Wearable pressure sensor for athletes’ full-range motion signal monitoring

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Abstract

In order to real-time grasp of various physiological signals of athletes during sports, a high-performance flexible pressure sensor that can monitor various physiological signals and human motion was designed. Porous polydimethylsiloxane (PDMS) foam prepared by the sacrificial template method and graphene as raw materials were used to prepare a flexible pressure sensor with wide working range (0–100 kPa), ultra-high sensitivity (the average sensitivity in the range of 0–30 kPa is 17.9 kPa⁻¹, the sensitivity in the range of 30–100 kPa reaches 79 kPa⁻¹), fast response ability (response time is 20 ms) and long-term work stability (more than 10 000 cycles). The excellent performance of this pressure sensor depends on the use of PDMS foam with a high elastic modulus and the graphene loading level is controlled to an appropriate ratio. Finally, we used the conductive porous PDMS foam based flexible pressure sensor to demonstrate accurate and real-time monitoring of athletes’ tiny physiological signals (including pulse and electrocardiograph signals), vocalization and facial emotions, as well as violent joint and limb movements (including joint bending, walking, squats, jogging, and jumping), showing the potential in coaching athletes.

1. Introduction

In recent years, due to the wide application prospects of flexible wearable electronic devices, many researchers have been interested [1–4]. As an important part of wearable electronic devices, flexible pressure sensors have attracted widespread attention due to their huge application potential in human motion detection, human physiological health monitoring, and human–computer interaction. At present, according to the working mechanism of the pressure sensor, it can be divided into a transistor type [5], a capacitance type [6], a piezoelectric type [7] and a resistance type [8, 9]. Among them, the resistive type flexible pressure sensor which usually consists of a conductive sensing element and a flexible polymer substrate, can convert the pressure signal applied to the sensor into an electrical signal [10, 11]. Due to the simple preparation, good operation flexibility and high sensitivity of resistive pressure sensors, they have gradually gained extensive research interest [12, 13].

At present, various strategies have been developed to prepare resistive flexible pressure sensors with the required sensitivity and pressure response range. For example, conductive materials such as metal nanowires [14–16] and carbon nanomaterials [17–24] are used as sensing elements [8, 11, 25], but there are still some distances for wide application. On the one hand, the preparation process of flexible pressure sensors is usually cumbersome, and on the other hand, it is difficult to obtain high sensitivity and wide pressure response range at the same time. Therefore, the flexible pressure sensor is limited to detect signals in a full range of athletes’ sports including vigorous limb movements and tiny human physiological signals. So, it is important to produce flexible pressure sensors with wide response range and high sensitivity on a large scale and low cost. The conductive porous polymer foam is an ideal material for manufacturing flexible resistance pressure sensors due to its good electrical conductivity and mechanical flexibility. In recent years, some researchers have prepared some conductive foams with high conductivity and good mechanical properties, such as conductive foams using...
carbon black combined with PU foam, and conductive foams obtained by soaking conductive nanomaterials on commercial sponges [22–24, 26–28].

In this work, we used a two-step method to prepare a conductive polydimethylsiloxane (PDMS) foam with excellent mechanical properties, and construct a flexible pressure sensor with ultra-high sensitivity and wide response range. First, a porous PDMS foam having a high elastic modulus was prepared by a sacrificial template method. After that, the porous PDMS foam is immersed in the graphene/ethanol solution, so that the PDMS foam fully contact the conductive graphene sheet, and a conductive PDMS foam is obtained. The sensitivity of the flexible pressure sensor constructed with this conductive foam is as high as 79 kPa$^{-1}$. In addition, it has a wide pressure response range (0–100 kPa) and cyclic stability under more than 10 000 times of high pressure, which ensures that the sensor can accurately detect the athlete’s full range of detection from tiny physiological signals to large limb movements.

2. Experiment

2.1. Preparation of conductive porous PDMS foam-based flexible pressure sensor

The process for preparing conductive porous PDMS foam-based flexible pressure sensor is: (1) mix the monomer and curing agent of PDMS uniformly according to a weight ratio of 10:1, and then spread the NaCl particles into the PDMS solution. (2) After putting at room temperature for 1 h, it was cured at 80 °C for 4 h. (3) dissolve the NaCl particles in the solidified PDMS with deionized water, and obtain a porous PDMS foam after drying. (4) immerse the porous PDMS foam in a 5 wt% graphene/ethanol solution for 5 min, and obtain the conductive porous PDMS foam after drying. (5) cut the conductive porous PDMS foam into rectangular strips, and apply conductive silver glue on both ends to connect with copper wires to obtain a flexible pressure sensor.

2.2. Characterization of graphene and porous PDMS foam

Morphological characterization of graphene and porous PDMS foam by field emission scanning electron microscope. The Raman spectrum of graphene was characterized by a Raman spectrometer with an excitation wavelength of 532 nm.

2.3. Sensing performance measurement of flexible pressure sensors

The Shimadzu universal testing machine and Keithley 2400 digital source meter were used to characterize the electro-mechanical properties of the pressure sensor. Shimadzu universal testing machine applies pressure to the pressure sensor and uses a digital source meter to collect the corresponding current signal.

2.4. Detect physiological signals and exercise signals of athletes during exercise using the flexible pressure sensor

Use medical tape to fix the sensors at different positions on the athlete’s body to detect signals during exercise. The specific operations are: fixing the sensor at the wrist radial artery to detect the pulse signal; fixing at the two wrists to monitor the electrocardiograph (ECG) signal; fixing at the throat to detect the sound signal; fixing at the face to detect facial expressions and fixing at the finger, wrist, ankle and knee to detect signals during exercise.

3. Result and discussion

3.1. Preparation and material characterization of conductive PDMS foam

The method for preparing porous PDMS foam based on the NaCl sacrificial layer is not only simple to operate, but the NaCl particles can be recovered and reused. PDMS has excellent flexibility and high elastic modulus, which meets the requirements of wide pressure response and mechanical flexibility of pressure sensors. The preparation process of conductive PDMS foam is shown in figure 1. Porous PDMS foam can be obtained by pouring a uniformly mixed PDMS solution into NaCl particles and then curing and dissolving the NaCl. Because the particles of NaCl are uniform and tiny, the obtained porous PDMS foam has tiny pores. In this work, we used high-quality few-layer graphene sheet as the conductive material, ethanol as a solvent to configure a 5 wt% graphene/ethanol solution. The porous DMS foam was fully immersed in a 5 wt% graphene/ethanol solution for 5 min, and then taken out and dried to obtain a conductive porous PDMS foam. The reason for using ethanol as the solvent is that the surface tension of ethanol is small, which is beneficial for graphene to fully immerse into each pore of PDMS foam. Because the concentration of the graphene solution is relatively small, it can give PDMS foam a large initial resistance, reaching 100 kΩ. When the sensor is under pressure, it has a higher current limit, which is beneficial to the sensor’s better electrical response and achieves better sensitivity.

Figure 2(a) is a photo of a porous PDMS foam prepared by the sacrificial template method, which is opaque and can be cut to any size. Figure 2(b) shows photographs of PDMS foam before and after loading graphene in a
After soaking, the conductive PDMS foam appears black. The purpose of using ethanol as the dispersion is that ethanol is easier to carry the GO sheet into the gaps of the PDMS foam than water, thereby helping the GO to be fully doped into the PDMS foam. In order to characterize the full immersion of graphene in every pore of PDMS, we cut the conductive porous PDMS foam and observed the filling of graphene at the cross section with the SEM (figures 2(c), S2) showing that the PDMS foam is covered with graphene uniformly, which guarantees uniform electrical conductivity of the material. Figure 2(d) is a Raman spectrum of the graphene flakes which shows that the graphene sheet has a very small D peak, indicating that graphene has few defects. The intensity ratio of the 2D peak to the G peak is greater than 1, indicating that graphene is few layers.

3.2. Mechanism study of the conductive PDMS foam-based flexible pressure sensor
Flexible pressure sensors based on conductive PDMS foam have ultra-sensitive performance depending on their rich pore design. As shown in figure 3, in the initial state, the pores in the conductive PDMS foam are in an unfolded state, and the graphene sheets on both sides of the pores are separated from each other without contacting. At this time, the resistance of the device is at the maximum. When external pressure is applied, the pore volume in the conductive PDMS foam will become smaller, which will cause the graphene on both sides of the pores to gradually contact, resulting in a reduction in electrical resistance. When the external force is withdrawn, the pores return to the original state again, the graphene is separated again, and the resistance returns to the original state. The mechanical characterization of the pure PDMS sponge and GO doped sponge as shown in figure S1 is available online at stacks.iop.org/MRX/7/105003/mmedia. After adding GO, the stress on the PDMS foam will increase. Therefore, the real-time resistance changes of the flexible pressure sensor can be sensitively detected when an external force is applied. This design has two advantages. Firstly, the amount of
graphene on the surface of the conductive PDMS foam is not large, and the initial resistance of the device is high. In the recovery phase of the device, the graphene will be separated in time to improve the stability of the device. Secondly, the base material of the device is PDMS, which has a higher elastic modulus, can withstand greater pressure during deformation, and increases the pressure response range of the device.

3.3. Electrical-mechanical properties of the conductive PDMS foam-based flexible pressure sensors

To characterize the performance of this flexible pressure sensor, we used a universal testing machine and a Keithley 2400 digital source meter to investigate its electrical-mechanical properties. Figure 4 (a) shows the change in current of the sensor with increasing pressure. The results show that under the pressure of 0–100 kPa, the current of the device increases monotonically. The sensitivity of the device can be expressed by gauge factor (GF) [29]:

$$ GF = (I - I_0) / (I_0^8 P) $$

Among them, $I$ is the current of the device after applying pressure; $I_0$ is the initial current of the device; $P$ is the external pressure applied.

The device’s relative current response can be divided into two parts (figure 4(a)). At low external pressure (0–30 kPa), GF is about 17.9 kPa$^{-1}$. When the external pressure is small, the pores in the conductive porous PDMS foam will be squeezed, which will cause the contact area to increase, so the resistance of the device will decrease, and the current will increase. When the applied pressure gradually increases, the compressive amplitude of the pores in the foam increases, and the contact between graphene on both sides of the cavity increases, causing the resistance of the device to further decrease. Therefore, under large external pressure (30–100 kPa), the sensitivity of the device is as high as 79 kPa$^{-1}$. Since the pressure generated by human movement is generally below 100 kPa, the sensor can meet the needs of detecting full-range human movement. The ultimate stress test of the sensor is about 140 kPa, and within the range of 0–140 kPa, the device can respond

![Figure 3. Pressure-sensing model of the conductive porous PDMS foam-based flexible pressure sensor.](image)

![Figure 4. Electromechanical properties of the conductive porous PDMS foam-based flexible pressure sensor.](image)
The ultra-sensitive and wide pressure response range of this flexible pressure sensor is significantly higher than similar sensors [26, 30–32].

In addition to the sensitivity and wide response range of a flexible pressure sensor, its fast response capability and long-term stability are also important. Figure 4(b) shows the response time of the device, showing that the response time of this device is less than 20 ms, which is advantageous for detecting complex and fast movements in real time. Figure 4(c) shows the current curve of the pressure sensor when the device applies a pressure of 1 kPa at different frequencies. It shows that the current variation of the sensor has almost no frequency dependence, and can detect signals during fast motion. Figure 4(d) shows that the current-voltage curve of the pressure sensor has good stability under different pressures.

In order to characterize the cyclic performance of the device, we tested the current response of the device under different pressures. Figure 5(a) shows the current response of the device under cyclic pressures of 10 Pa, 20 Pa, and 100 Pa. It shows that the device can sensitively detect small pressures and the current changes are uniform, giving the pressure sensor the ability to monitor the minute movements of the human body. When the external force is increased to 15 kPa, 30 kPa, and 60 kPa, the current response of the device is shown in figure 5(b), which shows that the device can detect the athlete’s vigorous exercise. The long-term cycling stability of pressure sensor is essential for real-time monitoring of athlete signals. As shown in figure 5(c), we applied 50 kPa pressure to the sensor and performed 10 000 cycles of testing. The pressure sensor exhibits a highly stable current response, which is essential for practical applications and can ensure the stability of athlete signals for long-term detection.

3.4. Detect athlete’s sports and physiological signals

Due to the flexible pressure sensor has extremely high sensitivity, wide response range, fast response time, and long-term work stability, we use this device to comprehensively detect athletes’ sports signals, including detecting the pulse and electrocardiogram signal (ECG) signals of athletes during exercise, voices and facial expressions of athletes and movements of joints and limbs of the body. Figure 6 shows the monitoring of the pulse signal of the pressure sensor during athlete exercise. First, we attached the sensor to the radial artery of the athlete’s wrist to detect the athlete’s pulse signal (figure 6(a)). Figure 6(b) shows the pulse signal collected within 10 s during the athlete’s exercise. Among them, there are 18 pulse waveforms, indicating that the athlete’s heart rate is 108 beats per minute. Figure 6(c) shows the specific peak signal of a single pulse waveform. The striking wave (P wave), tidal wave (T wave) and diastolic wave (D wave) in the signal can be clearly distinguished [33]. Furthermore, we fixed the sensors on the two wrists of the athlete to monitor the ECG signals in real time. We attached the sensor to the athlete’s wrist and the ECG signals of the athletes are shown in figure 7, showing a repeating stable ECG waveform.

The ultra-sensitive flexible pressure sensor can also be used to detect vocal and facial expression signals of athletes (figures 8 and 9). Figure 8(a) shows the device attached to the athlete’s throat. When the athlete speaks, the athlete’s throat will vibrate, which will cause the pressure on the sensor to fluctuate. Figures 8(b)–(d) show the changes in the relative current detected by the sensor when the athlete repeatedly said ‘haha’, ‘running’, and ‘sport’. The signals induced by speaking different words are repeatable and distinguishable, indicating a
Figure 6 Application of the conductive porous PDMS foam-based flexible pressure sensor in athlete pulse signal detection. (a) Photograph of detecting athletes’ pulse signals using pressure sensors, (b) Relative current change of pressure sensor caused by pulse beat when athlete is running, (c) Close-up of the pulse waveform detected by the pressure sensor.

Figure 7 Application of porous PDMS foam-based flexible pressure sensor in ECG signal detection of athletes.

Figure 8 Application of the porous PDMS foam-based flexible pressure sensor in detecting athlete’s voice. (a) Photograph of detecting athlete’s voices using the pressure sensors, (b)–(d) Relative current change of pressure sensor when they say ‘haha’, ‘running’ and ‘-sports’.
potential application of the sensor in capturing human speech by monitoring voice muscle movements. Figure 9(a) is a schematic diagram of the device attached under the eyes of the athlete, near the mouth and face to monitor the expression of emotions. A flexible pressure sensor installed under the eyes easily detects strain caused by eye movements. The movement of the eyeball will cause different deformations of the surrounding rectus muscle, resulting in a unique and distinguishable current change signal (as shown in figure 9(b)). Figures 9(c), (d) show the changes in the relative current detected by the sensor when the athlete smiles and cheek blows respectively, demonstrating the great potential of this sensor in mood analysis.

Based on the conductive porous PDMS-based flexible pressure sensor, it can not only sensitively detect tiny physiological signals, vocalizations and emotional expressions of athletes, but also attach the sensor to the athlete’s joints or skin to monitor the athlete’s motion signals, such as joint and limb movements. Figure 10(a) shows that the sensor is attached to the index finger joint of the athlete. When the athlete’s finger is bent, the current of the sensor will change. The greater the bending angle, the greater the pressure on the sensor, and the greater the current change. Figure 9(b) shows the relative change of the current caused by the increasing degree of bending of the index finger. In addition, we also fixed the sensor on the athlete’s knee (as shown in figures 10(c), (d)) to detect the changes in the relative current generated when the athlete’s joints are bent. As
shown in figure 11, the pressure sensor can also detect knee joint movements such as squatting, jumping, and jogging by directly attaching medical tape to the knee.

4. Conclusion

We have developed an ultra-sensitive and flexible wearable pressure sensor that can be used to comprehensively detect athletes’ sports signals, including tiny physiological signals, vocal and emotional expressions, and intense joint and limb motion signals. The conductive element of the sensor is a porous PDMS foam based on a sacrificial template method loaded with graphene. The high elastic modulus of PDMS gives the sensor a wide pressure response range, while controlling the amount of graphene loaded gives the sensor high sensitivity and device stability. This sensor exhibits high sensitivity (17.9 kPa\(^{-1}\) in the range of 0–30 kPa and 79 kPa\(^{-1}\) in the range of 30–100 kPa), fast response capability (<20 ms), and excellent long-term work stability (10 000 cycles) and durability. Based on the comprehensive performance advantages of the sensor, we have demonstrated its ability to monitor athletes’ full range of activities, including strenuous exercise (such as bending of joints, walking, squatting, jogging, and jumping) and gentle movements (such as pulse, ECG, vocal, and emotional expressions). This sensor is simple to prepare, easy to operate and has the potential for large-scale applications. It shows high application value in wearable electronic devices and human-computer interaction used by athletes.

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Statement

We declare that this study has the consent of participants and ethical recognition.

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