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Article

Structural Design and Performance Research of a Knitted Flexible Sensor

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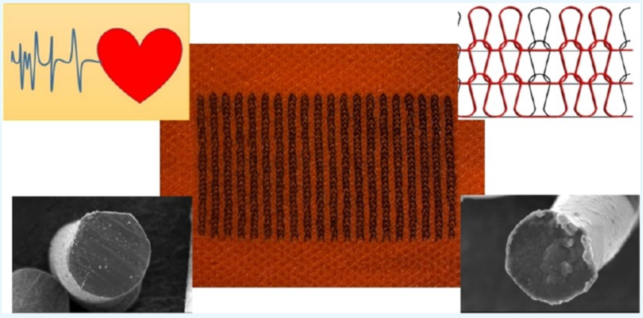

ABSTRACT: This paper mainly studies the structure and performance of a smart knitting sensor and selects three kinds, 1 + 1, 2 + 2, and 2 + 1, of fake rib stitches. 70D and 100D silver-plated conductive yarns with a 40D carbon black conductive yarn are knitted into different fabrics in the way of plating. Finally, the related properties of the conductive fabrics of different sizes are studied. This study found that the prepared knitted fabrics can not only meet the requirements of air permeability standards in both the plain needle area and the plated area greatly but also have good elastic recovery. When the number of the plated conductive yarn is the same, the conductivity of the fabric increases with the increase in the conductive yarn wale number, and the smaller the number of plated yarns, the greater the influence of the wale number on the change in conductivity. When the number of plated yarn wales is the same, the conductivity of the fabric decreases with the increase in the conductive yarn course number, and the smaller the wale number, the smaller the effect of the course number on the change in conductivity. When the fabric formed by a silver-plated conductive yarn is in a stretched state, the conductivity decreases. However, the electrical conductivity of the 100D silver-plated fabric is more stable than that of the 70D silver-plated fabric. The conductivity of the carbon black conductive fabric is in the order of MΩ, and the conductivity of the conductive fabric changes greatly and disperses when the conductive fabric is in a stretched state. The conductive stability of the 1 + 1 fake rib stitch samples was the best before washing. On the contrary, the conductive stability of the 2 + 2 fake rib stitch fabrics was relatively good after washing.

1. INTRODUCTION

With the continuous advancement of science and technology, traditional textiles continue to develop in the direction of functionalization and intelligence. To achieve intelligence, sensors are of vital importance. There are mainly four forms of sensors, such as hydrogels,[1,2] aerogels,[3−5] films,[6,7] and textiles;[8−11] while the first three traditional sensors all have certain defects, hydrogels usually have poor mechanical properties,[12] and the film is difficult to adapt to the curve changes of the human body.[13] The above-mentioned facts hinder the application of the top three kinds of sensors to a certain extent. The flexible wearable sensor such as the textile sensor can perfectly solve these defects. It can be worn by people like traditional clothing without being bulky; it can be completely indistinguishable from traditional clothing but at the same time, it does not affect wearing comfort. Textile sensors change the image of traditional sensors that are bulky, fragile, and unwieldy. At the same time, textile sensors also make traditional clothing no longer just used to cover the body and avoid the cold. Wearable flexible sensors are increasingly appearing in many fields such as human−computer interaction, medical health, etc. Therefore, this paper studied the structure design and performance of the knitted sensor. Because the knitted fabric has a unique loop structure, when the conductive yarn forms a loop in the knitted fabric, it is as if the wire forms a loop in the circuit. When the knitted sensor is worn by a wearer, the wearer's body movement and body curve cause the yarn to stretch and deform. The stretching action causes the conductive yarn to produce slight changes in the length and the cross-sectional area and causes the loops created by the conductive yarn in the knitted fabric to move, which further produces current changes. In our papers, we selected a silver-plated conductive yarn and a carbon black conductive yarn as conductive yarns. After comprehensively analyzing the advantages and disadvantages of the performance of various knitted fabrics, the fabric is designed. Finally, the conductive yarn is knitted into the fabric in the form of plating yarns on a

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single-cylinder seamless circular knitting machine, and the related properties of the fabric are studied.

It is found that the prepared knitted sensor can not only satisfy people's wearing comfort but also has excellent electrical conductivity. The conductivity also changes in different states, and after the washing simulation, the conductivity stability of the fabric by the carbon black conductive yarn is also improved compared with that before washing. This knitted flexible sensor can be applied to some functional underwear to detect some vital signs of the human body such as breathing, and then to carry out a certain auxiliary diagnosis of the human body's physical health state. Meanwhile, this knitted flexible sensor can be used as auxiliary diagnostic equipment for life and health detection, such as the Coronavirus disease 2019 (COVID-19) that is raging around the world. Because the COVID-19 is a respiratory disease, after infection with the virus, the human body's breathing conditions will change. Meanwhile, this sensor is directly knitted into the seamless underwear; when it is closely fitted to the human body, it can monitor the human body's breathing condition in real-time through the change of the electrical signal of the sensor caused by the thoracic movement based on breathing to assist diagnosing the wearer for respiratory symptoms of the virus.

2. EXPERIMENTAL SECTION

2.1. Test Standards. The tensile properties of conductive yarns were tested according to the GB/T 14337-2008 "Chemical fibers test method for tensile properties of short fibers".

According to the FZ-T 70006-2004 "Test method for tensile elastic recovery of knitted fabrics", the elastic recovery of the fabrics was tested.

According to the GB/T 5453-1997 "Testing of the air permeability of textile fabrics", the air permeability test of the fabric was carried out.

The fabrics were washed according to the GB/T_8629-2001 "Textiles_Household washing and drying procedures for testing".

2.2. Fabric Design and Weaving. Table 2 shows the specifications of the fabric relaxing off the loom and semifinishing, and the fabric is knitted according to this size. The specifications of the conductive yarn used and the craftsmanship are shown in Table 1. Figure 1 shows the pattern of underwear styles, which can be divided into six areas, a is the area that needs to be cut after relaxing off the knitting machine, b is the main part of the underwear, c is the chest contour area, d is the waist area, e is the pattern on the back area, and f is the hem area. Among them, d and f use the same organizational structure, so there are five kinds of organizational structures. b chooses a plain stitch, a adopts a staggered 1 + 1 fake rib stitch, c adopts a 2 + 1 fake rib stitch, d and f use a 1 + 3 fake rib stitch, and e staggers a 2 + 2 fake rib stitch.

Table 1. Introduction of Conductive Fibers

name of the conductive yarn	size of yarn/D	number of the multifilament	craftsmanship
silver-plated conductive yarn	70	24	silver-plated on nylon
	100	36	
carbon black conductive yarn	20	3	carbon nanopowder added into nylon

Table 2. Fabric Unloading and Semifinished Product Specifications

measuring parts	dimensions/cm	
	off machine	drying
1/2 chest	49	38
total length	92	66
bottom hem height	4.5	3.3
front center length	74	54
back center length	88	64

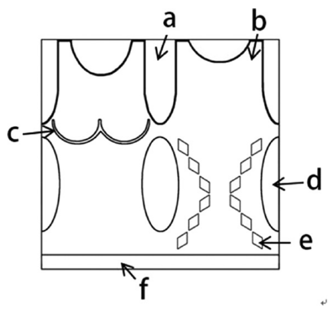

Figure 1. Pattern of the underwear style (a is the area that needs to be cut after relaxing off the knitting machine, b is the main part of the underwear, c is the chest contour area, d is the waist area, e is the pattern on the back area, f is the hem area).

The sensor is knitted in a rectangular shape to save costs. Meanwhile, conductive yarns are knitted into the fabric in the plating form that will minimize the float length in the transition area to better distinguish the fabric pattern from the ground and avoid serious "bottom exposure." The conductive yarn chooses a 1 + 1 fake rib stitch (Figure 2A), a 2 + 2 fake rib stitch (Figure 2B), and a 2 + 1 fake rib stitch (Figure 2C).

To observe the change of the fabric resistance more easily, the gradient of the number of stitches in the wale is designed to be 20. In this context, 40, 60, and 80 wales are selected to knit fabrics with different transverse dimensions. Since the conductive yarns along the longitudinal direction of the fabric are equivalent to parallel resistance, which will play an important role in reducing the influence of the increase in the number of conductive yarns on the resistance of the fabric, the gradient of the coil course number is set to 10. In this way, 10, 20, and 30 courses are taken to knit fabrics of different longitudinal sizes.

The GD-NJ08 single seamless circular knitting machine with a gauge of E28 is used for knitting, the diameter of the cylinder is 14″, the total number of needles is 1248, the yarn is fed by eight routes, each route has eight yarn feeders, the machine's speed is 60 rpm, and the speed is 45 rpm during conductive plating knitting. A nylon core-spun yarn is used as the ground yarn, and a 70D nylon high elastic yarn is used as the plating yarn. The black carbon conductive yarn and the silver-plated yarn are plated through the plating stitch. To facilitate the observation of the distribution of the conductive yarn, the carbon black conductive yarn and the silver-plated conductive yarn are knitted with orange and black ground yarns, respectively.

3. RESULTS AND DISCUSSION

Seamless knitted underwear, as a close-fitting garment, has the reputation of "the second skin of the human body".[14] Therefore, wearing comfort is an important factor in costume

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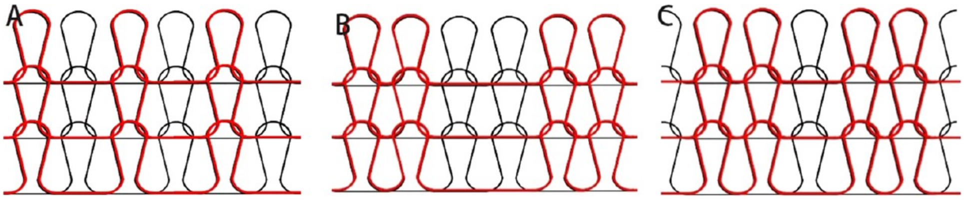

Figure 2. Plating structure of the conductive yarn (the red curve is equal to the conductive yarn and the black curve is the ground yarn) (A is the 1 + 1 fake rib stitch, B is the 2 + 2 fake rib stitch, C is the 2 + 2 fake rib stitch).

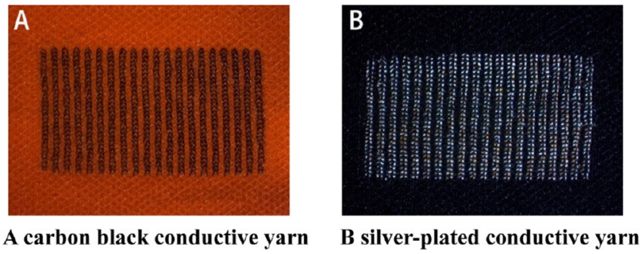

Figure 3. Photo of the conductive plated fabric relaxing off the loom.

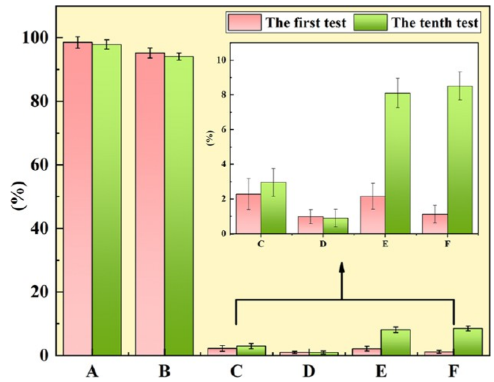

Figure 4. Fabric tensile resilience test (A is lateral elastic recovery rate, B is the longitudinal elastic recovery rate, C is the transverse plastic deformation rate, D is the longitudinal plastic deformation rate, E is the transverse stress relaxation rate, and F is the longitudinal stress relaxation rate).

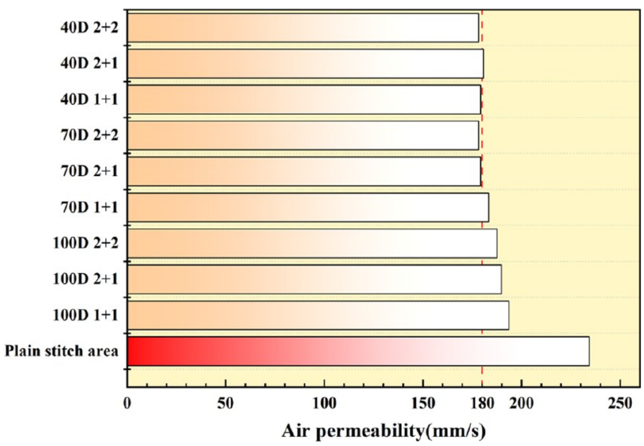

Figure 5. Fabric air permeability test.

evaluation. The seamless knitted fabrics were tested in terms of wearing performance, such as tensile resilience and breathability first. Youfang[15] suggested that the elastic modulus of the fabric can be used to predict the wearing clothing pressure to a certain extent based on the test results. Simultaneously, the pressure of clothing should not be too small or too large. If it is too small, it will not meet the required pressure requirements. If it is too large, it may cause damage to the internal organs of the wearer.[16] Therefore, the wearing comfort of the fabric can be estimated and evaluated by testing the elasticity of the knitted seamless underwear. Air permeability also plays an important role in underwear comfort. Good air permeable fabrics can quickly discharge the moisture generated by the body from the microenvironment between the human body and the clothing, so it will reduce the suffocation feeling.

3.1. Knitted Fabric Properties.

3.1.1. Tensile Resilience Performance. First of all, we test the tensile resilience of the plain area instead of the plating area to estimate the wearing comfort of the fabric because the area of the plating area is too small to test alone. The fabric tensile resilience was tested by the constant elongation method, and a parallel sampling method with a size of 20 cm × 5 cm sample was selected, and three samples were taken from each direction (vertical and cross directions). The results were analyzed after one constant elongation tensile test and 10 consecutive tensile tests on the sample. Clamping distance: 200 mm; pretension: 5cN; tensile speed: 100 m/min; predetermined elongation: 50% transverse elongation and 50% longitudinal elongation[17] and stationary for 1 min; and recovery speed: 50 m/min and stationary for 3 min (Figure 3).

The test results are shown in Figure 4. It can be observed that the fabric transverse elastic recovery rate is slightly better than the longitudinal elastic recovery rate, and after 10 tests, the elastic recovery rate decreases slightly. The elasticity of knitted fabrics is not necessarily better in the transverse direction than in the longitudinal direction. It is not only related to the loop structure but also to the yarn.[18] Since the raw yarn of the garment's main part has not changed in the experiment, it is the loop structure of the knitted fabric that contributes to the transverse elasticity that is greater than the longitudinal elasticity. When the loop structure is subjected to an external force, the loop of the knitted fabric will deform first, that is, the needle loop and sinker loop will be straightened and the leg will be displaced and rotated. When this process is over, the stretching of the yarn causes some fibers to slip in the yarn. The combination of these two factors results in the elasticity of knitted fabrics. However, due to the large elongation of the loop arc in the transverse direction, the transverse elasticity of the fabric is greater than the longitudinal elasticity, and the elasticity of the fabric has good stability, which will not be greatly reduced due to the increase in the number of tests. The experimental results indicate that the longitudinal and transverse plastic deformation rates are not higher than 5%. However, the plastic deformation rates in the two directions after 10 consecutive tests are different. The transverse plastic deformation rate of the tenth test is higher than that of the first test, but the longitudinal plastic

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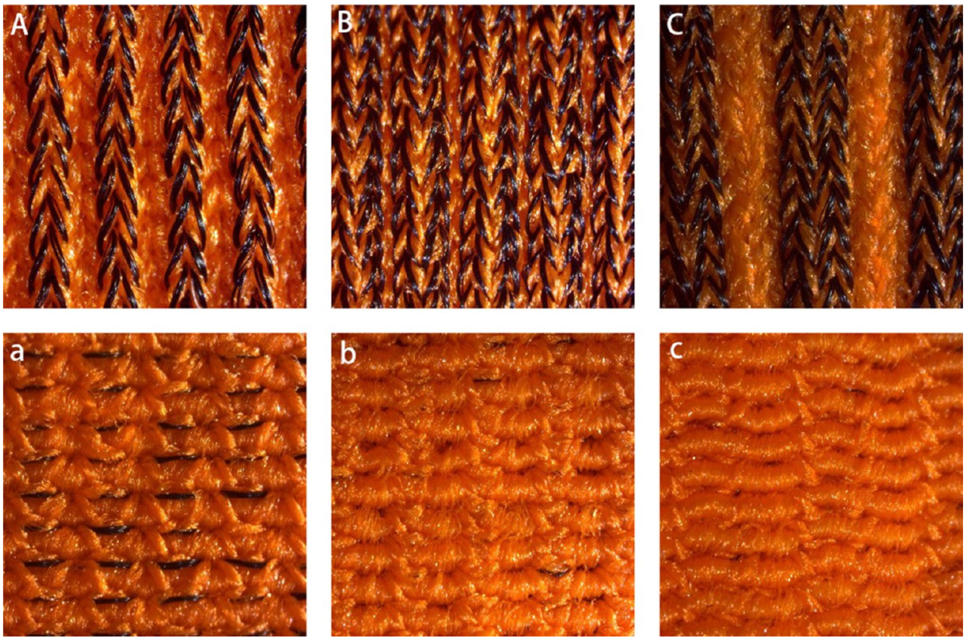

Figure 6. Zeiss observation photo of the conductive plating part of the knitted seamless underwear of the carbon black conductive yarn (A is the 1 + 1 fake rib stitch; B is the 2 + 1 fake rib stitch; C is the 2 + 2 fake rib stitch; a, b, c are the back side of A, B, C, respectively).

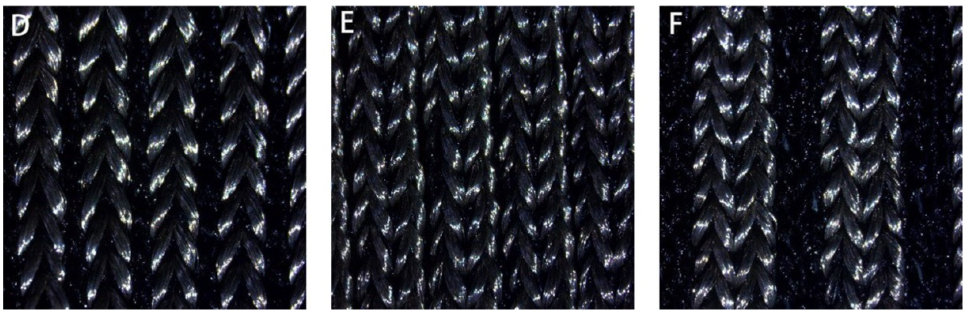

Figure 7. Zeiss observation photo of the conductive plating part of the knitted seamless underwear of the 70D silver-plated conductive yarn (D is the 1 + 1 fake rib stitch, E is the 2 + 1 fake rib stitch, the F is 2 + 2 fake rib stitch).

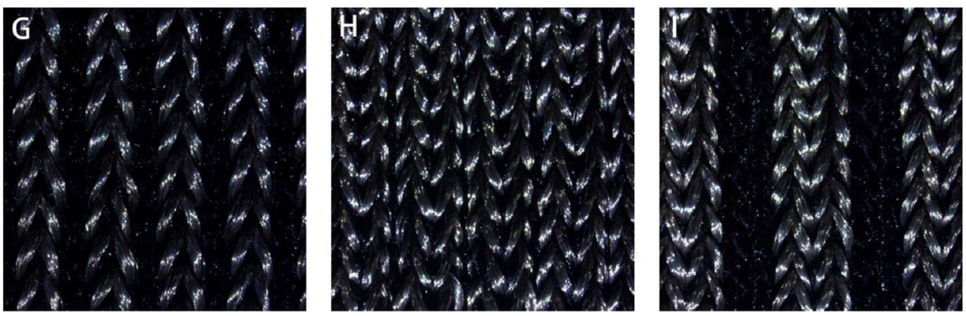

Figure 8. Zeiss observation photo of the conductive plating part of the knitted seamless underwear of the 100D silver-plated conductive yarn (G is the 1 + 1 fake rib stitch, H is the 2 + 1 fake rib stitch, I is the 2 + 2 fake rib stitch).

deformation rate of the tenth test decreases slightly compared with the longitudinal plastic deformation rate of the first test. This is because of differences in the coil structure of the weft-knitted fabric. Then, due to the fatigue of the yarn and the fabric after repeated stretching, the properties of the yarn and the fabric are lost, and the plastic deformation of fabric samples is accumulated. Finally, the weft-knitted fabric is formed by yarn weaving each coil horizontally in sequence, which means that when plastic deformation of yarn accumulates, it will greatly affect the transverse plastic deformation of the fabric.

All of the above-mentioned results show that the fabric has a certain dimensional stability. However, it is found that although the stress relaxation rate of the first test is low, as the number of tests accumulates to the tenth time, the stress relaxation rate increases significantly, indicating that although the fabric has a certain dimensional stability, with the increase of wear and use, certain deformation will also occur.

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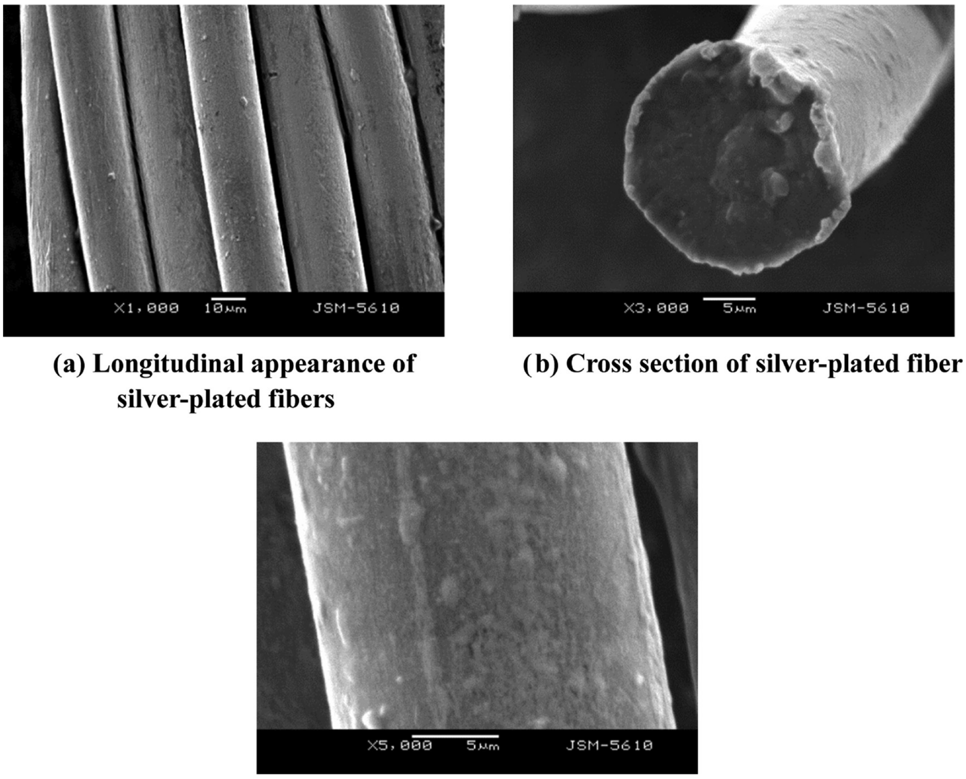

(a) Longitudinal appearance of silver-plated fibers

(b) Cross section of silver-plated fiber

(c) Surface details of silver-plated fiber

Figure 9. SEM photo of the silver-coated fiber.

3.1.2. Air Permeability. Samples with an area of 20 cm^2 were cut at different parts of the fabric, the pressure drop on both sides of the sample was set to 100 Pa, and the nozzles were automatically replaced. Overall, 10 tests were performed in each area to get average results. The existing standard FZ/T 73022-2019 requires the air permeability to be implemented by GB/T 5453, that is, the air permeability is greater than 180 mm/s. It is important to be aware that the plating area is too small to test the air permeability alone and the test area is 20 cm^2. So the plated area is tested together with the plain stitch area, and the plated area is placed in the center of the test orifice plate.

Figure 5 suggests the air permeability of the fabric conductive plating area. As we can see, the air permeability of the plain area without plating is the highest (243.31 mm/s) and higher than that under the current standard. The air permeability changes sharply when the plain stitch area becomes the plated knit area. Thankfully, though the air permeability is lower than the plain stitch area, most of it can meet the requirement of 180 mm/s. Although four samples were not able to reach the requirements, they can also reach 178−179 mm/s. From this, yarn and fabric's structures have an influence on the air permeability of the fabric, but the influence is slight. Therefore, the knitted seamless underwear can satisfy the wearing comfort of the wearer.

3.2. Conductive Fabric Morphology. The plated parts of the three kinds of conductive plated fabrics were observed by a Zeiss microscope (Figures 6−8). By comprehensively observing the plating structure of the silver-plated conductive yarn, it can be found that the patterns of 70D and 100D are displayed. There is a clear outline between the two wales, and the arrangement of positive and negative loops can be seen in each wale. Since the ground yarn is 75D nylon, the 70D and 100D silver-plated conductive yarns can cover the area of the jersey stitch well.

Compared with the silver-plated conductive yarn, it can be observed that the carbon black conductive yarn can not cover the area of the jersey stitch well because the size of the carbon black conductive yarn is only 40D. At the same time, the visual effect of the 2 + 1 fake rib stitch pattern of the carbon black conductive yarn is messy (Figure 6B), which contributes to the wales not being distinguished. The 1 + 1 fake rib stitch and the 2 + 2 fake rib stitch are similar to the silver-plated conductive yarn, which can clearly distinguish the contours between the wales and see the arrangement of the positive and negative stitches.

Since the carbon black conductive yarn and the ground yarn have easily distinguishable colors, we analyzed with the reverse side of the carbon black conductive plating fabric. Figure 6a shows that the structure of the 1 + 1 fake rib stitch can observe the needle loops formed by the conductive yarn, and there are obvious outline boundaries between different wales. However, when the plating structure becomes 2 + 1 and 2 + 2, the needle loops can not be observed (Figure 6b,c).

3.3. Conductivity. *3.3.1. Conductivity of the Yarn.* We observe the longitudinal morphology and the cross section of the conductive yarn by scanning electron microscopy (SEM), which is useful for analyzing the influence that is caused by the difference in the morphology on the conductivity of fabrics.

It is obvious that silver-plated fibers' longitudinal appearance is rough instead of smooth, which means that there are some bulges owing to inhomogeneous distribution of the silver coating (Figure 9a,c). Meanwhile, Figure 9b presents the skin-core structure of the silver-plated fiber.

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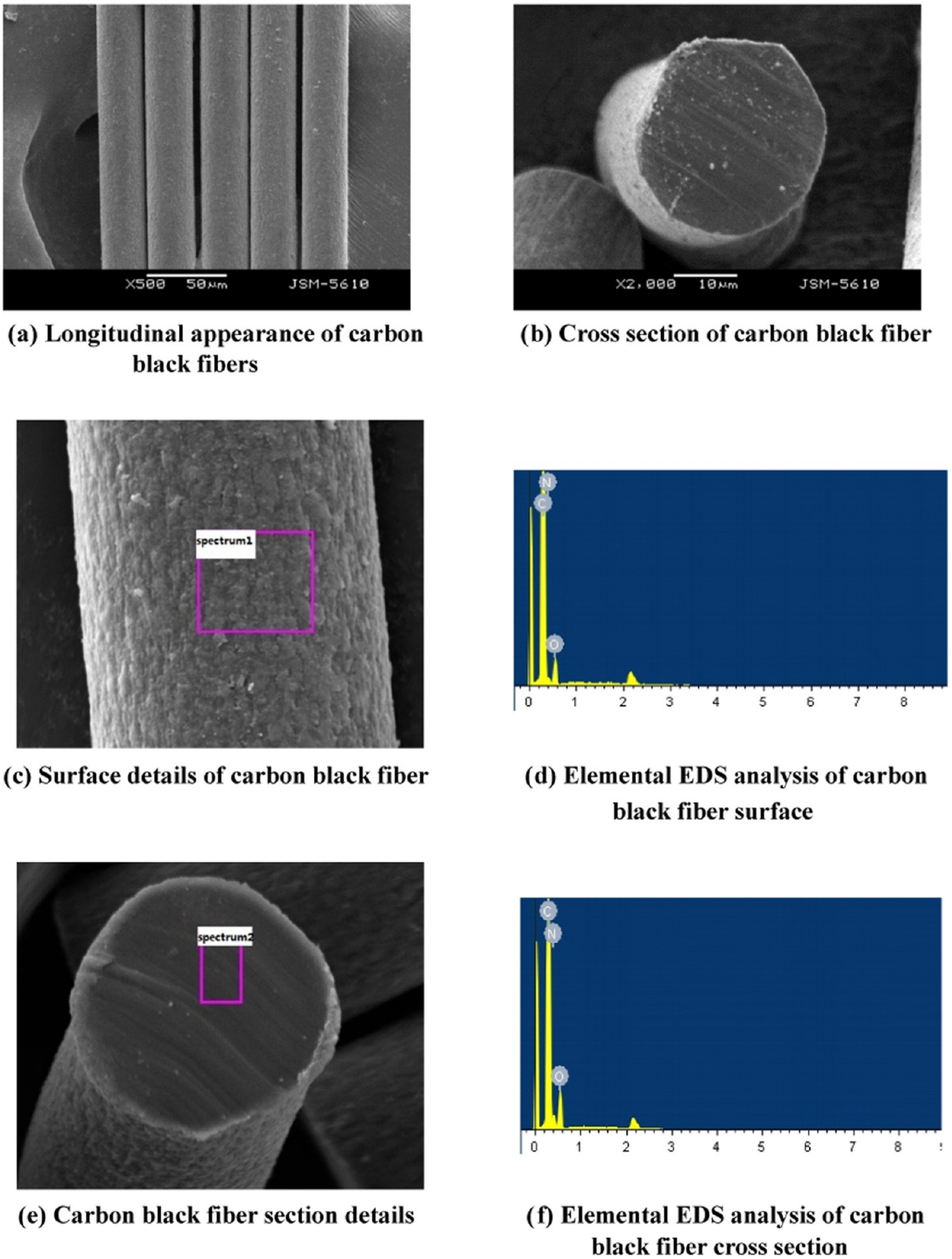

Figure 10. SEM photo and elemental EDS analysis of the silver-coated fiber.

It is not difficult to find that the longitudinal appearance of the carbon black fiber is rougher than the sliver-plated fiber, and there are many grooves (Figure 10a,c). The cross section of the carbon black fiber is round. To analyze the distribution of the carbon nanopowder, elemental energy-dispersive X-ray spectroscopy (EDS) analysis was conducted. The results suggest that the mass proportion of element C on the fiber surface is 74.65%, which is higher than that inside the fiber (64.31%). Meanwhile, the main elements of nylon are C, N, and O. All of the above-mentioned findings indicate that element C is attached to the fiber surface and it is the conductive component of conductive yarns.

3.3.2. Conductivity of Fabrics. Conductivity is a necessary performance for flexible wearable sensors, and the electric resistance can most intuitively and accurately display the conductivity of fabrics. The resistance of the fabric is related to the numerical value and stability. In this experiment, the resistance value of the conductive fabric is measured first. The

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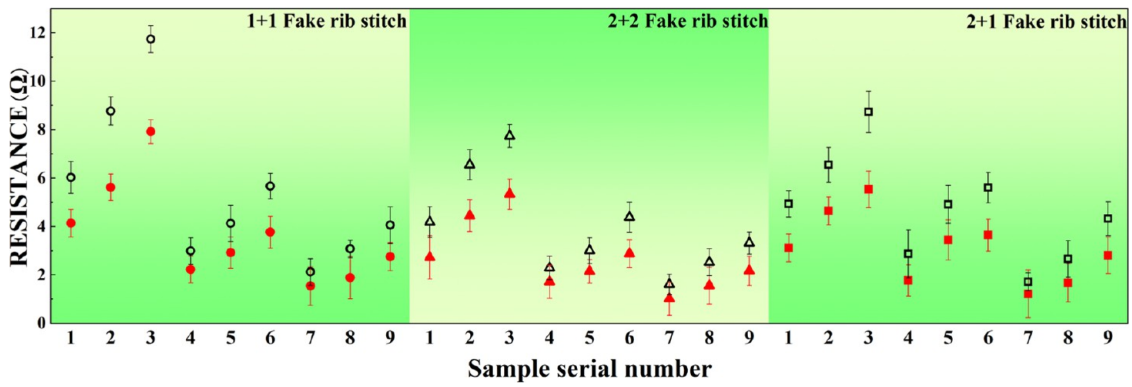

Figure 11. 70D silver-plated conductive yarn's plating fabric resistance (the open figure is the resistance of the stretched fabric and the red solid figure is the resistance in the natural state).

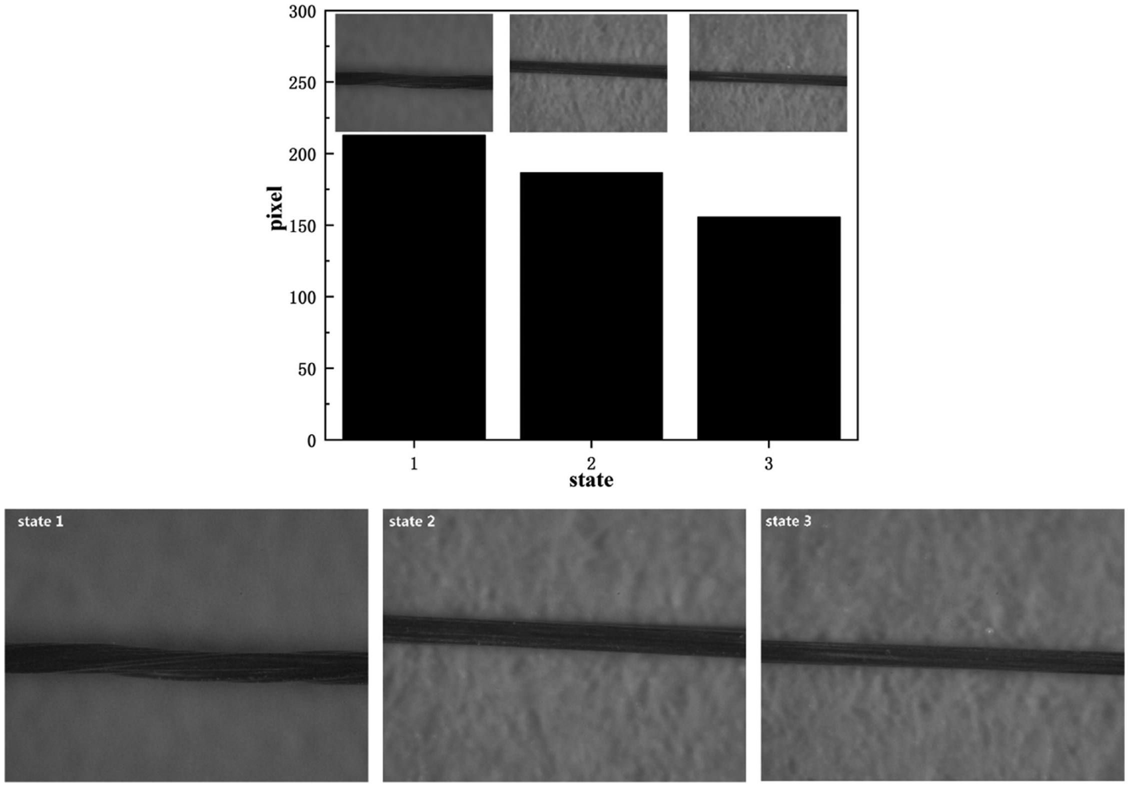

Figure 12. 70D silver-plated conductive yarn's change in the length in different states (state 1 is the natural state; state 2 is the stretched state; state 3 is also a stretched state, but the external stretching force is higher than that of state 2).

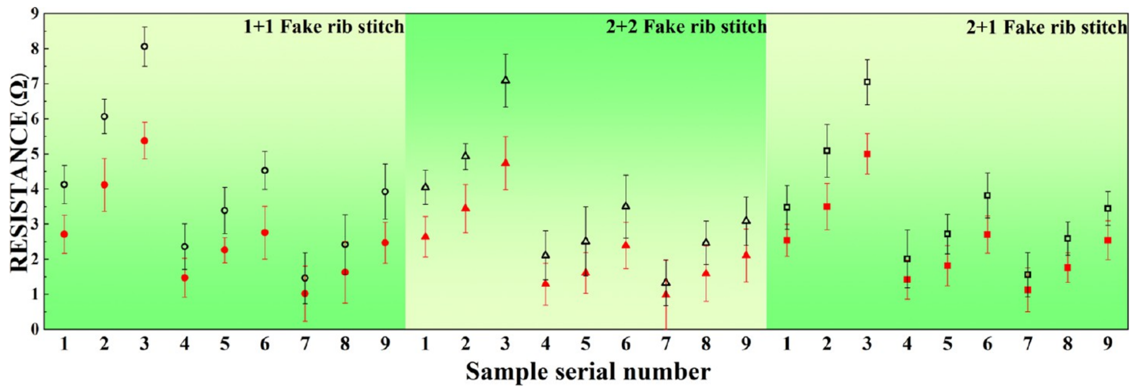

Figure 13. 100D silver-plated conductive yarn's plating fabric resistance (the open figure is the resistance of the stretched fabric and the red solid figure is the resistance in the natural state).

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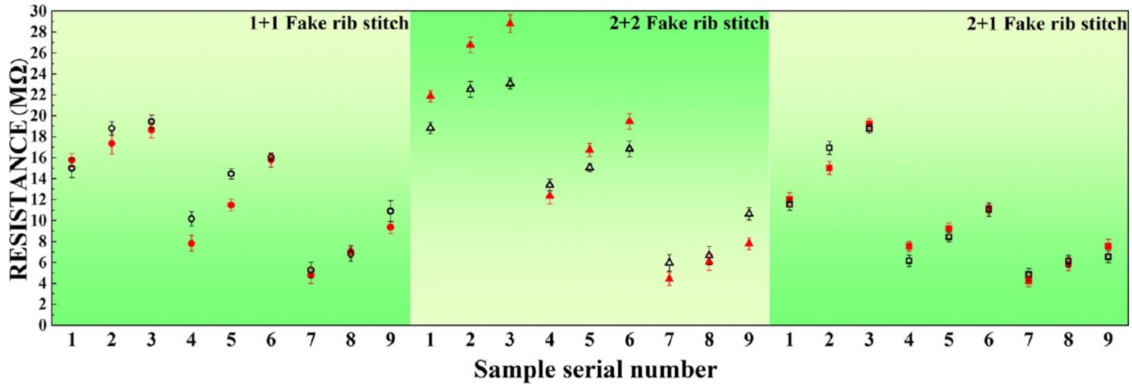

Figure 14. 40D carbon black conductive yarn's plating fabric resistance (the open figure is the resistance of the stretched fabric and the red solid figure is the resistance in the natural state).

Table 3. Sample Number

number	course's number	Wale's number	total number of loops/pcs	area of fabric/cm^2 A	B	C
1	10	40	400	1.1	0.86	0.68
2	10	60	600	1.67	1.14	1.04
3	10	80	800	2.21	1.56	1.53
4	20	40	800	2.16	1.74	1.49
5	20	60	1200	3.24	2.64	2.13
6	20	80	1600	4.46	3.36	2.97
7	30	40	1200	3.31	2.75	2.34
8	30	60	1800	5.11	4.08	3.51
9	30	80	2400	6.86	5.52	4.62

specific method is as follows: reserved conductive yarns of a 10−20 stitch length in knitting fabrics are bundled and twisted, and then wrapped with a conductive copper foil to ensure that no yarn is missed. A circuit loop is formed with a DM3068 $6^{1/2}$ digital multimeter and a conductive fabric placed on an insulating plate for resistance measurement. In this way, the fabric and the digital multimeter are in series, and the copper foil is in parallel.

When the garment is worn on the body, each part of the garment will have varying degrees of deformation due to body movement and body curves. Therefore, to test closer to the actual application scenario, the resistance of the fabric stretched by the external force is measured. The specific method is as follows: when the garment is worn on the medium mannequin, the part with an elongation of 130% or so is taken to conduct the same test of measuring the resistance in the natural state. To ensure the validity of the data, the resistance test under the two states shall record the data when the variation range of the resistance indication is less than 5%. Each sample is tested 50 times, and the average value is taken. The wire of the digital multimeter is small but can not show negligible resistance, and the value of resistance is 0.1 Ω. Similarly, the copper foil's resistance also should be taken into consideration. To get the value of the copper foil, we test it by a digital multimeter alone after testing the resistance of the fabric, and the resistance of the copper foil is 0.16 Ω. In this way, the minus reading of the digital multimeter is not the real resistance of the fabric. The real value of the fabric should be calculated according to the series−parallel relationship between the fabric and the two states.

Figure 11 shows the resistance of the plating fabric with a 70D silver-plated conductive yarn. It can be observed that under the same fabric number, the resistance of the fabric in the natural state is slightly higher than that of the other two fabrics when the plating stitch is a 1 + 1 fake rib stitch. The juxtaposed wales formed by conductive yarns constitute a parallel resistance, which can effectively reduce the resistance in the loop to a certain extent, explaining the phenomenon. The resistance values of the 2 + 2 fake rib stitch and the 2 + 1 fake rib stitch in the natural state are similar, which is because the two fabrics have the same number of wales of the conductive yarn. Therefore, the conductive yarn knitted in the clothing is the same, which means that the length is the same. From the perspective of Figure 11, the fabric resistance in the stretched state is increased to varying degrees compared with the resistance in the natural state. The possible reason for this phenomenon is that when the fabric is stretched, the yarns in the fabric begin to slip between fibers. The yarn will be slightly thinner than the original yarn. According to the law of resistance $R = \rho\frac{L}{S}$ (L represents the length of resistance, S represents the cross-sectional area of resistance, ρ represents the resistivity of the resistance material), it can be known that when the value of L becomes longer and the value of S becomes smaller, the resistance will increase. Because of stretching, the length of the yarn increases compared to the original yarn length, and the thickness decreases. The above results led to an increase in electrical resistance. The above reasons can be confirmed by Figure 12; we test the diameters that are presented by the pixel width of the section in different states by observing Zeiss photos. It is easily seen that the diameter becomes thinner with increasing tensile force. Surprisingly, we can also find that the loose fibers in the yarn become tighter under tension.

It can be found that the pattern has little effect on the fabric resistance when the fabric number is the same, and the resistance of the three fake rib stitches is alike (Figure 13). In the tensile state, the resistance value of the fabric will increase to a certain extent compared to the natural state, just like the resistance of the plated fabric with a 70D silver-plated conductive yarn. This can also be explained by the law of resistance. Comprehensive observation of Figure 8 shows that although the plating stitch is different, as long as the serial number of the fabric is the same, the difference between the resistance value of the tensile state and the resistance value of the natural state is similar.

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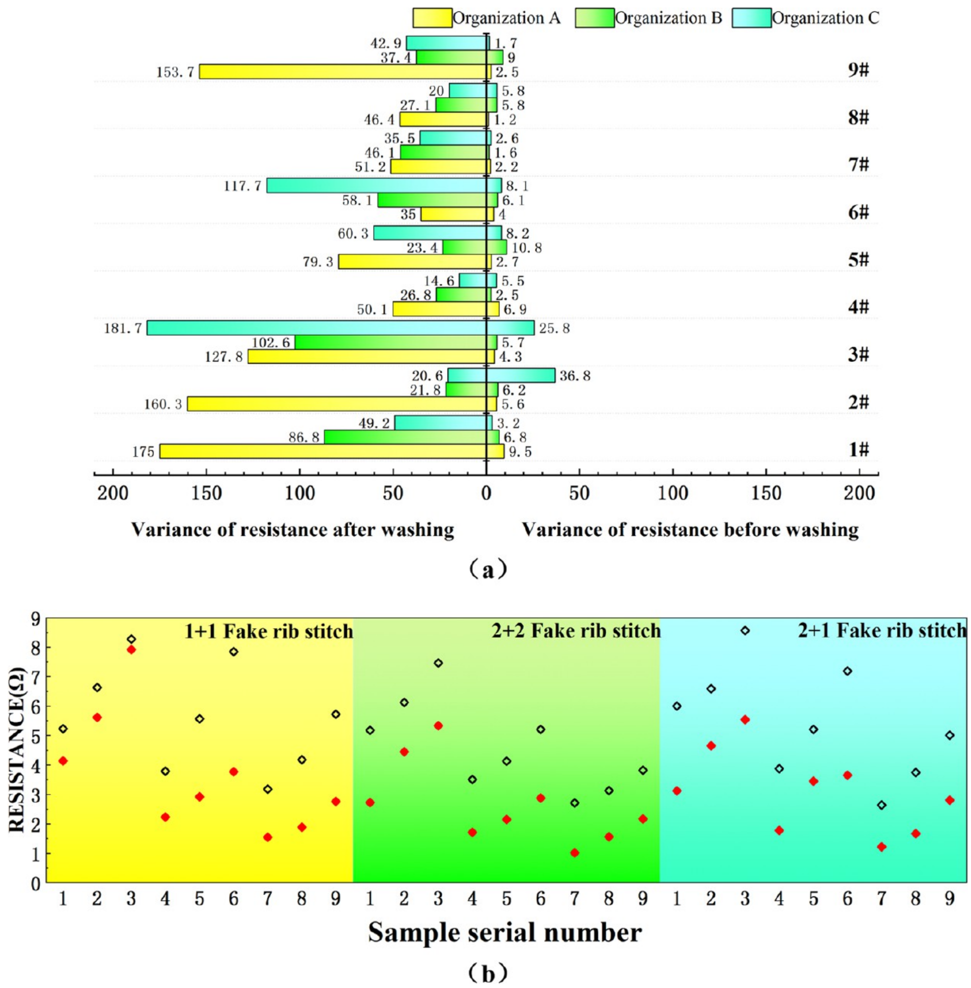

Figure 15. Variance in the resistance value (a) and conductivity (b) of the 70D silver-plated conductive yarn fabric before and after washing (the open figure is the resistance after washing and the red solid figure is the resistance before washing).

On observing Figures 11 and 13, it can be found that under the conditions of the same plating stitch and the same serial number, the resistance value of the plating fabric with the 100D silver-plated conductive yarn is smaller than that of the 70D silver-plated conductive yarn to varying degrees. Because Denier[19] is the mass grams of 9000 m long fibers at given moisture regain, the 100D yarn is thicker than the 70D yarn when the raw materials are the same, and according to Ohm's law, the larger the resistance cross-sectional area S, the smaller the resistance value R. In this way, it will illustrate the result.

The effect of the plating stitch on the fabric's electrical conductivity is obvious (Figure 14). In the case of the same serial number, the resistance value of the 2 + 2 false rib fabric is the largest, followed by the 1 + 1 fake rib stitch, and the resistance value of the 2 + 1 fake rib stitch is the smallest. Combining Figures 11, 13, and 14, it can be found that the resistance value of the fabric is closely related to the types of conductive yarns, the specifications of the conductive yarns, and the plating stitch. The resistance value regularity of the carbon black conductive yarn under tension is different from that of the silver-plated conductive yarn. The carbon black conductive yarn plating fabric of the 1 + 1 fake rib stitch is the only one in that the resistance increases slightly after stretching. The resistance value of the 2 + 2 fake rib stitch and the 2 + 1 fake rib stitch shows a significant decrease in different degrees after stretching. This is because the carbon black conductive yarn has a large resistance, which is not twisted during knitting, so the fiber paths inside the yarn are randomly distributed and the fiber orientation is low. In the stretched state, the fibers in the yarn are stretched and oriented along the axial direction of the yarn due to the external force, and the originally loose and disorderly distributed fibers become dense and straight fibers. As shown in Figure 12, the loose fibers in the yarn become tighter under tension. However, while the phenomenon occurs in all stretches, the conductivity of the fabric knitted by the silver-plated yarn is lower than that in the natural state and the conductivity of the fabric knitted with the carbon black yarn is higher than that in the natural state. There is a silver coating on the surface of the silver-plated yarn and it will be broken when stretching. On the contrary, carbon black yarn's conductivity is owing to the carbon nanopowder being uniformly dispersed on the fiber surface, and the external force stretching will not break the conductive material layer on its surface and cause discontinuity. All of the above-mentioned findings lead to conductivity becoming better or remaining stable. Nevertheless, some of the samples' conductivity is lower than in the natural state. This is because there is no change in the continuity of the conductive components on the surface, but the distance between the conductive components changes in the stretched state, so its conductivity changes unstably.

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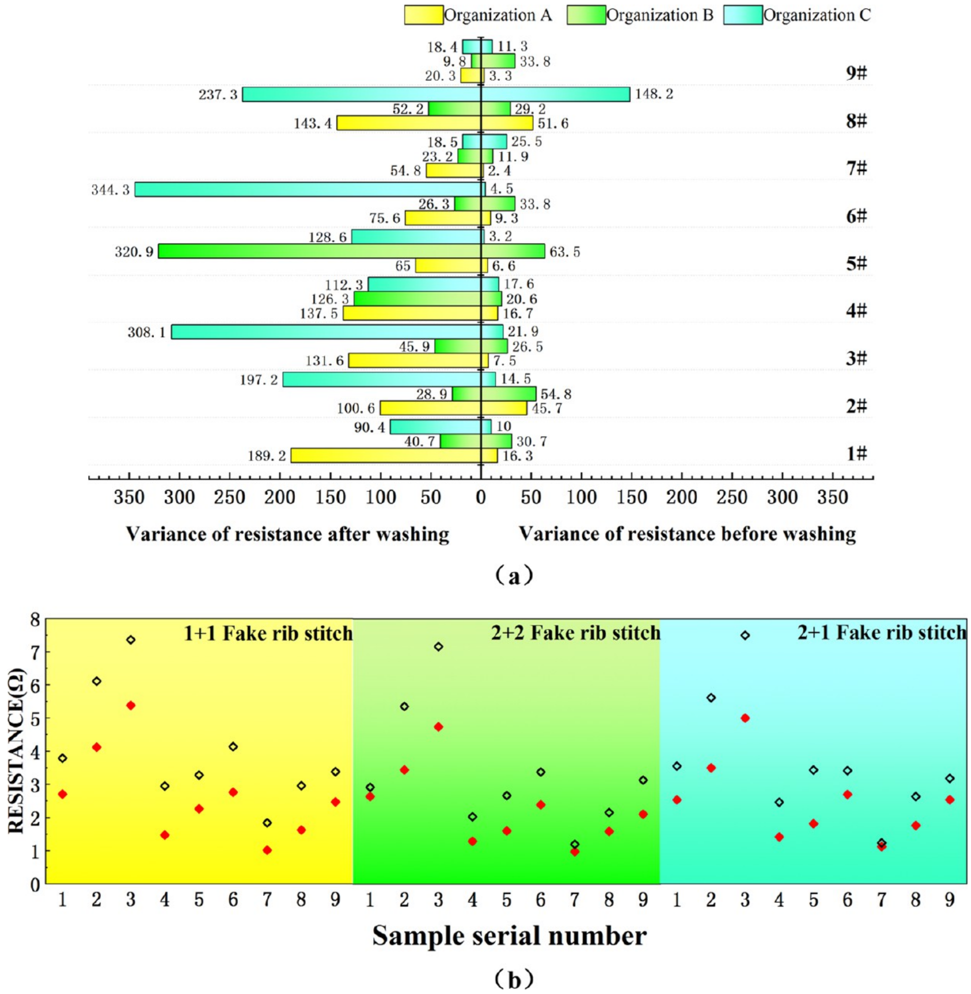

Figure 16. Variance of the resistance value (a) and conductivity (b) of the 100D silver-plated conductive yarn fabric before and after washing (the open figure is the resistance after washing and the red solid figure is the resistance before washing).

Comprehensive observation of Figures 11, 13, and 14 shows that the number of wales and courses also have a regular influence on the electrical conductivity of the fabric. Fabric sample nos. 1−3 have the same number of courses. The number of wales is 40, 60, and 80, respectively. The three groups of experimental results all show that the resistance values of nos. 1−3 samples show an increasing trend. Similarly, sample nos. 4−6 and 7−9 have the same regularity, which can be equivalent to increasing the length of the resistance with the number of wales increasing. According to the law of resistance, when the resistance length L increases, the resistance value R also increases. According to Table 3, it can be seen that the three groups of samples 1, 4, and 7; 2, 5, and 8; and 3, 6, and 9, respectively, have the same number of wales of 40, 60, and 80, and the samples with the same number of wales also increase the number of courses from 10 to 20, and 30 with the increase in the serial number. The three sets of experimental results suggest that with the increase in the number of courses, the resistance value of the fabric gradually decreases. It can be interpreted by the law of resistance that the increase in the cross-sectional area of the resistance element will result in a decline in the value of resistance. Coincidentally, the increase in the number of courses corresponds to an increase in the cross-sectional area of the resistor.

3.4. Conductivity Stability of Fabrics before and after Washing. Washing is a cleaning process that must be faced during the use of the garment, and it will affect the relevant properties of the fabric to a certain extent. As a fabric sensor, the effect of washing on the electrical conductivity of the fabric must be studied. Therefore, the fabric is washed in a washing machine with several laundry items. The accompanying laundry is a pure polyester textured filament knitted fabric, and the specification is four pieces of the fabric with a mass per unit area of 310($\pm$ 20) g/m^2 sewed into a square whose specification is 20($\pm$4) cm × 20($\pm$4) cm; the washing mode is a chemical fiber mode, the washing temperature is 20 °C, and the time of washing is 30 cycles (each cycle is 10 min of clean water washing, 1 min of dehydration). After washing, the fabric is placed in an oven and dried at 65 °C for 30 min and cooled for 5 min. Finally, the resistance value is measured and the variance in the resistance value is calculated by the same method as mentioned above. The variance value reflects the resistance stability of the fabric to a certain extent.

It can be seen from the experimental results that the variance in the resistance of the 70D silver-plated conductive yarn fabrics before washing is relatively small (Figure 15a); most of the variances are below 10, and all of the samples' variances in resistance are in the range of 20−30, except no. 2 and no. 3 of the 2 + 1 fake rib stitch (group C). On the whole, the variance

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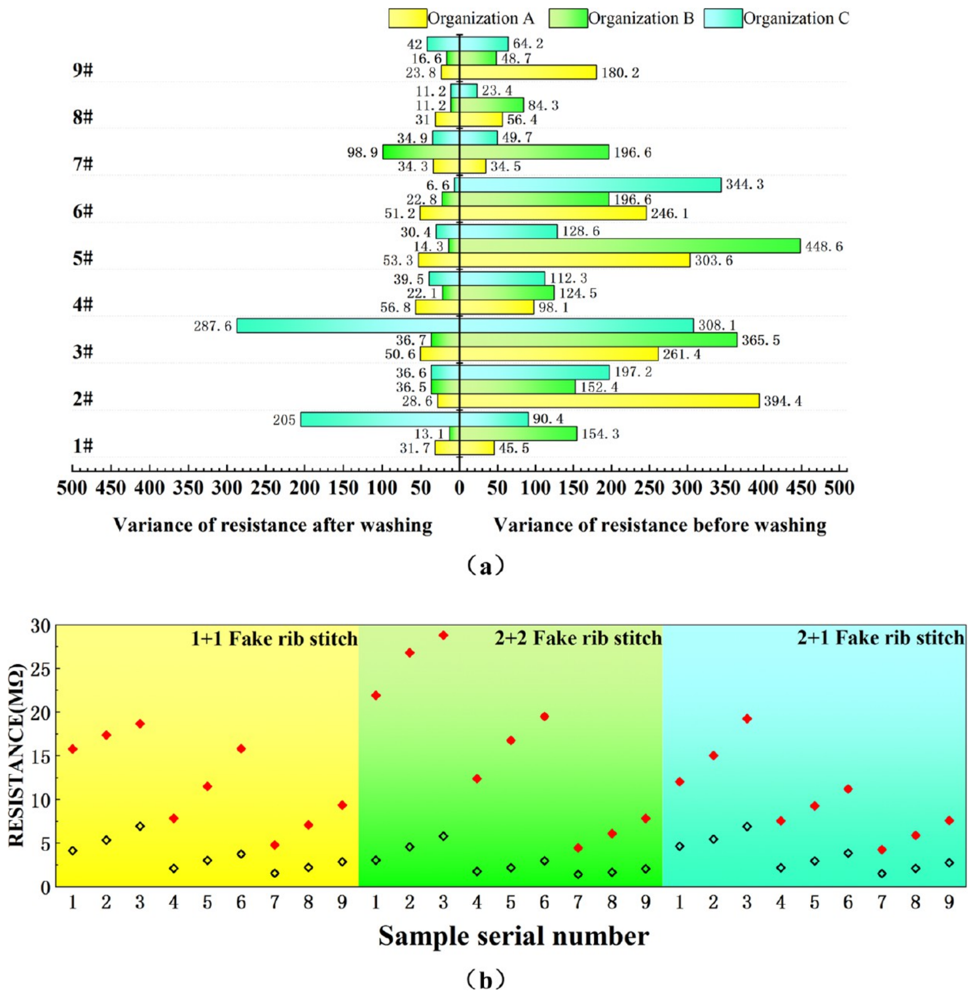

Figure 17. Variance of the resistance value (a) and conductivity (b) of the carbon black conductive yarn fabric before and after washing (the open figure is the resistance after washing and the red solid figure is the resistance before washing).

in the resistance value of the fabric with the 1 + 1 fake rib stitch before washing is minimum, which means the electrical conductivity of the fabric is the most stable. On the contrary, the conductive stability of the fabric with the 2 + 1 fake rib stitch is the worst. Meanwhile, the resistance of the fabric before the washing test is lower than that after washing (Figure 15b). In other words, washing influences the conductivity of the fabric. As for the fabric knitted with the silver-plated conductive yarn, washing is harmful to its conductivity. The possible reason is divorce and oxidation of the silver coating on the yarn surface during washing.

In general, the electrical conductivity of the three kinds of plated fabrics before washing is similar.

After washing, the variance in the resistance value of the 70D silver-plated conductive yarn fabric increases significantly, which can reach tens or even hundreds. It is not difficult to find that the plating stitch with the best conductivity stability before washing is the 1 + 1 false rib stitch. However, it becomes the worst and the conductive stability of the fabric with the 2 + 2 fake rib stitch becomes the best after washing. Because the difference between the conductive stability of the fabric before washing is small, it can be considered that the conductive stability of the 2 + 2 fake rib stitch fabric is the best.

As shown in Figure 16, although the variance in the resistance value of the 100D silver-plated conductive yarn fabric before washing is also small, it is larger than that of the 70D silver-plated conductive yarn fabric before washing. In other words, the conductive stability of the fabric knitted from the 100D silver-plated conductive yarn before washing is worse than that of the 70D silver-plated conductive yarn fabric before washing, which indicates that the size of the conductive yarn has an influence on the conductive stability of the fabric to a certain extent. The best conductive stability after washing is still the 2 + 2 fake rib stitch fabric. Similarly, the conductivity of the fabric knitted with the 70D silver-plated conductive yarn before washing is also higher than that after washing too (Figure 16b).

The conductive stability of the carbon black conductive fabric is significantly different from the first two fabrics (Figure 17). It can be found that the carbon black yarn fabric has excellent conductivity and conductive stability after washing. Among them, the conductive stability of the 2 + 2 fake rib stitch fabric is improved, and the conductive stability is the best after washing. Owing to the single fiber in the carbon black yarn being thinner and the yarn twist being low, the yarn making up the fabric was subjected to an external force, such as repeated stretching and squeezing during washing. Consequently, the fibers are easy to curl during the washing process. At the same time, the entanglement between fibers is more tightened, which can increase the contact area between fibers. In addition, washing can properly reduce the hairiness of the yarn to a certain extent. In other words, part of the

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hairiness will stick to the surface of the yarn. In this way, the conductivity of yarn can be promoted. Last but not least, carbon black conductive yarn's conductive component is carbon nanopowder distributed on the surface uniformly, which is rarely affected by the washing or stretching process. Consequently, the electrical conductivity is improved.

Combined with Table 3, the influence of the number of courses and wales on the conductive stability of the fabric before and after washing is analyzed. It can be seen from the results that when the number of courses in the fabric is the same, the number of wales of 40 is smaller than the number of wales of 60 and 80, indicating that with the increase in the number of wales, the electrical conductivity of the fabric will decline. Moreover, the conductive stability of the carbon black conductive fabric and the 100D silver-plated conductive fabric is the best when the course is 30, and in this case, the number of wales has little effect on the conductivity stability. In Figure 17, the larger variance of resistance values of sample no. 8 of organization C may be due to the abrasion of the yarn. This leads to distortion of experimental data.

4. CONCLUSIONS

Through research, it is found that the fabric has certain shape retention. Although the shape retention is reduced after repeated stretching, it can still maintain a certain performance. The fabric also has good air permeability in every part. It can well meet the air permeability standards.

Regarding the electrical conductivity of the fabric, the electrical conductivity of the fabric formed by the carbon black conductive yarn is improved after stretching, and the conductive stability is also significantly improved after washing. The conductive fabric formed by the silver-plated conductive yarn is just the opposite of the fabric formed by the carbon black conductive yarn. After the fabric formed by the silver-plated conductive yarn is stretched, the resistance is higher than that in the natural state. That is, the conductivity is decreased, and after washing, the conductivity stability of the fabric is not as good as before washing. Therefore, from the perspective of long-term use, the carbon black conductive yarn is more suitable for knitted fabric sensors. The number of courses and wales of the fabric also has a certain influence on the electrical conductivity of the fabric. As the number of wales increases, the electrical conductivity of the fabric gradually decreases, and with the increase in the number of courses, the electrical conductivity of the fabric gradually increases. At the same time, for the samples in the experiment, the number of wales has little effect on the electrical conductivity stability of the fabric, and when the number of courses is 30, the number of courses has the least effect on the electrical conductivity of the fabric.

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