily attributed to diverse elastic deformations under varying forces due to the geometric characteristics of the microcone patterned structures.

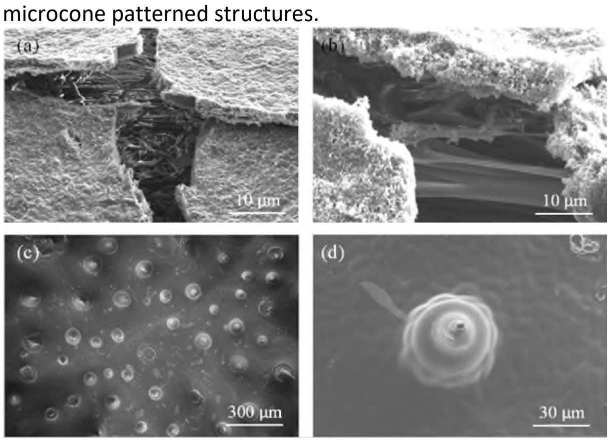

Figure 5. FIB-SEM image of (a) crack fracture and (b) the TPU fibers with adhered MWCNTs. SEM image of (c) the micro-structured PDMS membrane and (d) one bio-inspired micro-cone.

3.2. Electromechanical performance of the dual-mode e-skin

Fig.6 (a) illustrates the electrical response of the sensor under varying pressures. The pressure sensitivity S_p is defined as follow:

The sensor exhibits a high sensitivity of 140.04 Pa^{-1} in the low-pressure range (0~5 kPa), which decreases to 2.47 Pa^{-1} in the high-pressure range (5~100 kPa). This trend indicates that as the applied pressure increases, the conductive network within the MWCNTs layer becomes progressively compacted, leading to the formation of additional conductive pathways on the TPU substrate and a consequent enhancement in conductivity, which results in a significant decrease in relative resistance. Moreover, stress concentration occurs at the local microcracked regions of the TPU/MWCNTs layer, leading to a more sensitive response under low pressure.

Fig.6 (b) presents the sensor's electrical response under different strains. The strain sensitivity G_F is defined as follow:

As strain increases, the relative resistance of the sensor rises sharply, with sensitivity also increasing correspondingly. This behavior is attributed to the gradual disruption of the conductive network formed by overlapping MWCNTs blocks. As these pathways are broken, electrical conductivity decreases, resulting in a rapid increase in relative resistance. Nevertheless, the robust TPU fibrous network can retain conductive particles, allowing stable conductive paths to persist under certain strain conditions, thereby enabling consistent electrical signal output. As shown in Fig.6 (c), there were no significant changes in relative resistance at any of the stretching rates, indicating that the sensor possesses an excellent ability to detect different external stimuli consistently across all stretching rates.

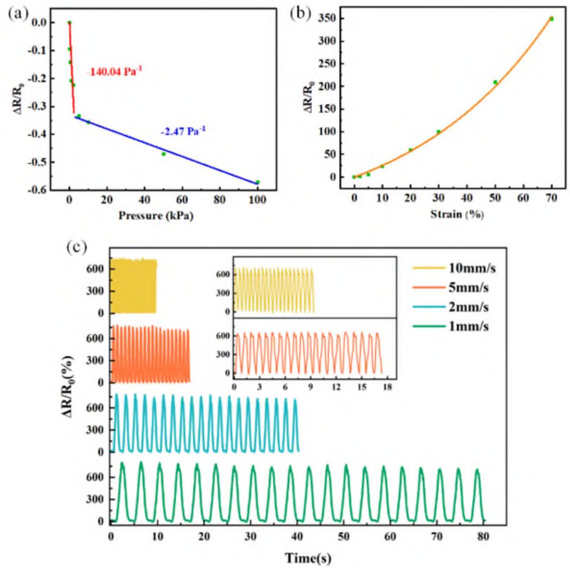

Figure 6. (a) pressure sensitivity of the sensor. (b) strain sensitivity of the sensor. (c) relative resistance curves under 20% strain were recorded at stretch rates of 1 mm/s, 2 mm/s, 5 mm/s, and 10 mm/s during a 20-cycle stretching-releasing test.

3.3. Tests of the dual-mode e-skin in human motion

As shown in Fig.7 (a), the sensor maintains stable resistance without external contact. Under cyclic finger pressing (Fig.7 (b)), it produces rapid, repeatable resistance drops and recoveries. During finger joint bending (Fig.7 (c)), resistance increases sharply with strain and returns upon release, showing high consistency. For pulse monitoring (Fig.7 (d)), the sensor detects periodic resistance fluctuations corresponding to heartbeat cycles. In blink detection (Fig.7 (e)), eye closure causes a rapid resistance rise, and reopening leads to a quick drop, with signal amplitude reflecting blink strength and speed. In steering wheel grip tests (Fig.7 (f)), the sensor responds sensitively to gripping/releasing actions and reflects grip strength through resistance changes. During heart rate monitoring (Fig.7 (g)), two distinct signal peaks represent ventricular contraction and relaxation, with a cardiac cycle of 0.8~0.9 s, consistent with physiological data. For respiratory monitoring (Fig.7 (h)), the sensor tracks chest movement, with resistance variations indicating breathing cycles and depth. These results confirm the sensor's high sensitivity, stability, and repeatability across multiple physiological and motion detection scenarios, supporting its potential in real-time health and driver monitoring applications.

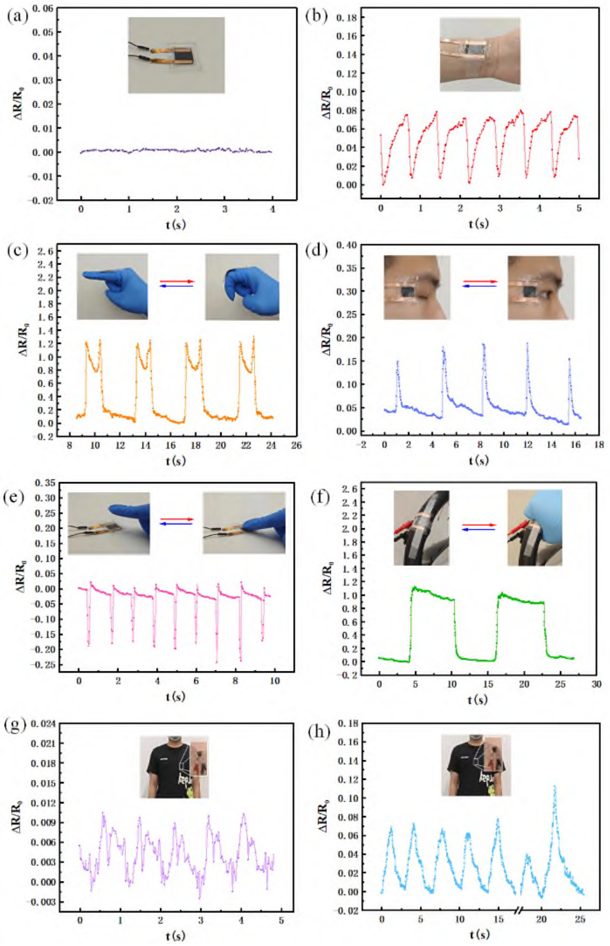

Figure 7. Applications of the e-skin in detecting various body signals, including (a) static state; (b) finger pressing; (c) finger joint bending; (d) wrist pulse; (e) blinking motion; (f) steering wheel gripping; (g) heart rate; (h) respiration rate.

4. Conclusion

In this study, we successfully developed a miniaturized, highly sensitive and multifunctional electronic skin capable of distinguishing between pressure and strain stimuli through non-overlapping signals. It demonstrates remarkable electromechanical performance, characterized by rapid response times (response time of 78ms, recovery time of 63ms) and excellent fatigue resistance across numerous cycles (>10,000 cycles). The unique structural design, particularly biomimetic microstructures and the controlled introduction of microcracks within the MWCNT layer, plays a pivotal role in achieving high sensitivity (pressure: -0.14004 kPa^{-1}, 0~2.5k; strain: 630, 70%) and a broad operational range (pressure: 200kPa; strain: 70%) for both compressive and tensile forces. The comprehensive characterization of the e-skin underscores its potential for various smart applications, including wearable motion detection. The integration of biomimetic microstructures and advanced conductive materials enhance the device's mechanical robustness and detection efficiency, making it a promising candidate for future applications in future health detection.

5. Acknowledgement

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