Indian Journal of Fibre & Textile Research
Vol. 49, March 2024, pp. 72-82
DOI: 10.56042/ijftr.v49i1.9552

Strain sensing performance of conductive polyester knitted fabric and its application in body motion monitoring

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Received 6 June 2022; revised received and accepted 12 September 2023

The effect of PVA (polyvinyl alcohol) content in solution system on the structure and performance of conductive PET/PANI/PVA (polyester/polyaniline/PVA) composite yarns has been studied. Conductive knitted fabrics of 2+2 rib structure are then prepared by conductive composite yarns; the strain–resistance sensing performances of the conductive knitted fabrics and their application in body motion monitoring are studied. The results indicate that an appropriate amount of PVA could help the conductive PANI layer on the fibre surface to form a stable interpenetrating polymer network structure, and improve its structural uniformity and conductivity. When the mass ratio of PVA to aniline in the solution system is 5%, the conductivity of the PET/PANI/PVA composite yarn could reach 1.887 S/cm, which is about 40% higher than that without PVA. Similarly, it's wash fastness and abrasion resistance are significantly higher than that without PVA. Under the action of stretch-recovery, the electrical resistance of the conductive knitted fabric is first increased, then decreased, again increased and decreased. The conductive fabric shows a good sensing linearity when the resistance dropped or increased monotonously. In the process of cyclic tension, the resistance of the fabric increases and then tends to be stable. The fabric has good sensing repeatability after dozens of stretching cycles, and the addition of PVA in the conductive yarn is beneficial for the conductive fabric to obtain better sensing repeatability. The conductive knitted fabric has good sensitivity, with its gauge factor reaching up to 126.99. The strain sensor based on the conductive PET/PANI/PVA knitted fabric can be used to monitor real-time movement of a human body.

Keywords: Conductive fabric, Knitted fabric, Body motion monitoring, Polyester fabric, Polyvvinyl alcohol, Polyaniline, Strain-resistance sensing

1 Introduction

Monitoring of human movement and vital signs play an important role in sports training, human health assessment, disease diagnosis, patient rehabilitation, and various other fields[1, 2]. A strain sensor is an important electronic component for monitoring human movement patterns and vital signs. The traditional strain sensors are mostly based on metal and semiconductor materials, which suffer from disadvantages, such as poor portability, lack of flexibility, and discomfort. With the rapid development of flexible electronic materials and sensing technology, the development of flexible and wearable strain sensors for textile structures has become a research hotspot.

Intrinsically conductive fibres, such as metal and carbon fibres have been applied in strain sensors. For example, Li *et al.*[3] prepared a knitted strain sensor with a conductive yarn containing metal fibres, which was used to monitor human respiratory signals. Li *et al.*[4] prepared a flexible normal stress sensor of honeycomb fabric structure with carbon fibres and studied its sensitivity, hysteresis, and repeatability. However, owing to cost and performance considerations, the researchers have been looking for a new type of conductive fibre material that is more suitable for strain sensors. Post-treatment of common fibre materials is a common method to maintain the fibre characteristics and provide them with excellent conductivity.

Highly conductive materials, such as graphene, carbon nanotubes, and silver nanowires [5–9] can be used to enhance the conductivity of the fibres. The conductive polymer PANI is also widely used in the conductive treatment of textiles owing to its advantages, such as easy synthesis, low cost, high conductivity, and good stability[10–14].

A conductive PANI composite fabric or fibre for a strain sensor is primarily prepared through *in-situ*

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polymerization. *In-situ* polymerization refers to the polymerization of aniline monomer on the surface of the fabric or fibre under the action of oxidant and doped acid, thus forming PANI conductive layer. The conventional *in-situ* polymerization method of preparing conductive fibres through step-by-step solution impregnation reaction is inefficient. In previous study, the authors proposed a method for the continuous preparation of conductive PANI composite yarns, based on *in-situ* polymerization, with a processing speed of >200 m/min. This significantly improved the preparation efficiency. Presently, continuous conductive treatment of various yarns has been realized[15–17], with the conductivity of the conductive yarn reaching 1~2 S/cm.

The durability and stability of the PANI layer have significant influence on the sensor performance. PANI is a pi-conjugated organic polymer with a high rigidity and poor flexibility[18]. The PANI conductive layer on a fibre surface is prone to brittle fracture when subjected to external force, so blocking the conductive channel and reducing the conductivity. At the same time, the physical combination of the fibre surface and PANI mainly has low fastness, which leads to the damaged part of the PANI layer easily falling off from the fibre surface. Furthermore, it does not have the ability of long-term fixation, which makes it difficult to withstand various external forces during fibre processing and product use. Aiming to address this problem, the researchers in this field have improved the surface energy of the fibre by using chromic acid etching[19], alkali deweighting[20], and epoxy group modification[21]. It is of positive significance to enhance the bond fastness between PANI and the fibre matrix and improve the conductivity and durability of the composite conductive fibre; however, it cannot fundamentally solve the problem of low flexibility of the conductive layer. To improve the flexibility of PANI, some researchers used other polymers such as polyvinyl alcohol (PVA) mixed with PANI to make the films [22, 23]. The presence of PVA would increase its elongation at the break from approximately 2 % to over 40 %; however, there are no similar studies on the preparation of conductive fibres.

In this work, conductive PET/PANI composite yarn has been prepared via a continuous conductive treatment method based on *in-situ* polymerization. PVA has been used as a blend polymer to improve the durability of the PANI layer on the fibre surface. Among all textile structures, knitted fabric has a unique advantage in flexible wearable sensors because of its coil structure, which is easy to deform when subjected to external force and has a large strain. So, the knitted fabrics are prepared by a flat knitting machine with conductive PET/PANI and PET/PANI/PVA yarns. The strain–resistance sensing performance of the conductive knitted fabrics under the action of reciprocating tension has been studied, along with their application in human motion monitoring.

2 Materials and Methods

2.1 Materials

PET filament yarn of 333.3 dtex was used as a substrate. Aniline (An) (Shanghai Lingfeng Chem Reagent co., Ltd., China; analytical purity), hydrochloric acid (HCl) (Kunshan Jincheng Reagent Co., Ltd., China; analytical purity), ammonium persulfate (APS) (Shanghai Reagent Factory, China; analytical purity), and PVA with an alcoholysis of 88% (Wuhan Shuou Tech co., Ltd., China) were used as the monomer, dopant, oxidant, and blend polymer respectively.

2.2 Preparation of Conductive PET/PANI/PVA Composite Yarn

Firstly, an appropriate amount of PVA particles was added to deionized water and heated in a pot placed inside a constant temperature water bath. The mixture was mechanically stirred until the PVA particles were completely dissolved. Then a solution mixture A of An, HCl, and PVA was prepared. Next, APS was used as the oxidant to prepare oxidant solution B with a concentration of 1 mol/L. The PET yarn was placed in the air, and run through two tanks containing the solution mixture A and the oxidizing solution B respectively, so that the yarn surface would adsorb both A and B, and get oxidized and polymerized in the air, thus forming a PANI conductive layer. The continuous running speed of the yarn was 50 m/min. Four kinds of conductive yarns with different PVA contents were prepared. The solution concentrations for the four different yarns are shown in Table 1.

2.3 Preparation of Conductive Knitted Fabric

Using PET/PANI and PET/PANI/PVA composite yarns, a number of 2 + 2 rib knitted fabrics of the same specification were knitted on E12 manual flat knitting machine. To improve the strain recovery ability of the knitted fabrics, 83.3 dtex spandex yarn

Table 1 — Solution concentrations of four conductive yarns

Sample	Mass ratio of PVA to An,%	Concentration of An, mol·L^{-1}	Concentration of HCl, mol·L^{-1}	Concentration of APS mol·L^{-1}
PET/PANI	0	3	3	1
PET/PANI/PVA-2	2	3	3	1
PET/PANI/PVA-5	5	3	3	1
PET/PANI/PVA-8	8	3	3	1

was used together with the conductive yarns. The width of the fabrics is 3 cm; the length is greater than 15 cm; the longitudinal density is 39 courses /5 cm; and the transverse density is 45 wales /5 cm.

2.4 Characterization

2.4.1 Surface Morphology

The surface morphology of the PET yarns before and after the conductive treatment was observedbySNE-3000 scanning electron microscope (SEC Electric Machinery Co., Ltd., South Korea).

2.4.2 Electrical Conductivity

The resistance of the conductive PET/PANI and PET/PANI/PVA composite yarn was measured using a ZC-90G high insulation resistance measuring instrument (Shanghai Taiou electronic co., Ltd., China), and the electrical conductivity of the yarn was calculated using following equation:

$$\sigma = \frac{L}{R \times S} \qquad \ldots(1)$$

where σ is the electrical conductivity (S/cm); *L*, the test length (cm); R, the resistance and S, the cross-section area of the composite yarn.

2.4.3 Durability of Conductive Composite Yarns

In order to avoid severe breakage of polyaniline caused by standard washing method and reduce conductivity damage, a relatively mild washing method was adopted in this study, just to prove that PVA has a certain effect on improving the water resistance of polyaniline.

To analyze the wash fastness of the four composite yarns, they were placed in beakers with deionized water and oscillated with a water bath vibrator, with vibration times of 5, 30, 60, and 120 min respectively. After the set time was reached, the yarns were taken out, dried in the oven, and left standing for 24 h under standard atmospheric conditions (temperature 20°C ± 2°C, and RH 65% ± 2%). The resistances of the yarns were measured and their conductivities were calculated using Eq. (1).

To analyze the rub fastness of the composite yarns, an FFZ622 yarn abrasion resistance tester (Wenzhou Fangyuan Instrument co., Ltd., China) was used. The composite yarn sample was fixed at one end and a hammer of 5 g was suspended at the other end. Start the rotary table to allow the cotton coated friction roller to rub the yarn repeatedly. The resistance at the position of friction of the yarn after 10, 50, 100, 200, and 500 rubbing motions were recorded, and the conductivity was calculated according to Eq.(1).

2.4.4 Sensing Performance of Conductive Knitted Fabrics

The strain–resistance sensing performance testing system for the knitted fabrics consists of a computer, a PGSTAT302N electrochemical workstation (Vantone Electric Co., Ltd., Switzerland), and an elastometer (Shanghai Xinxian Instrument Co., Ltd., China).The knitted fabric was clamped between the fixed and movable grips of the elastometer, and the two signal input grips of the electrochemical workstation were clamped to both ends of the conductive fabric.

The working mode of the electrochemical workstation was set to record the change of current under a constant voltage of 10 V, and the current data collection interval was set as 0.05 s. When the electrochemical workstation is started, the elastometer and electrochemical workstation will automatically record the current changes of the fabric under different strains. Then the recorded current values were converted into resistances using the relation $R = U/I$ (where *R*, *U*, and *I* are the resistance, voltage, and current respectively).

2.4.5 Body Motion Monitoring

The knitted fabric was used as the sensing element with wires attached at both ends to make it a flexible wearable sensor. The sensor was fixed on the tester's elbow and knee, with both ends of the fabric connected to the signal input grip of the electrochemical workstation, and the resistance change of the fabric sensor was recorded.

3 Results and Discussion

3.1 Surface Morphology

Figure 1 shows the surface morphology of the PET yarn after the conductive treatment. The PANI layer was generated on the surface of the treated PET yarn. When the conductive layer does not contain PVA, the structure uniformity of the PANI layer on the fibre

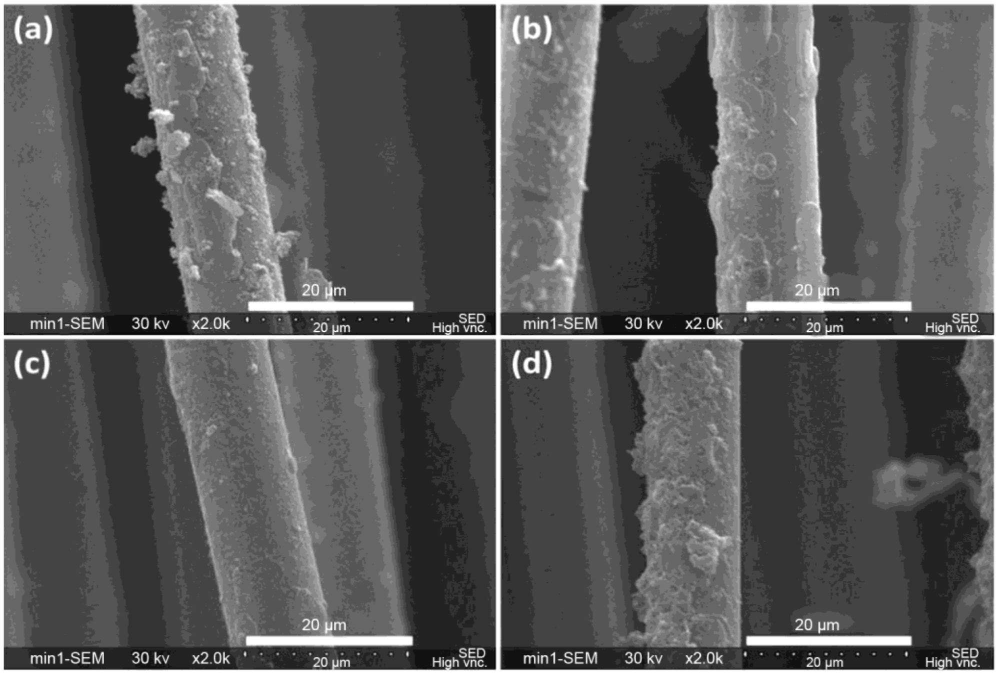

Fig. 1 — Surface morphology of (a) PET/PANI, (b) PET/PANI/PVA-2, (c) PET/PANI/PVA-5, and (d) PET/PANI/PVA-8 h

surface is poor and there are large agglomerated particles, as shown in Fig. 1(a). When the PVA content in the mixed solution is increased gradually, the size of the PANI aggregates on the yarn surface tend to decrease. When the PVA content reaches 5% [Fig. 1(c)], the large-size particles and aggregates on the yarn surface basically disappear, the conductive layer is smooth and flat, and the yarn is completely covered. With the further increase of the PVA content, the surface roughness of the yarn increases again [Fig. 1(d)]. It indicates that the addition of PVA in an appropriate amount could help PANI form a stable interpenetrating polymer network structure and improve its uniformity; however, excessive PVA would have a negative effect on the uniformity of the PANI structure [23].

3.2 Electrical Conductivity and Durability of Conductive Composite Yarns

Figure 2(a) shows the effect of PVA content on the conductivity of the conductive PET/PANI/PVA composite yarn. It can be seen that the conductivity of the composite yarns gradually increases from 1.342 S/cm to 1.887 S/cm as the PVA concentration is increased from 0% to 5% respectively. This corresponds to an increase of approximately 40%. However, as the PVA concentration further increases to 8%, the conductivity of the composite yarn drops to 1.274 S/cm. The improvement in the conductivity could be mainly attributed to the improvement in the structural uniformity of the conductive layer on the yarn surface owing to PVA blending (Fig. 1). This improves the capacity of the carriers in the conductive layer. Therefore, even though the PVA itself is not conductive, an appropriate amount of PVA is helpful to improve the conductivity of the PANI/PVA mixed conductive layer. However, when the content of the PVA is high, the conductive barrier formed in the PANI/PVA mixed conductive layer affects the passage of the carriers. In addition, a higher concentration of PVA would have a negative effect on the uniformity of the structure of the conductive layer, increasing the roughness of the conductive layer, which would also not be conducive to the passage of the carriers. Therefore, when the PVA content is ultimately increased to 8%, the conductivity of the composite yarn decreases.

To analyze the influence of PVA on the durability of the conductive layer of the PANI, the samples PET/PANI and PET/PANI/PVA-5 have been washed and rubbed.

The electrical conductivity of PET/PANI and PET/PANI/PVA-5 under different washing times is shown in Fig. 2(b). It can be seen that washing reduces the conductivity of the composite yarn, which decreased with the extension of the washing time. After washing with water for 5 min, the conductivity of PET/PANI rapidly decreased to 0.895±0.184 S/cm,

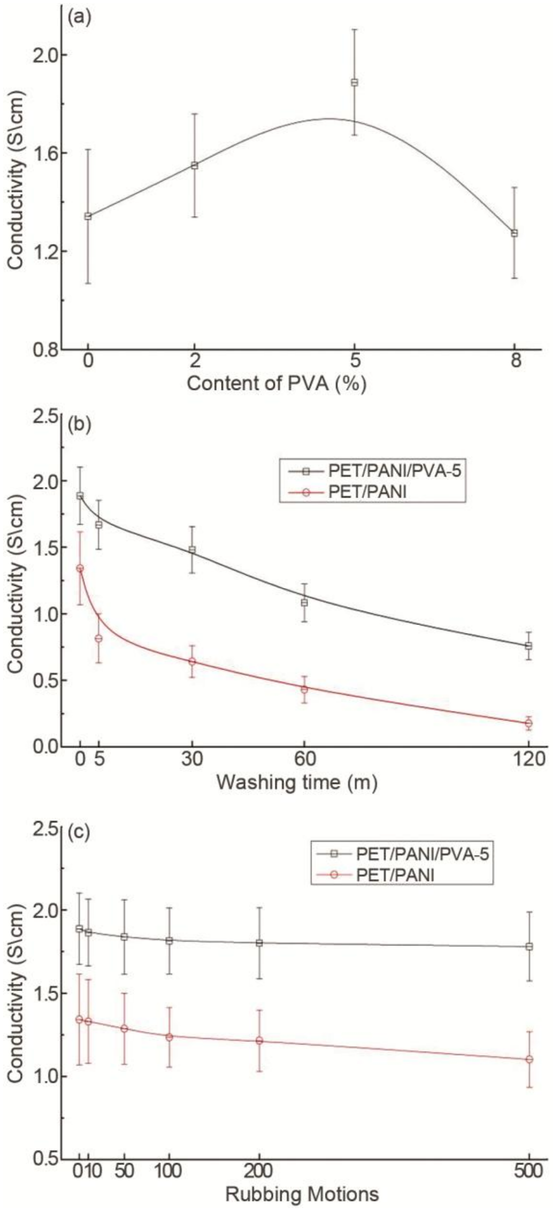

Fig. 2 — Conductivity of PET/PANI/PVA composite yarns, (a) effect of PVA concentration on conductivity of composite yarns, (b) conductivity of PET/PANI and PET/PANI/PVA-5 after washing, and (c) effect of friction by cotton fabric on conductivity of PET/PANI and PET/PANI/PVA-5

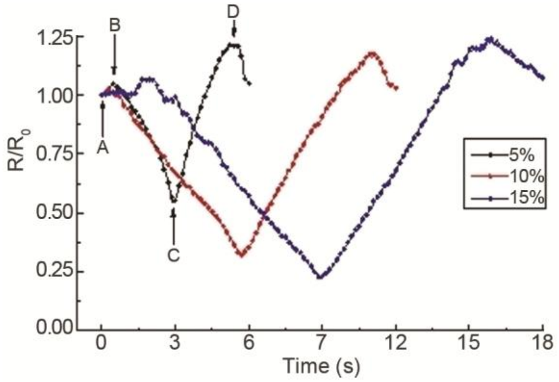

Fig. 3 — Strain–resistance curves of conductive knitted fabrics under different strain in first cycle

which is 67% of that before washing. Furthermore, after washing for 60 min, its conductivity is further decreased to 0.431±0.1 S/cm, which is only 32% of that before the washing. On the other hand, the conductivity of PET/PANI/PVA-5 after washing for 5 and 60min are 1.668±0.184 and 1.08±0.141 S/cm, which are 88% and 57% of that before washing respectively. This is a significant improvement as compared to the corresponding electrical conductivity values of PET/PANI. Furthermore, when washed for 120 min, the conductivity of the two samples are 40% and 12% respectively of those before washing. Therefore, it can be seen that the wash fastness of the composite yarn containing PVA is significantly better, as compared to that without PVA.

Under the friction of the cotton fabric, the changes in the conductivity of PET/PANI and PET/PANI/PVA-5 are shown in Fig. 2(c). It can be seen that the effect of friction on the conductivity of the composite conductive yarn with PVA is less than that without PVA. After 500 rub cycles, the conductivity of PET/PANI is decreased to about 85% of that before the friction, while the conductivity of PET/PANI/PVA-5 almost remains the same, i.e. the conductivity retention rate remains at approximately 95%. It can be inferred that the addition of PVA improves the flexibility of the conductive layer on the yarn surface, reduces the possibility of the conductive layer being damaged and falling off under the action of friction, and helps to improve the durability of the conductive layer under the action of small external forces.

3.3 Effect of Strain on Resistance of Conductive Fabric

Figure 3 shows the strain resistance curves of the first stretch-recovery cycle of the fabrics under the strain of 5%, 10%, and 15% respectively, and the stretch-recovery speed is 100 mm/min. It can be seen that the resistance of the knitted fabrics increases to a certain extent in the initial stage of stretching. As the stretching continues, the resistance decreases and reaches a minimum value when the fabric elongation attains a maximum value. The resistance of the fabric increases first and then decreases with the shrinkage of the fabric. In other words, in the stretch-recovery cycle, the resistance of the fabric alternately increases and decreases. Furthermore, under different strain conditions, the resistance of the fabric is increased – decreased – increased – decreased in a stretch-recovery cycle. In the figure, Points A, B, C, and D represent the following: A — the fabric is not stretched; B — the resistance is increased to the highest value at the initial stage of fabric stretching; C — the maximum elongation of the fabric takes pace (i.e. the resistance attains the lowest value); and D — the resistance is increased to the highest value at the recovery stage of the fabric.

Knitted fabric has a large deformability. When stretched, the length of each section of the coil, the contact area, and contact force between the coil and the coil change, results in a change in the resistance of the fabric. Figure 4(a) shows the coil structure model of the knitted fabric. A knitted coil is composed of three parts, viz (i) a needle loop (blue), (ii) a limb (green), and (iii) a sinker loop (red). Figure 4(b) is the equivalent circuit model of the woven fabric, where R_{L1} is the length wise resistance of the needle loop; R_{L2} is the length wise resistance of the limb; R_{L3} is the length wise resistance of the sinker loop; R_{C1} is the contact resistance between the sinker loop of the upper coil the needle loop of the lower adjacent coil; R_{C2} is the contact resistance between the left and right adjacent coils; and R_{C3} is the contact resistance of two limbs in the coil.

The distribution of polyaniline on the yarn surface is relatively uniform, and the conductive yarn can be regarded as a complete conductive body. When voltage is applied along the longitudinal direction of the fabric, the current flows along the longitudinal direction of the coils. Then, R_{L1}, R_{L3}, R_{C2}, and R_{C3} only play the role of a "bridge", and has little impact on the total resistance of the fabric. In fact, the fabric could be regarded as a parallel circuit with multiple series resistors of R_{C1} and R_{L2}, and the total resistance of the fabric is mainly affected by $R_{C1}$and R_{L2}. The resistance could be calculated by following equation:

$$R_{total} = \frac{(n-1)\times(R_{C1}+R_{L2})}{2m} \qquad \text{...(2)}$$

where n represents the number of courses in the fabric, and m represents the wales.

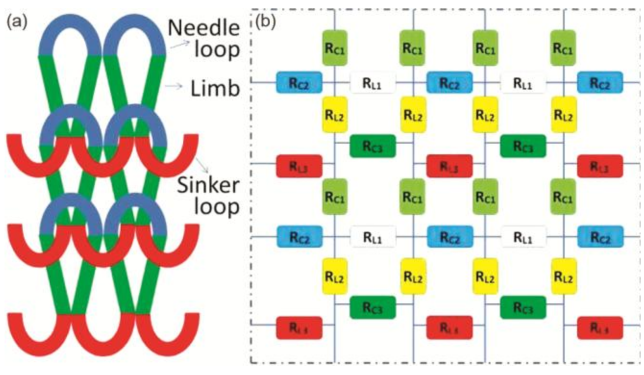

Fig. 4 — Diagram of (a) loop structure model of the knitted fabric and (b) its equivalent circuit

The influencing factor of length wise resistance (R_{L2}) is relatively simple, which is only related to the length of limb. When the fabric is elongated, the needle loop and the sinker loop of the coil are transferred to the limb, so that the limb become longer and R_{L2} increases. Conversely, it is reversed when the fabric is recovered.

The contact resistance (R_{C1}) is related to the contact area and pressure between the sinker loop of the upper coil and the needle loop of the lower coil. The contact resistance decreases with the increase of contact area. And according to the calculation formula of contact resistance, the contact resistance is decreased as a power function with an increase of contact pressure[24].

Therefore, in the initial stage of the fabric stretching, with an increase in the strain, the length of the limb is increased and the lengthwise resistance is increased. Meanwhile, the yarn in the overlapped part of the upper and lower coils is slipped, the length of the sinker loop and the needle loop is shortened, the contact area is decreased, and the contact resistance is increased. This results in an increase in the total resistance of the fabric. When the strain reaches a certain degree, the contact pressure between adjacent horizontal coils increased, as the strain continues to increase. At the same time, because the yarns in the overlapped part of the upper and lower coils are squeezed and deformed under a large force, the contact area between the coils is increased, thus reducing the contact resistance. This results in a decrease in the total resistance of the fabric. This "bidirectional strain sensing" characteristic, in which the resistance first increases and then decreases with an increase in the tension, has made it possible to apply it in situations, wherein the strain is kept within a certain reasonable range. In addition, a certain deformation could be applied to the knitted fabric in advance, as the initial structure to obtain a monotone linear strain-resistance sensing performance.

3.4 Sensing Performance of Conductive Knitted Fabrics

Figure 5 shows the strain–resistance curves (60 cycles) of the conductive PET/PANI and

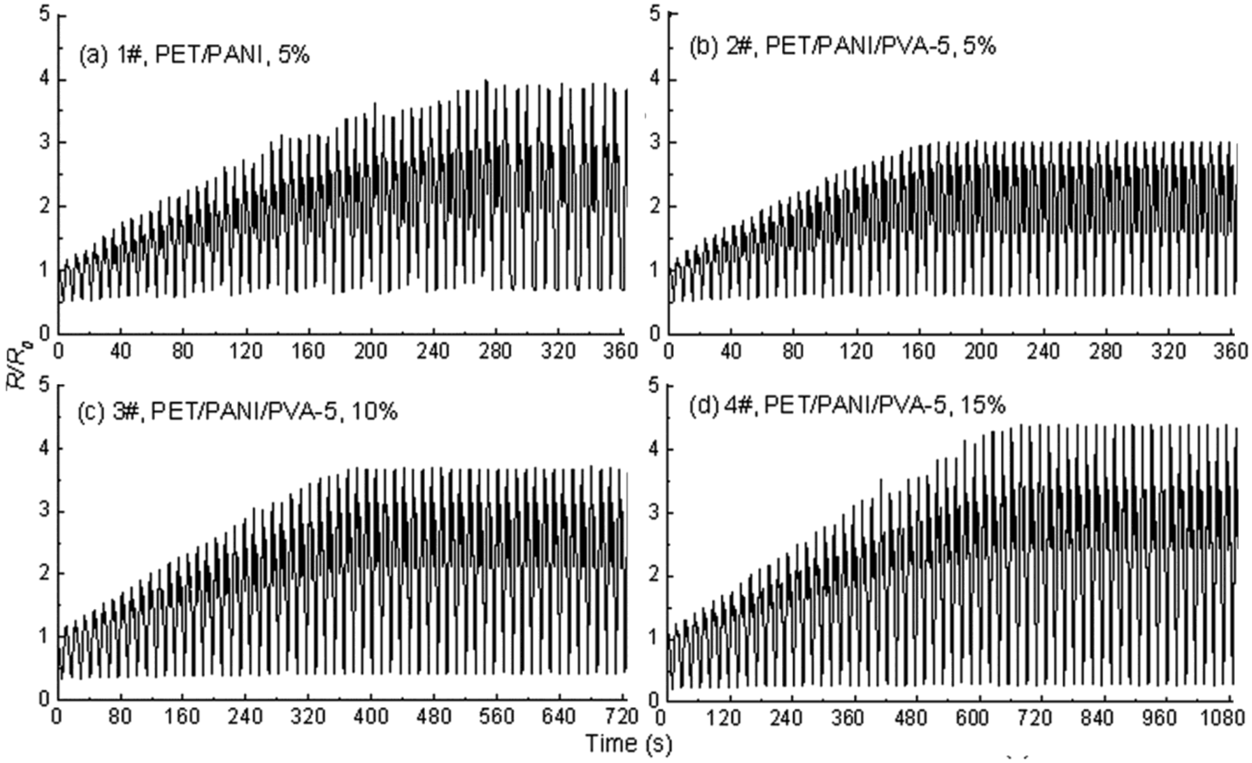

Fig. 5 — Strain–resistance curves of conductive knitted fabrics at strains of (a) 5% (PET/PANI), (b) 5% (PET/PANI/PVA-5), (c) 10% (PET/PANI/PVA-5), and (d) 15% (PET/PANI/PVA-5)

PET/PANI/PVA-5 knitted fabrics under different test conditions. It can be seen from Figs 5(a) and (b) that the resistance change stability of PET/PANI conductive knitted fabric is significantly worse than that of PET/PANIPVA conductive knitted fabric. Based on Fig. 5, the strain–resistance sensing performances of conductive knitted fabrics are studied, including linearity, repeatability and sensitivity.

3.4.1 Linearity

Linearity is an important index of the sensor performance. As can be seen from Fig. 5, the resistance of each fabric varies linearly from point B to point C, and then from point C to point D; that is, the fabric has a strong linear sensitivity under this strain condition. The cycles of 1, 10, 20, 30, 40, 50 and 60 of the samples are selected to analyze the sensing linearity of the knitted fabrics, with R/R_0 value as the dependent variable (y) and strain as the independent variable (x). The fitting line is obtained by regression analysis using the least squares method and the fitting results are shown in Table 2. As can be seen from this table, that under different test conditions, the correlation coefficient (r) of the fitting equation is greater than 0.95 from point B to point C, and from point C to point D in the 1st, 10th, 20th, 30th, 40th, 50th and 60th cycles, indicating that the conductive knitted fabrics demonstrate good linear sensing performances.

3.4.2 Repeatability

The repeatability of a sensor refers to the consistency of the characteristic curve obtained from a continuous change in the input quantity in the same direction, over a range or the whole range, under the same working conditions. In this study, the strain–resistance sensing repeatability of the conductive knitted fabrics is represented by the variations in A, B, C, and D in each cycle. The values of the points A, B, C, and D in the 1st, 10th, 20th, 30th, 40th, 50th and 60th cycles of the corresponding curve in Fig. 5 are shown in Table 3.

As can be seen from Fig. 5 and Table 3, with the increase in number of stretch-recovery cycles, the resistance of the fabric generally presents a trend of gradual increase, but the resistance changes of samples with different raw materials and different strains are also different. The resistance of sample 1# (without PVA) remains unstable after 60 cycles of 5% stretching, while the resistance of sample 2# becomes stable after about 27 cycles of 5% stretching. By comparing sample 2#, 3# and 4#, the number of

Table 2 — Linearity equations of conductive knitted fabrics under different test conditions

Sample	Cycle	B→C		C→D	
		Linear equation	*r*	Linear equation	*r*
1# (PET/PANI, 5%)	1	y = -0.108x + 1.0793	0.9964	y = -0.1468x + 1.3078	0.9869
	10	y = -0.2616x + 2.0909	0.9711	y = -0.3695x + 2.5171	0.9971
	20	y = -0.4241x + 3.0152	0.9617	y = -0.5569x + 3.3935	0.9989
	30	y = -0.5855x + 3.8991	0.9712	y = -0.7094x + 4.1251	0.9979
	40	y = -0.6517x + 4.1857	0.9708	y = -0.8034x + 4.708	0.9969
	50	y = -0.6603x + 4.3525	0.9704	y = -0.8449x + 4.953	0.9970
	60	y = -0.6858x + 4.51	0.9708	y = -0.8869x + 5.1201	0.9969
2# (PET/PANI/PVA-5, 5%)	1	y = -0.1106x + 1.1763	0.9822	y = -0.1728x + 1.4388	0.9889
	10	y = -0.3108x + 2.3552	0.9547	y = -0.3709x + 2.5675	0.9813
	20	y = -0.4755x + 3.3099	0.9543	y = -0.5418x + 3.4307	0.9803
	30	y = -0.5747x + 3.8851	0.9513	y = -0.6051x + 3.8596	0.9721
	40	y = -0.5571x + 3.885	0.9504	y = -0.6085x + 3.813	0.9735
	50	y = -0.5756x + 3.8877	0.9514	y = -0.6054x + 3.8605	0.9721
	60	y = -0.5566x + 3.8835	0.9507	y = -0.6092x + 3.8157	0.9736
3# (PET/PANI/PVA-5, 10%)	1	y = -0.0739x + 1.0685	0.9986	y = -0.0973x + 1.3187	0.9965
	10	y = -0.155x + 2.0745	0.9903	y = -0.199x + 2.4054	0.9904
	20	y = -0.2374x + 3.0283	0.9848	y = -0.3068x + 3.5292	0.9908
	30	y = -0.3013x + 3.8073	0.9818	y = -0.4064x + 4.5354	0.9916
	40	y = -0.3138x + 4.0039	0.9802	y = -0.4167x + 4.6246	0.9908
	50	y = -0.3137x + 4.0033	0.9802	y = -0.417x + 4.6262	0.9907
	60	y = -0.314x + 4.0051	0.9803	y = -0.4169x + 4.6255	0.9907
4# (PET/PANI/PVA-5, 15%)	1	y = -0.074x + 1.3278	0.9985	y = -0.0926x + 1.5948	0.9959
	10	y = -0.1451x + 2.507	0.9972	y = -0.1896x + 3.0641	0.9988
	20	y = -0.2178x + 3.6801	0.9955	y = -0.2735x + 4.3587	0.9976
	30	y = -0.2818x + 4.68	0.9975	y = -0.3608x + 5.5788	0.9970
	40	y = -0.3294x + 5.3647	0.9973	y = -0.4117x + 6.3129	0.9982
	50	y = -0.3288x + 5.3873	0.9973	y = -0.411x + 6.2726	0.9981
	60	y = -0.3286x + 5.3848	0.9972	y = -0.411x + 6.2723	0.9981

Table 3 — Change in resistance of conductive knitted fabrics in different cycles

Sample	Point	Cycle						
		1	10	20	30	40	50	60
1# (PET/PANI, 5%)	A	1.000	1.159	1.655	1.975	2.367	2.246	1.995
	B	1.016	1.576	2.122	2.583	2.770	2.854	2.981
	C	0.538	0.652	0.653	0.649	0.674	0.698	0.725
	D	1.189	1.940	2.735	3.227	3.569	3.900	3.935
2# (PET/PANI/PVA-5, 5%)	A	1.000	1.298	1.598	1.657	1.606	1.664	1.601
	B	1.048	1.674	2.296	2.651	2.651	2.650	2.653
	C	0.547	0.602	0.605	0.625	0.626	0.624	0.629
	D	1.217	2.001	2.642	3.030	3.032	3.032	3.033
3# (PET/PANI/PVA-5, 10%)	A	1.000	1.378	1.707	2.046	2.245	2.241	2.239
	B	1.027	1.652	2.352	2.954	3.128	3.128	3.129
	C	0.318	0.365	0.388	0.418	0.420	0.415	0.416
	D	1.176	2.006	2.890	3.605	3.682	3.674	3.675
4# (PET/PANI/PVA-5, 15%)	A	1.000	1.508	2.071	2.530	2.950	2.918	2.924
	B	1.071	1.778	2.480	3.127	3.472	3.477	3.479
	C	0.221	0.273	0.295	0.302	0.295	0.294	0.291
	D	1.238	2.158	3.129	4.117	4.687	4.684	4.682

cycles, in which resistance changes tends to be stable, increases with the increase of strain. For example, for sample 3#, resistance changes tend to be stable after about 31 cycles, while for sample 4#, it tends to be stable after about 40 cycles. This indicates that the structure of the polyaniline on the surface of the yarn is damaged to a certain extent under the action of bending and friction, resulting in the increase of the resistance of the fabric. When stretching to a certain number of times, the damage effect gradually weakens, so that the resistance becomes stable. For sample 1# and sample 2#, the addition of PVA improves the flexibility of the conductive layer, which is beneficial to reduce the damage of the conductive layer in the process of drawing. Therefore, sample 2# shows better sensing repeatability than sample 1#.For 2#, 3#, and 4# samples, the larger strain will lead to greater damage of the conductive layer, and the resistance change will require more times of stretching to stabilize.

3.4.3 Sensitivity

Sensitivity is an important index of a sensor's performance. As can be seen from Fig. 5 and Table 3, when the strain is 5%, the resistance of sample 1# and sample 2# is decreased to approximately 50 – 70% of the initial value. When the strains are 10% and 15%, the resistances of samples 3# and 4# are decreased to 30 – 40% and 20 – 30% of their initial values respectively. After the recovery, the resistance could reach 3–4 times its initial value. As the sensitivity calculation needed to be carried out under the condition of high linearity, the sensing sensitivities of each sample in the 1st, 10th, 20th, 30th, 40th, 50th and 60th cycles when the resistance is changed monotonously from point B to point C, and from point C to point D are calculated. The sensitivity is expressed by a gauge factor and calculated using following equation:

$$GF = \frac{\Delta \mathrm{R}/R_0}{\Delta L/L_0} \qquad ...(3)$$

where *GF* is the gauge factor; ΔR, the difference between the resistance after stretching and the original resistance; R_0, the original resistance; ΔL, the difference between the tensile lengths of the sample and the original length; and L_0, the original length.

The calculated results are shown in Table 4. It can be seen from this table, that in the same samples, with

Table 4 — Gauge factor of conductive knitted fabrics under different test conditions

Sample	Cycle No.	B→C		C→D	
		Strain strange, %	*GF*	Strain strange, %	*GF*
1# (PET/PANI, 5%)	1	0.345→5	10.14	5→0.517	28.34
	10	1.552→5	17.27	5→1.379	57.28
	20	1.552→5	20.39	5→1.207	88.26
	30	1.897→5	24.59	5→1.207	109.96
	40	1.724→5	23.50	5→1.207	118.90
	50	1.724→5	23.46	5→1.207	126.99
	60	1.897→5	24.85	5→1.207	122.57
2# (PET/PANI/PVA-5, 5%)	1	0.776→5	11.41	5→0.862	31.08
	10	1.638→5	19.36	5→1.034	61.53
	20	1.638→5	22.27	5→0.862	85.43
	30	1.638→5	23.10	5→0.690	93.74
	40	1.724→5	23.72	5→0.603	91.78
	50	1.638→5	23.11	5→0.690	94.01
	60	1.724→5	23.69	5→0.603	91.27
3# (PET/PANI/PVA-5, 10%)	1	0.522→10	7.54	10→0.957	32.82
	10	2.261→10	9.47	10→1.217	56.31
	20	2.174→10	10.15	10→1.391	82.39
	30	2.348→10	10.43	10→1.478	98.41
	40	2.261→10	10.64	10→1.391	99.24
	50	2.261→10	10.54	10→1.391	100.34
	60	2.261→10	10.66	10→1.391	100.10
4# (PET/PANI/PVA-5, 15%)	1	3.202→15	6.04	15→2.781	25.39
	10	4.551→15	7.80	15→4.551	49.48
	20	4.972→15	8.74	15→4.382	69.84
	30	5.309→15	9.33	15→4.298	81.93
	40	5.478→15	9.59	15→4.382	84.11
	50	5.562→15	9.70	15→4.298	84.39
	60	5.562→15	9.70	15→4.298	84.18

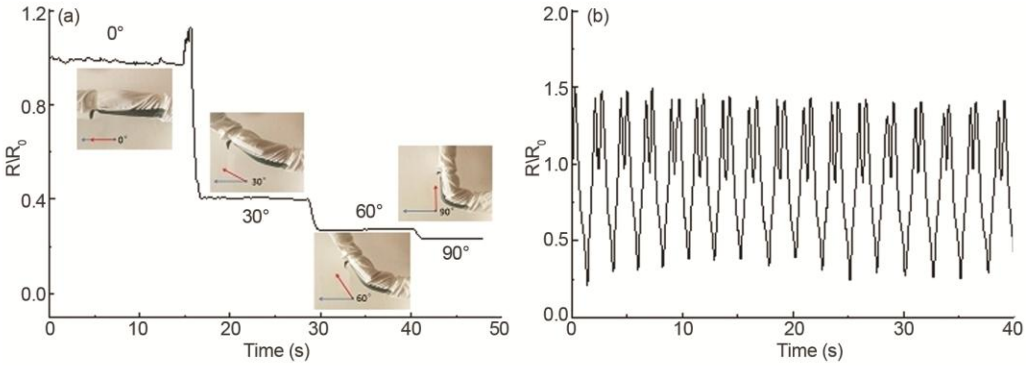

Fig. 6 — Changes in resistance of sensor during (a) intermittent and (b) continuous movement of elbow

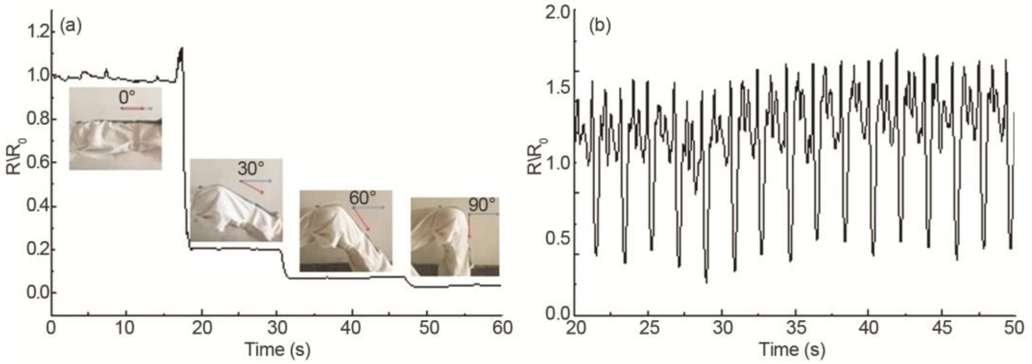

Fig. 7 — Changes in resistance of the fabric sensor during (a) intermittent movement of the knee and (b) walking

an increase in the stretch-recovery cycle number, the sensing sensitivity of the conductive fabric has a tendency to improve. For example, for sample 1#, from point B to point C, the gauge factors of the 1st, 10th, 20th, 30th, 40th, 50th and 60th cycles are 10.14, 17.27, 20.39, 24.59, 23.50, 23.46 and 24.58, and from point C to point D, the gauge factors of the 1st, 10th, 20th, 30th, 40th, 50th and 60th cycles are 28.34, 57.28, 88.26, 109.96, 118.90, 126.99 and 122.57 respectively. The variation trends of samples 2#, 3# and 4# are similar to that of sample 1#.

From point B to point C, the sensitivity of the conductive fabrics tends to decrease with an increase in the strain. This is mainly because when the fabric is stretched by 5%, the resistance is greatly reduced, and when the fabric continues to be stretched to 10% and 15%, the strain has doubled and tripled; however, the fabric resistance is decreased to a lesser extent, resulting in a drop in the sensitivity. From point C to point D, the sensing sensitivity of the conductive knitted fabrics shows a similar trend with an increase in the strain from that of point B to point C.

3.5 Body Motion Monitoring

The fabric sensor is fixed on the elbow of the volunteer, and the change in the resistance of fabric as the volunteer bent the forearm is shown in Fig. 6. Figure 6(a) shows the change in R/R_0 value when the forearm is making an intermittent movement. As can be seen from the figure, the fabric resistance is basically unchanged when the forearm is unmoved (0°).When the forearm is bent up to 30°, the fabric resistance decreases rapidly to approximately 40% of the original resistance after a short period of increase, and it is increased at the initial stage of the fabric stretching, which is consistent with the previous analysis. When the forearm is flexed 60° and 90°, the fabric resistance decreases to 27% and 23% of the original value respectively, and remains stable. Figure 6(b) shows the change in R/R_0 value when the forearm is in random flexion motion. It can also be seen that when the forearm performs a continuous irregular cyclic flexion motion, the fabric elongation deformation could be rapidly fed back through the change of resistance, showing the number of elbow bends, and giving a real-time feedback on the elbow motion.

The fabric sensor is fixed on the knee of the left leg of the volunteer, and the resistance changes during an intermittent movement and walking with a speed of about 4 km/h are recorded to monitor the movement of the knee (Fig.7). As can be seen from Fig. 7(a), the resistance change in intermittent movement of the knee is basically the same as that in intermittent movement of the elbow. With the increase in bending angle of the leg, the resistance decreases and remains basically unchanged in the movement gaps. The difference is that, at the same angle, the resistance reduction caused by knee movement is more significant, such as at 60 ° and 90°, the resistance decreases to 7.5 % and 3.8 % of the unbent state respectively. Figure 7(b) shows the resistance change curve of the fabric sensor during continuous walking. Each trough in the curve corresponds to the moment when the left knee is bent to its maximum, and each trough represents a maximum bend of the left knee (two steps). During walking, the resistance changes regularly with the knee flexion and the fluctuation is relatively stable. The fluctuation of the curve is similar during the periodical period, which indicates that the sensor can effectively monitor the knee motion. The time interval between adjacent troughs is the time taken for each 2 steps. In the first 30 steps, the volunteers spend an average of about 1.8 s per 2 steps, or 0.9 s per step.

4 Conclusion

An appropriate amount of PVA could help the conductive PANI layer to form a stable interpenetrating polymer network structure, and to improve the structural uniformity and conductivity. When the mass ratio of PVA to aniline in the solution system is 5%, the conductivity of the conductive PET/PANI/PVA composite yarn is increased from 1.342 S/cm without the PVA to 1.887 S/cm, showing an increase of ~ 40%. Furthermore, the wash fastness and rub fastness are significantly improved.

When the conductive fabric is stretched, its resistance first increases and then decreases; when it recovers, the resistance rises first and then falls. The conductive fabric has good sensing linearity in the phase of monotone rise or fall of resistance. The addition of PVA in the conductive yarn is beneficial for the conductive fabric to obtain better sensing repeatability.

Through the monitoring of the elbow movement, it is found that the resistance of the fabric could change rapidly in the state of motion, and it remains stable in a state of rest, which could accurately and effectively monitor the movement of the human body.

Acknowledgement

Authors acknowledge with thanks the funding supported by the Applied Research Project of Public Welfare Technology of Zhejiang Province (No. LGG20E030002) and “Pioneer” and “Leading Goose” R&D Program of Zhejiang（No. 2022C01166.

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