Polypyrrole coated fabrics as high performance sensors and heating elements

Hao Liu (liuhao_0760@163.com)  
TGU: Tiangong University  https://orcid.org/0000-0003-0089-4254

Yu Wang  
TGU: Tiangong University

Tanyu Wang  
TGU: Tiangong University

Jin Li  
TGU: Tiangong University

Yuanjun Liu  
TGU: Tiangong University

Yitao Liu  
Donghua University

Li Liu  
Beijing Institute of Fashion Technology

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Polypyrrole coated fabrics as high performance sensors and heating elements

Yu Wang\textsuperscript{a}, Tanyu Wang\textsuperscript{a}, Jin Li\textsuperscript{a}, Yuanjun Liu\textsuperscript{a}, Yitao Liu\textsuperscript{c}, Hao Liu\textsuperscript{ab,*}, Li Liu\textsuperscript{d,*}

\textit{(a School of Textile Science and Engineering, Tiangong University, Tianjin, China)}
\textit{(b Institute of Intelligent Wearable Electronic Textiles, Tianjin, China)}
\textit{(c Innovation Center for Textile Science and Technology, Donghua University, Shanghai, China)}
\textit{(d Beijing Institute of Fashion Technology, Beijing, China)}

(*Correspondence: liuhao@tiangong.edu.cn; fzyll@bift.edu.cn)

Abstract

Flexible piezoresistive sensors and electrically heated elements as an important part of flexible electronics, due to its wide range of application are studied. In this paper, a low-cost and large-scale manufacturing method to build high-performance sensors and heating elements was proposed. In order to construct a polypyrrole(PPy)/dopamine(PDA)/cotton fabric, the in-situ polymerization was used to prepare dopamine coated cotton fabrics and to deposit PPy to prepare high performance fabrics. The PPy/PDA/cotton fabric as sensors has an operating range of 0~16 kPa, a sensitivity of up to 60.23 kPa\textsuperscript{-1} and a minimum detection limit of 64 Pa. It has excellent electric heating performance with a fast temperature rise response of 100 s, a maximum equilibrium temperature of 115.5 °C and a thermal stability of 7200 s. The PPy/PDA/cotton fabric can be used to detect minute signals such as pulse movement and human movement with real-time stable heating, which shows the good prospect of PPy/PDA/cotton fabrics in the field of smart wearable devices.

Keywords: Polypyrrole; fabric; sensor; electric heating

Introduction

The development of wearable devices has led to the wide spread use of portable and smart devices. The function of devices for wearable devices involves pressure change monitoring, temperature sensing and heating. Among these, devices that can detect pressure changes and heating elements that safeguard human health have been extensively investigated. However, relatively little research has been conducted on devices using a single active material to detect pressure changes and heating of the human body. Recently, Li et al.\textsuperscript{[1]} proposed a wearable sensor and heater using pyrrole polymerised in situ on a cellulose knitted fabric. The knitted fabric coated with conductive polypyrrole(PPy) exhibited a conductivity of 303 Ω/sq. Polyester knitted fabric has high sensitivity and can be used as a strain sensor. At the same time, due to the Joule heating effect under low voltage, it can also be used as a wearable heater.

Keeping warm has long been a human problem to be solved and electric heating elements, which can be combined with clothing to play a role in body warmth and heat therapy, are one of the most widely used smart wearable elements today. Indium tin oxide is often used as a key heating element and is widely used in heater manufacturing. However, due to the
brittle nature of indium and rising costs, some promising polymers exhibit excellent electrical
and mechanical properties, such as PPy. Among them, Xie et al.\textsuperscript{[2]}, prepared flexible and
highly conductive polyurethane/PPy composite films for use in electric heaters using a
combination of wet and in situ-polymerisation. The composite film had a low resistance of
about 10.5 Ω/sq and were heated from room temperature to 110 °C in 28 s at a voltage of
7 V.
As an important component of flexible wearable devices, flexible pressure sensors have
received widespread interest in the real-time monitoring of human health and movement
status.\textsuperscript{[3-7]} At present, most pressure sensors mainly have three types: piezoresistive \textsuperscript{[8-10]},
capacitive\textsuperscript{[11-13]} and piezoelectric\textsuperscript{[14-16]}. Among them, the piezoresistive sensors are one of the
most widely used types of sensors due to their simplicity of production, ease of signal
acquisition and excellent performance.\textsuperscript{[17,18]} PPy has also been widely used in the preparation
of piezoresistive sensors\textsuperscript{[19-21]} due to its good electrical conductivity, biocompatibility and
environmental stability\textsuperscript{[22]}. Such as Lin et al\textsuperscript{[23]} used in situ vapour growth to grow polypyrrole
on the cellulose fibres of cotton mats and obtained devices with response and recovery
times of 220 ms and 240 ms, respectively. The best PPy cotton fabric sensors had detection
limits as low as 50 Pa. The sensors prepared by this process can be mounted at different
locations on the body and used to record physiological signals.
In order to prepare flexible devices, the substrate material should be soft, light, bend
resistant, homogeneous and with good mechanical properties, etc. Currently, the commonly
used flexible substrate materials include Ecoflex, polydimethylsiloxane (PDMS) and TPU.
These materials have unknown toxicity and environmental unfriendliness in applications.
Compared to this type of substrate material, cotton fabrics produced using spinning and
weaving processes have a thin texture, moisture absorption and breathability,
environmentally safe raw materials and more reactive groups for easy finishing, making them
one of the best substrates for preparing components with pressure sensing and heating
properties. And dopamine is rich in catechol and amine functional groups to ensure strong
adhesion to any substrate included, resulting in a durable and strong coating surface on the
substrate.
In this study, PPy was grown in situ on dopamine coated cotton(PDA/cotton) fabric by in-situ
polymerisation and composites with piezoresistive and electrical heating properties could be
obtained in bulk. By immersing the PDA/cotton fabric in a homogeneously dispersed pyrrole
solution, the pyrrole can be firmly and uniformly polymerised on the surface of the
PDA/cotton fabric. This method helps to maintain the homogeneity of the piezoresistive and
electrical heating properties of the composite. The flexible piezoresistive sensors developed
based on this method can be used to monitor physiological signals such as wrist pulses and
joint movements, and the rapid thermal response and thermal stability of the developed
electrical heating element suggest that the composite material has great potential for
wearable flexible devices and healthcare applications.

**Experimental**

**Material**

Acetone was purchased from Tianjin Yuanli Chemical Co., Ltd. Anhydrous ethanol and ferric
chloride were purchased from Tianjin Fengchuan Chemical Technology Co., Ltd. Dopamine
hydrochloride was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd.
Tris(hydroxymethyl)aminomethane was purchased from Tianjin Yuyuan Technology Co., Ltd.
The pyrrole monomer was purchased from Shanghai Kewang Industrial Co., Ltd. (Shanghai,
China). P-toluenesulfonic acid was purchased from Tianjin Komiou Chemical Reagent Co., Ltd.
All chemical reagents used in this work are of analytical grade (AR) and can be used without
further purification.
Preparation

Commercially available fabrics were cut into 5 x 5 cm sizes and cleaned and dried. The fabric was first placed in a beaker and ultrasonicated for 20 min with an amount of acetone that did not cover the fabric to remove greasy impurities from the fabric. The fabric is then sonicated for 20 minutes with anhydrous ethanol to remove the acetone solution. The fabric is then washed several times with deionized water. Finally, the cleaned cotton fabrics are dried in an oven at 60 °C. A 500 ml beaker was taken, 350 ml distilled water and 150 ml anhydrous ethanol were added and mixed well, then 0.4235 g tris(hydroxymethyl)aminomethane (Tris) was added for pH adjustment to obtain a slow release solution with a pH value of about 8.5, then 1.4 g dopamine hydrochloride (4 g/L) was added to the beaker, and then the pretreated cotton fabric was put into the beaker to make the dopamine. After the reaction was completed, the polydopamine-coated fabric was removed from the solution, cleaned with deionized water and left to dry at room temperature. 30 ml of deionized water and the corresponding concentration of pyrrole were placed in a clean 100 ml beaker and stirred at constant speed on a magnetic stirrer until the pyrrole was homogeneously mixed with the water. The dried fabric is then placed in the well-mixed solution and stirred at constant speed for 30 min. 30 ml of deionized water, zinc chloride and p-toluene sulphonic acid are placed in a 50 ml beaker and stirred until the drug is completely dissolved. The prepared solution of ferric chloride is slowly poured into the beaker of the pyrrole solution. The mixed solution continues to be stirred slowly on a magnetic stirrer for a certain reaction time. When the reaction is complete, the sample is removed and washed in distilled water and baked in an oven at 60 °C until the sample is dry.

Figure 1 Preparation process of PPy/PDA/cotton fabric

Characterization

Observe the surface morphology of the sample by scanning electron microscope (SEM, S-4800, Japan) under scanning electron microscope (voltage 15kV, electron number 3.0). The composition and structure of the samples were analyzed by Fourier transform infrared spectroscopy (FTIR, Nicolet i550, USA) and X-ray photoelectron spectroscopy (XPS, K-Aepna, USA).

Results and discussion

Figure 2(a) shows the base cotton fabric. Figure 2(b) shows a polypyrrole coated dopamine fabric (PPy/PDA/Cotton). Figure 2(c) shows the dopamine layer on the surface of the cotton fabric. Figure 2(d)-(i) shows the SEM images of the PPy/PDA/Cotton at different pyrrole concentrations (0.1 mol/L, 0.2 mol/L, 0.3 mol/L, 0.4 mol/L, 0.5 mol/L, 0.6 mol/L). As shown in Figures 2(d)-(f), the PPy/PDA/Cotton prepared in pyrrole solutions with concentrations of 0.1 mol/L, 0.2 mol/L and 0.3 mol/L showed three states of polypyrrole growth on the surface of the yarns, namely, dotted flakes, branching and large uniform growth. At a pyrrole concentration of 0.4 mol/L, the outermost layer of the yarn was clearly covered with polypyrrole, but the polypyrrole did not completely penetrate into the yarn, as shown in
Figure 2(g). In figure 2(h), at a pyrrole solution concentration of 0.5 mol/L, the polypyrrole is uniformly coated throughout the yarn. As in figure 2(i), at a pyrrole concentration of 0.6 mol/L, the polypyrrole on the yarn appears to come off in large pieces, resulting in an uneven polypyrrole coating on the fabric.

During the preparation process, the PPy/PDA/Cotton fabric prepared with varying pyrrole concentration showed different properties. The polypyrrole coated cotton fabrics prepared at a pyrrole concentration of 0.5 mol/L showed the lowest resistance and the highest loading, while showing the lowest thin layer resistance. (Figure 3(a))

ATR-FTIR spectroscopy was used to characterize the surface composition of the samples. Figure 3(b) shows the FTIR spectra of the PPy/PDA/Cotton fabric[24-26]. The peak at 1523 cm\(^{-1}\) is attributed to the C=C stretching vibration in pyrrole ring. The band at 1435 cm\(^{-1}\) is related to the C–N stretching vibration. The broad peak at 1286 cm\(^{-1}\) is assigned to the C–H and C–N in plane deformation modes. The in-plane deformation vibration of NH\(^2\) groups derived from the protonated PPy chains is located at 1128 cm\(^{-1}\). The peak at 1075 cm\(^{-1}\) is ascribed to the N–H in-plane deformation vibration. The band at 1006 cm\(^{-1}\) and 958 cm\(^{-1}\) is assigned to the C–H out-of-plane ring deformation mode. The curve of the pristine cotton fabric shows the characteristic peaks of cellulose at 1642, 1421, 1160 and 895 cm\(^{-1}\), which can be assigned to the overlapping bands of the functional groups (C–O, C–C and C–O–C)[33]. Absorption peaks of the original PDA/Cotton fabric at 3600 cm\(^{-1}\) and 3100 cm\(^{-1}\) belonged to the N–O stretching vibrations in PDA, and another peak at around 1612 cm\(^{-1}\) is due to the aromatic ring stretching vibrations and N bending vibrations [34]. The main characteristic peaks of cotton fabric and PDA/cotton fabric were not observed after in-situ polymerization of PPy, indicating that PPy has been successfully deposited onto the fabric.

XPS is a useful tool for obtaining information on the doping level of conductive polymers. Figure 3(c) shows an XPS measurement spectrum of the PPy/cotton fabric. The presence of C, N, O, Cl and S can be observed from the figure. The elements Cl and S are attributed to the
negative ions doped in PPy, which are probably derived from ferric chloride and p-toluenesulphonic acid. Figure 3(d) shows the C1s spectrum with two peaks centered at 285.5 and 283.35 eV, corresponding to the C-C and C=C bonds, respectively. The N1s spectrum is shown in Figure 3(e) with three peaks at 401, 400.3 and 399 eV, associated with N=C, -NH₂ and -OH. These results indicate the successful deposition of PPy on the surface of the cotton fabric.

Table 1 Surface resistivity of PPy/PDA/cotton fabric

<table>
<thead>
<tr>
<th>Concentration of pyrrole (mol/L)</th>
<th>0.1</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface resistivity (Ω/sq)</td>
<td>32.3</td>
<td>22.9</td>
<td>14.2</td>
<td>12.4</td>
<td>11.6</td>
<td>19.4</td>
</tr>
</tbody>
</table>

Figure 3 (a) The relationship between the load and resistance of PPy/PDA/cotton fabric under different pyrrole concentrations; (b) FTIR spectra of cotton fabric, PDA/cotton fabric and PPy/PDA/Cotton fabric; XPS spectrum of (c) PPy/PDA/cotton fabric; (d) C1 s; (e) N1 s.

The sensitivity versus PPy content is shown in Figure 4(a), where the slope of the curve represents the sensitivity of the device. When the PPy content is in the range of 0.1-0.5 mol/L, the sensitivity of the device increases with increasing PPy content. As the PPy content exceeds 0.5 mol/L, the sensitivity of the device decreases as the PPy content increases further. When the PPy content is low, the resistance between the cotton fibres is high and there is no significant change in resistance, even at high applied pressures.

Figure 4(b) shows the relative rate of change of resistance with pressure load ingover a test range of 0-16 kPa. When a piezoresistive sensor is subjected to externally applied pressure, the PPy/PDA/cotton fabric comes in close proximity to each other, thus forming a conductive path between the fabric and the PPy. When the applied pressure is less than 2 kPa, the sensitivity of the PPy/PDA/cotton fabric pressure sensor is 60.23 kPa⁻¹, which is significantly better than most sensors reported in the literature (Table 2). As the external loading pressure increases, the contact resistance between the conductive fillers decreases. A sensitivity of 10.52 kPa⁻¹ can be observed from the 2-5 kPa region, which is due to the limited overall resistance change due to the overall deformation of the substrate at high pressures, so that the S-value is approximately 1.632 kPa⁻¹ when the skin sensor is applied to a high pressure condition (5-16 kPa).

Figure 4(c) shows the minimum detection limit of the PPy/PDA/cotton sensor. The device can
detect pressures down to 64 Pa. In addition, the single response and recovery process of the PPy/PDA/cotton sensor was tested. As shown in Figures 4(d)(e), the response time is about 200 ms, and the recovery time is about 100 ms. Figure 4(f) shows the cyclic response behavior of PPy/PDA/cotton fabric under different compressive strains, and a stable and reproducible shadow pattern is observed in a wide strain range. Figure 4(g) shows the variation in response time due to different rates of applied pressure at the same stress. Good performance of the PPy/PDA/cotton fabric was found by dynamically loading and unloading for 4 cycles over a pressure range of 0.064 kPa - 3.18 kPa. Increasing pressure caused a higher change in the rate of change of resistance, as shown in Figure 4(h). The steady increase in the rate of change of resistance with increasing pressure indicates that the pressure sensor is reliable at all pressures.

Finally a durability test of the compression resistance behaviour of the PPy/PDA/cotton fabric was also carried out at a strain rate of 0.1 mm/s for 3000 s cycles at a pressure of 3.18 kPa. From Figure 4(i), it can be found that $\delta R/R_0$ exhibits excellent recoverability due to the good elasticity and compressibility of the PPy/PDA/cotton fabric. All of the above demonstrates the high repeatability, stability and durability of the piezoresistive sensing performance.

Figure 4 (a) The change curve of the resistance change rate of PPy/PDA/Cotton fabric with time under different pyrrole concentrations; the PPy/PDA/Cotton fabric (b) the relative change rate of resistance at 0-16 kPa; (c) the lowest detection limit; (d) Response curve and (e) Recovery curve; (f) Continuous change of resistance change rate under different pressures; (g) Change of resistance change rate with time at different rates (h) PPy/PDA/Cotton fabric intermittent response of resistance change rate under pressure; (i) Relative resistance change rate-time curve under 3000 s cycle

Figure 5(a) shows the surface temperature change of the fabric monitored by the infrared camera when 5 V was applied to the PPy/PDA/Cotton fabric with different pyrrole concentrations. It can be observed that the samples have the highest surface temperature and temperature change rate at a pyrrole concentration of 0.5 mol/L.

Figure 5(b) shows the surface temperature curve of PPy/PDA/Cotton fabric under a load voltage of 1 to 5 V with time. It can be seen that higher load voltages result in higher surface
temperatures and a faster heating rate during the first 50s. When a constant voltage of 5V load is applied to the PPy/PDA/Cotton fabric, its maximum equilibrium temperature can be as high as 115.5°C, which can meet the temperature requirements of electric heating elements. At the initial stage when the power switch is turned on, the sample is heated at a higher rate than the heat dissipation rate. After 50s, the temperature gradually stabilizes as the heating rate decreases. After 100s, the surface temperature gradually increases and reaches equilibrium as the sample surface heat dissipation rate equals the heating rate over the stable heating time. At 230s, the temperature drops sharply as the power is switched off, indicating that the sample has good thermoelectric properties and power supply capability.

The stability of the PPy/PDA/Cotton fabric was tested by cyclic heating/cooling as in Figure 5(c) and the temperature change of the PPy/PDA/Cotton fabric was recorded for 600 s (5 v heating for 300 s and 0 v cooling for 300 s). After 120 cycles, the heating/cooling profile remained essentially constant, with good stability and repeatability. During each 300 s heating process, the temperature could be increased from room temperature to above 50°C within 100 s, indicating that the PPy conductive coated fabric has a high heating rate. Due to the insulation function of the cotton fibers, the fabric dissipates heat relatively slowly during the 0 V cooling power-off process.

The temperature dependence of the PPy/PDA/cotton fabric was investigated as shown in Figure 5(d). The PPy/PDA/cotton fabric was heated continuously at a constant voltage of 5 V for 7200 s. The results show that the surface temperature of the fabric increased rapidly throughout the heating process and then stabilized in a narrow temperature interval (68 ± 3 °C). The temperature fluctuation may be due to the fact that the electron flow at the fiber junctions under goes several separations/reorganizations, thus reaching dynamic equilibrium at each point of the fabric. This demonstrates the remarkable resistance heating properties and thermal stability of the PPy/PDA/cotton fabric.

An operating voltage of 5 V was applied to the PPy/PDA/Cotton fabric and the thermal infrared map recorded by the infrared camera was observed. As can be seen in Figures 5(e)-(i), the temperature of the fabric is increasing during the 0-100 s time period. At the 100s the imaging is no longer different from that at the 200 s and 300 s, and the maximum equilibrium temperature is reached and remains stable during this time period. After 300 s, the temperature starts to cool down and there is a significant decrease in the imaging temperature in Figure 5(i). The 3D temperature distribution trends processed by Matlab are shown in Figures 5(j)-(l). The heat distribution in the 3D, side and top views shows that the sample is heated uniformly and steadily within the effective heating region.

Figure 5 (a) The temperature of the PPy/PDA/Cotton fabric under different concentrations of pyrrole under a constant voltage of 5 V vs. time; (b) The electric heating temperature of PPy/PDA/Cotton fabric under the optimal preparation conditions as a function of time; (c)
Temperature cycle stability for 120 repeated cycles (300 s at 5 V, 300 s at 0 V); (d) Temperature-time curve at a constant voltage of 5 V. (e-i) Two-dimensional thermal infrared image and three-dimensional thermal image of PPy/PDA/Cotton fabric when an external voltage is applied.

In order to facilitate comparison, Table 2 shows the piezoresistive sensing parameters and electric heating performance parameters of some recent documents. In the work of this article, the PPy/PDA/Cotton fabric shows excellent performance in terms of operating range, sensitivity and maximum equilibrium temperature, proving that the PPy/PDA/Cotton fabric is a promising high performance products both as flexible piezoresistive sensors and as electrically heated elements.

Table 2 Comparison of performance parameters of literature and this work

<table>
<thead>
<tr>
<th>material</th>
<th>The scope of work(kPa)</th>
<th>Sensitivity(kPa⁻¹)</th>
<th>Voltage(V)</th>
<th>Maximum equilibrium temperature(℃)</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPy/PDA/Cotton</td>
<td>0-16</td>
<td>60.23</td>
<td>5</td>
<td>115.5</td>
<td>本文</td>
</tr>
<tr>
<td>PPy/Cotton</td>
<td>0-5</td>
<td>4.48</td>
<td>-</td>
<td>-</td>
<td>[23]</td>
</tr>
<tr>
<td>GO/PPy@PU Sponge</td>
<td>0.075-15</td>
<td>0.79</td>
<td>-</td>
<td>-</td>
<td>[27]</td>
</tr>
<tr>
<td>PPy@PVA-co-PE nanofiber</td>
<td>0-6</td>
<td>1.24</td>
<td>-</td>
<td>-</td>
<td>[28]</td>
</tr>
<tr>
<td>PPy/Paper</td>
<td>0-0.3</td>
<td>-2</td>
<td>-</td>
<td>-</td>
<td>[29]</td>
</tr>
<tr>
<td>PPy/PDMS</td>
<td>0-2</td>
<td>19.32</td>
<td>-</td>
<td>-</td>
<td>[30]</td>
</tr>
<tr>
<td>PPy/PET</td>
<td>-</td>
<td>-</td>
<td>35</td>
<td>100</td>
<td>[31]</td>
</tr>
<tr>
<td>PU/PPy</td>
<td>-</td>
<td>-</td>
<td>7</td>
<td>110</td>
<td>[32]</td>
</tr>
<tr>
<td>PPy/Cotton</td>
<td>-</td>
<td>-</td>
<td>9</td>
<td>83</td>
<td>[33]</td>
</tr>
<tr>
<td>PPy/Cotton</td>
<td>-</td>
<td>-</td>
<td>6</td>
<td>100</td>
<td>[34]</td>
</tr>
<tr>
<td>PPy/Cotton</td>
<td>-</td>
<td>-</td>
<td>5</td>
<td>168.3</td>
<td>[35]</td>
</tr>
</tbody>
</table>

The high sensitivity and low pressure detection limit of PPy/PDA/Cotton fabric pressure sensors can provide many applications from monitoring the tiny signals of human pulse beats to recording the hard mechanical movements of human organs. Figure 6(a) shows a pulse wave detected by the PPy/PDA/Cotton pressure sensor. As shown in Figure 6(a), the device was fixed to the wrist of a 25 year old adult for a one-to-one test with the aid of medical tape. According to the test data, the heart rate is about 67 bpm (beats per minute), which is consistent with the beat-to-beat rhythm measured from a commercial blood pressure monitor. In addition, the inset of Figure 6(a) clearly distinguishes three waves from a single response cycle: percussive wave (P wave), tidal wave (T wave) and diastolic wave (D wave), which are related to heart rate, ventricular Blood pressure, systolic blood pressure and diastolic blood pressure. The results can reflect the state of the circulation and monitor physiological indicators such as blood pressure and heart rate. Therefore, the flexible piezoresistive sensor made from PPy/PDA/Cotton fabric is suitable for pulse monitoring applications, which would be a simple and cost-effective way to observe the state of the heart.

Pressure sensors with High sensitivity, a large working stress range and high stability are able to monitor the full range of human movement. As shown in Figures 6(b)-(d), PPy/PDA/Cotton fabric sensors are fixed on the joints (insets of Figures 6(b)-(d)) to test their response to the bending of fingers, wrists, and knees. The $\Delta R/R_0$ of the sensor is zero when the joint is kept straight at the joint. The $\Delta R/R_0$ value of the sensor increases in real time as the joint is bent. When the joint returns to extension, the sensor relaxes to its original state and $\Delta R/R_0$ drops to its original value. The periodic bending and straightening of the joint cause a periodic increase and decrease in $\Delta R/R_0$ and produces the curve shown in Figure 6(b).

As a practical application demonstration, an electric heating element made from PPy/PDA/Cotton fabric is fixed on a knee brace in the position of the human knee position as shown in Figure 6(f). The temperature of the electric heating element varies uniformly with the voltage change (Figure 6(e)). The electric heating element in the knee brace can be controlled by the voltage in three steps with uniform heating effect (Figure 6(f)). The stable...
electrical conductivity ensures that the heated fabric for joint thermotherapy can be operated effectively even when the wearer is in motion, for example when the knee is naturally flexed and extended. Joint thermotherapy involves frequent mechanical deformations during human movement and keeps the body warm and protected from the cold, especially for those with mobility problems such as infants, the elderly and the disabled. Electric heaters therefore have great potential for use in joint thermotherapy.

Figure 6 (a) Monitoring curve of pulse signal; (b) Curve for detecting finger movement state; (c) Curve for detecting wrist movement state; (d) Curve for detecting knee movement state; (e) The temperature-time curve of the heating element under different voltages; (f) the temperature-time curve under three voltages

Conclusion

In this paper, the PPy/PDA/Cotton fabric was prepared by in situ polymerisation using textile materials as a flexible substrate and PPy as a conductive material. The surface morphology, polymerisation composition, electrical conductivity, sensing properties and electrical heating properties of the materials were analyzed and the PPy/PDA/Cotton fabric was found to have a resistance of 7.544 Ω and a surface resistivity of 11.6 Ω/sq. The PPy/PDA/Cotton fabric has excellent sensing properties, i.e. an operating range of 0-16 kPa, a sensitivity of 60.23 kPa⁻¹, a minimum detection limit of 64 Pa, and excellent electrical heating properties, i.e. a fast temperature rise response of 100 s rapid temperature rise response, a maximum equilibrium temperature of 115.5 °C and a thermal stability of 7200 s. The ability of the flexible piezo resistive sensors to detect weak signals and human motion was demonstrated by mounting the flexible piezoresistive sensors prepared from the PPy/PDA/Cotton fabricate the wrist artery, finger, wrist and knee to detect pulse signals and human motion. By placing a heating element prepared from the PPy/PDA/Cotton fabric at the knee for stable heating, the flexible electrical heating element was demonstrated to be capable of real-time stable heating, illustrating the potential of the PPy/PDA/Cotton fabric in the field of smart wearable devices.

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Conflict of interest All authors declare that they have no conflict of interest.
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