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ELECTRICAL PROPERTIES OF PPY-COATED CONDUCTIVE FABRICS FOR HUMAN JOINT MOTION MONITORING

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Abstract:

Body motion signals indicate several pathological features of the human body, and a wearable human motion monitoring system can respond to human joint motion signal in real time, thereby enabling the prevention and treatment of some diseases. Because conductive fabrics can be well integrated with the garment, they are ideal as a sensing element of wearable human motion monitoring systems. This study prepared polypyrrole conductive fabric by in situ polymerization, and the anisotropic property of the conductive fabric resistance, resistance–strain relationship, and the relationship between resistance and the human knee and elbow movements are discussed preliminarily.

Keywords:

body motion; conductive fabric; PPy; anisotropic; resistance–strain

1. Introduction

Measuring human movements is beneficial to rehabilitation, training, or exercises. A motion capture system, which consists of cameras, accelerometers, and flexible electrogoniometers, has been used to monitor human motion [1]. Although the motion capture system is capable of accurate measurements, conventional sensors fixed on the cloth by strap or other methods make them inconvenient and comfortable to use. During the flexion of a limb, the skin around the joint stretches, as does the surrounding clothing. The skin around the knee stretches lengthwise about 40% of its normal length, and it requires 25–30% stretchability from the fabric to ensure general comfort [2]. Textile solutions are well suited for constructing a sensing system that is comfortable for the wearer, because it can integrate well with clothing.

Textile-based deformation sensors for wearable devices can be produced by coating a thin layer of piezoresistive material on conventional fabrics, or by knitting and weaving conductive yarns with nonconductive yarns. The technique permits continuous, long-term monitoring of a human joint, based on the stretch of the skin and the elastic fabric, where a conductive fiber [3] or conductive elastomer [4] is attached to the fabric. During bending, the conductive fiber increases the wire length between the two terminals leading to an increase in resistance. If the conductive fabric is attached to clothes worn next to the skin, its resistance also increases during the bending process. In addition, elastic conductive webbing by conductive yarns and elastic yarns [5] was designed for monitoring the flexion angle of elbow and knee movements, and the elastic conductive webbing shows a linear response of resistance to the flexion angle. Sensors are directly integrated into Lycra fabrics by using conductive elastomer sensors [6], which are realized by a silicon rubber and graphite mixture. These test devices can be worn for a long period and be used for monitoring without discomfort.

In recent years, the technology for conductive fabric sensing elements from conductive polymers has been extensively studied. These materials offer several advantages with respect to other sensors: lightness, large elasticity and resilience, resistance to corrosion, flexibility, and so on [7]. Among typical kinds of conductive polymers (polypyrrole [PPy], polyaniline [PANI], and polythiophene [PTh]), PPy has some advantages such as high conductivity, good environmental stability, ease of synthesis, adhesion, nontoxicity, and so on. Furthermore, PPy conductive fabric is generally used for wearable fabric sensors. The surface resistance of PPy conductive fabric shows a high sensitivity to its elongation [8] and the strain–resistance relationship of PPy coating Lycra fabric and its strain sensitivity coefficient is up to 25 [9]. Thus, the sensor made from PPy conductive fabric can be used to detect knee joint movements.

Body joint motion was detected by monitoring the resistance change of the conductive fabric. For human joint movement, its movement is usually multidirectional, such as the torsional flexion of an elbow joint. In this case, the fabric sensor around the joint is not only stretched along the axial direction of extremities, the sensor can also deform in the other direction, which is usually neglected in previous studies. To characterize the joint movement□ the resistance in all directions should be monitored. Therefore, it is necessary to understand the directional resistance distribution of the conductive fabric. Due to more or less anisotropic structure of the fabric, the PPy-coated fabric will show to some extent anisotropic electrical resistance [10]. In this sense, it is significant to investigate the dependence of the anisotropic resistance on fabric structure.

In this paper, the electrical conductivity of PPy woven fabric has been studied with respect to the surface resistance and its directional distribution, as well as the elongation–resistance relationship. And then, the PPy-coated conductive fabric is used to monitor the extension angle of the knee and elbow, and the angle–resistance relationship is discussed.

2. Preparation for PPy-coated fabric

2.1 Materials

Pyrrole monomer from Sinopharm was redistilled and stored below 4℃. Anthraquinone-2-sulfonic acid sodium salt (AQSA) monohydrate 97% was selected as the dopant and iron(III) chloride (FeCl3) hexahydrate 98% used as the oxidizing agent. Both of them were from Sinopharm. All other chemicals used were of analytical grade. All aqueous solutions were prepared with deionized water. Three kinds of fabrics were chosen, and their parameters are summarized in Table 1.

2.2 Polypyrrole polymerization

First, a pre-scour was carried out on the original fabric specimens to remove surface impurities such as waxes, oils, and particulates. The scoured fabric was immersed in sodium hydroxide solution of 1 mol/L and then rinsed repetitively with deionized water. After that, the fabrics were placed in an oven with 80℃ for 20 min. Subsequently, the treated fabric samples were placed into a beaker, containing a solution of doping agents AQSA (0.01 mol/L) and FeCl3 (0.18 mol/L), and then the beaker was moved to an ice–water bath at 0 ℃ for 1 hour. Following this, FeCl3 was added into the beaker slowly with a burette and dropwise addition, and then the beaker was placed into the ice–water bath again for 2 hours. After the reaction, the PPy-polymerized fabric was repeatedly rinsed by deionized water until the washing liquid became colorless. Finally, the PPy fabric was dried in an oven with 80℃ for 20 min.

3. Characterizations

3.1 Surface resistivity

The surface resistivity of the conducting-polymer-coated fabrics was measured according to AATCC 76-2002 by placing two copper strips on the fabric samples at a distance of 1 cm. The resistance was measured using a multimeter.

3.2 Surface resistance and Anisotropy

The assessment of the anisotropy of conductive fabric resistance is based on the anisotropy function [10]. This function defines the dependence of the resistance R of the angle α indicating the direction in which the sample resistance value has been calculated based on the four-electrode method concept [11]. The anisotropy function has the following form [10]:

$$R\alpha \equiv \frac{U}{I\alpha}, \tag{1}$$

where U—the forced value of the voltage between the neighboring electrodes, I—the current as measured between the second pair of neighboring electrodes, and α—the angle related to the direction of determining the textile sample resistance value, α ≥ 0. In order to assess the degree of electrical resistance anisotropy of the material, the plane and normal anisotropy coefficients are determined [12,13]. The latter is the ratio of the greatest value to the least value of a measured physical quantity. This paper uses Equation (2) to assess the degree of anisotropy of conductive fabric resistance:

$$0.95 \leq \frac{R_{min}}{R_{max}} \leq 1 \tag{2}$$

When the ratio of the minimum resistance value to the maximum value in each direction on the sample is in the interval [0.95,1], the sample is said to exhibit an isotropy of its resistance; the ratio lies outside this interval if it shows more obvious resistance anisotropy.

The following test procedures are followed: the sample is circular in shape, with the electrodes being arranged in the vertexes of the square inscribed in the circle. The sample maintains this fixed position during testing, while the square is moved rotationally along its edge in the clockwise direction. The angle α is counted from the initial position, for example, one at which the line connecting the voltage electrodes has a horizontal direction, to the final position. The initial position may not necessarily be associated with the directional features of the fibrous structure, for example, with the direction of the weft in woven fabrics. This situation is depicted in Figure 1. Based on the performed Mann–Whitney test, it was found that exchanging the voltage sources for current sources and vice versa did not have any significant effect on the resistance measurement results for both the woven fabric and the knitted fabric [10].

Table 1. Constructional properties of three kinds of fabrics

No.	Weave	Component	Count warp (tex)	Count weft (tex)	Warp density (threads/10 cm)	Weft density (threads/10 cm)
1	plain	93%C7% SP	17	17	900	880
2	plain	93%T7% SP	8	8	360	240
3	twill	80%C20% SP	25	25	460	350

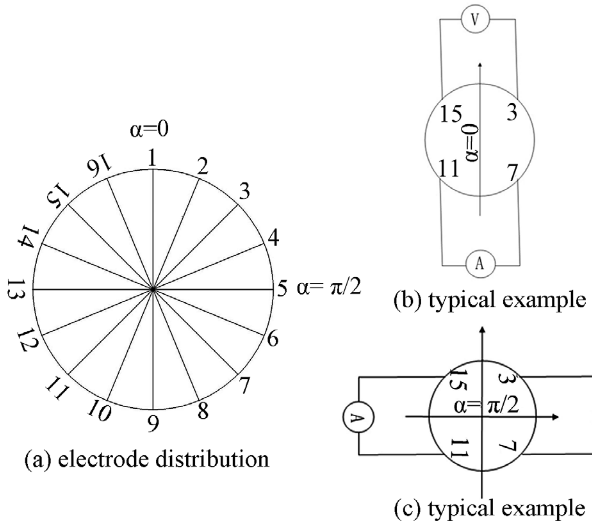

Figure 1. Test schematic of resistance anisotropy

According to such a principle, a customized fixture is used to fix the round specimen in one position with 16 electrode holes evenly distributed along the edge of the sample, as shown in Figure 2. Each sample is cut into a circle with a radius of 10 cm, and then a conductive fabric is formed by in situ polymerization. Four electrodes are arranged on the vertexes of the square inscribed in the circle. A pair of adjacent electrodes is used to supply a constant voltage by a regulated DC power supply, and another pair of adjacent electrodes is used to test the current with a PROVA901 type digital multimeter. Measurement results were recorded. The tests for the anisotropy of resistance of samples were conducted in the range $\alpha \in [0, 2\pi]$ with an angle step of $\pi/8$. Each measurement was repeated five times.

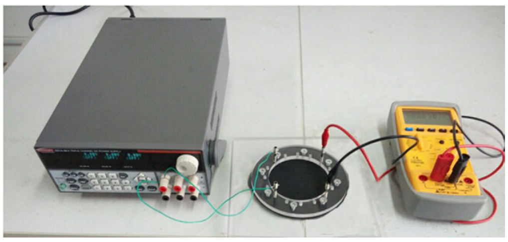

Figure 2. Test device of anisotropic resistance

3.3 Strain–resistance relationship

A microcomputer-controlled universal testing machine is used to stretch the conductive fabric, and the PROVA901 digital multimeter is linked to record the change of electrical resistance. Five samples were tested, and the average value of the resistance was calculated. The size of the fabric test sample is 5 × 15 cm. The testing machine's running speed is 10 mm/min; the fabric resistances under elongations of 5%, 10%, 15%, 20%, and 25% are tested.

3.4 Extension angle–resistance relationship

The change in the fabric's electrical resistance under different bending angles of human knee and elbow was tested. The bending movement of human knee and elbow joints is shown in Figure 3, and the bending angle is successively increased from θ1 to θ4. Such a process is accompanied by the elongation of the fabric around the joint. The conductive fabric was fixed on the knee and elbow pads during the test process, and two copper electrodes were used to connect a multimeter for measuring the resistance of the conductive fabric. The PPy conductive fabric has a size of 2 × 18 cm, and the distance between the two copper electrodes is 15 cm. After that, the knee and elbow pads were worn on the corresponding parts of the subject, and the real-time resistance value was recorded by the digital multimeter. The detailed test procedures are shown in Figure 3, and the movements of the elbow joint and the knee joint are depicted in Figure 4(a) and Figure 4(b), respectively. The subgraphs indexed by a, b, c, and d correspond to Figure 3 sequentially (θ1, θ2, θ3, and θ4). Each bending test is repeated five times.

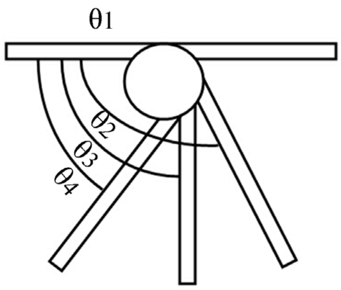

Figure 3. Illustration for different bending angles of knee and elbow joints

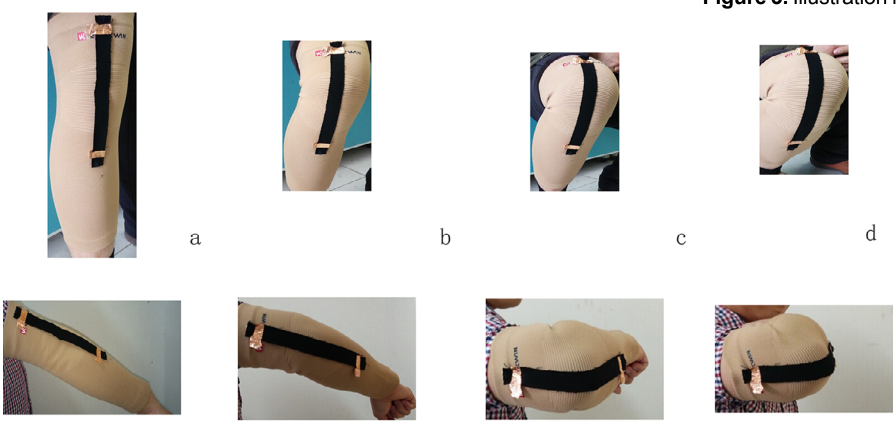

Figure 4. Bending tests of human knee and elbow joints

4. Results and Discussion

4.1 Anisotropy of electrical resistance

For the fabric 1 sample, the conductive resistances are in the range [2.39, 3.83] kΩ, the fabric 2 sample in [1.23,3.21] kΩ, and the fabric 3 sample in [0.67,1.84] kΩ. The value obtained by Equation (2) was equal to 0.63 for fabric 1, 0.38 for fabric 2, and 0.36 for fabric 3. Their magnitudes indicate the occurrence of anisotropy of electrical resistance for the three samples. The lowest anisotropy degree is for fabric 1, and this fabric has the most uniform distribution of resistance. The values in Table 1 also show that fabric 1 is a plain fabric and has similar warp and weft yarn density. That is to say, the structure of fabric 1 is more uniform than fabric 2 and fabric 3. Therefore, the anisotropy of PPy conductive fabric resistance is highly related to the structure of the fabric itself.

The directional distribution of electrical resistance of three fabric samples is illustrated in Figure 5. Each piece of data corresponds to an average value of electrical resistances in five repeated tests for specified α angles as in Figures 1 and 2. As can be seen from Figure 5, each of three fabrics shows a periodic anisotropy and a symmetry at about α = π. In the case of fabric 2, the greatest resistance value, being equal to 3.21 kΩ, was achieved for an angle of 0 rad, and the lowest resistance value, 1.25 kΩ, was obtained for an angle of π/2 rad.

This characteristic distribution of electrical resistance is attributed to the regularity of the fabric structure, that is, the warp and weft yarns in woven fabric are orthogonal. When the electrodes are parallel to the direction of the warp or weft yarn, as shown in Figure 5(a)–(c), extreme values occur. Thus, the interval between the maximum and minimum values is π/2 rad. After rotating π rad, the test is only to exchange the voltage for current electrodes and the current for voltage electrodes, and values along all directions have no significant change. Of course, a little difference was observed, and it is due to the not absolutely uniform fabric structure, such as yarn spacing and warp and weft contact area. When the current is input from different terminals of one direction, the nonuniform structure features affect the current transmission, and the resistance changes with the exchanged positive and negative electrodes. To note, test results show that the electrical resistance distribution trend in each direction is independent of the fiber contents of the fabric and the base weaving texture (plain or twill).

4.2 Strain–resistance relationship

Fabric 3 is taken as an example to discuss the strain–resistance relations. Test results are shown in Figure 6. The figure indicates that with an increase of elongation up to 15% the resistance has a slow increase. After the elongation reaches 25%, the resistance remains almost constant. This behavior is attributed to the electrical resistance nature of woven fabric. The tested electrical resistance of each yarn consists of two parts [14]: contact resistance Rc, which holds the resistance between the crossing points, and yarn resistance R, which comes from the yarn segment.

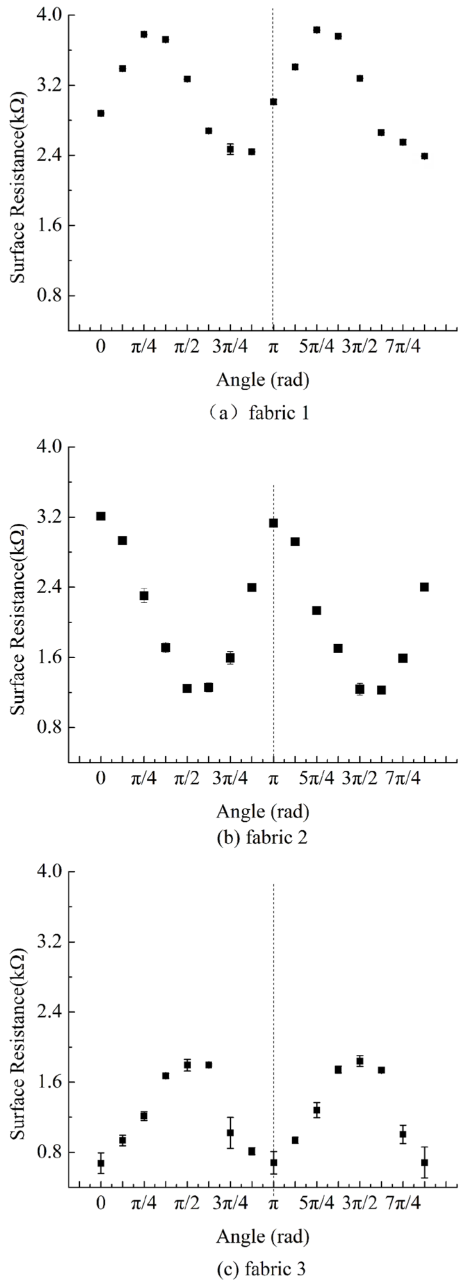

Figure 5. Values of the anisotropy function for the fabrics

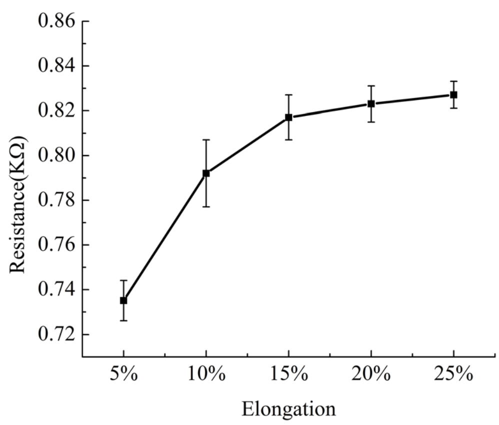

Figure 6. Resistance–strain relation of fabric

During stretching, the elongation of the conductive fabric leads to variation in length and cross-section of the yarns in the fabric. From formula $R = \rho L / A$ (ρ is the electrical resistivity of a material, L the length of the conductor, and A the cross-sectional area of the conductor), with the increase in elongation, the lengths of the yarns increase and their cross-sectional areas decrease, thereby increasing electrical resistance. On the other hand, the elongation of the woven fabric decreases the contact area between the warp and the weft; thus the contact resistance Rc increases. Therefore, at the initial stage of stretching conductive woven fabric, the fabric resistance increases dramatically. When the elongation reaches a certain size, yarn stretching reaches its upper limit, and thus the fabric resistance does not change significantly.

4.3 Human motion test

Fabric 3 is chosen for conducting preliminary tests of human movement states. The test result is shown in Figure 7. Figure 7(a) indicates that the resistance also increases with the increase in the degree of elbow bending. Similarly, the knee bending angle can be monitored by the surface resistance as shown in Figure 7(b). In this study, the conductive fabric was attached to the kneepad (elbow pad) and fit skintight. When the body joint bends, the fabric around the joint has a certain degree of elongation. The resistance–strain relations of the conductive fabric show that the fabric resistance increases with the strain.

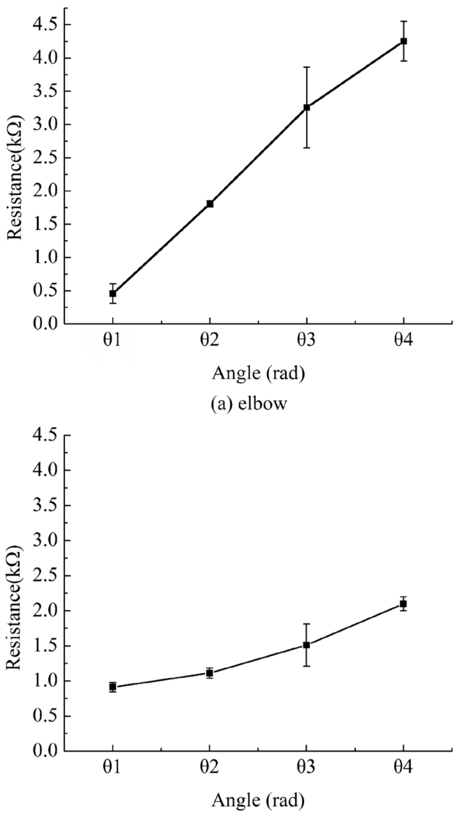

Figure 7. Dependence of electrical resistance on the extreme joint bending angle

5. Conclusion

From the above analysis, the conductive resistance of PPy-coated woven fabric is anisotropic, and the anisotropy feature of PPy conductive fabric resistance is dependent on the structure of the fabric itself. And the trend of PPy conductive woven fabric resistance distribution in each direction depends only on the orthogonality of the fabric sample structure, and the extremes occur in the direction that parallels the direction of the warp or the weft yarn. The electrical resistance change of PPy conductive fabric has an upper limit and depends on the fabric structure. Moreover, PPy conductive woven fabrics can be used to monitor the movement of human joints.

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