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ORIGINAL RESEARCH ARTICLE

Research progress of knitted sensors in the field of sports and fitness apparel

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ABSTRACT

Knitted sensor has the advantages of lightness, conformity, good strain tensile recovery and formability, which provides a possibility for flexible and non-inductive motion signal monitoring and smart wearable sports health clothing preparation. This paper reviews the preparation methods of knitted sensors, analyzes the influence of yarn types, fabric microstructure and tensile sensing direction on its sensing performance, and compares the advantages and disadvantages of knitted sensors in the fields of life and health, human movement and other fields. It is pointed out that the type, structure and weaving method of the conductive yarn are important factors affecting the performance and wearing comfort of knitted sensors, and the electrical characteristics of the two-dimensional extension and three-dimensional deformation in the strain stretching process of knitted sensors determine the effective strain sensing range. This paper outlines the development opportunities and challenges faced by knitted sensors in the field of sports and health clothing.

Keywords: knitting sensor; knitting technology; conductive yarn; sensitivity; exercise health

1. Introduction

With the development of science and technology and the enhancement of national health awareness[1,2], people's demand for wearable products that can achieve daily sensing and real-time monitoring of human motion data has become increasingly urgent, which has led to the birth of smart bracelets, sports wristbands and other smart wearable devices[3]. At present, these smart wearable devices mostly use gravity sensors, multi-axis acceleration sensors and image sensing technologies to collect human motion information. Although they can better reflect the state of human motion in daily sensing, they still have high hardness, poor elasticity and other technical problems such as poor wearing comfort and lack of motion detail signals[4,5]. Therefore, the development of highly integrated, comfortable and wearable flexible strain sensors to realize human body signal sensing or motion recognition is an important problem that needs to be solved urgently. Knitted strain sensors are made of conductive yarns through different processes to make conductive knitted fabrics or conductive treatment on knitted fabrics to form smart wearable devices with sensing properties. The knitted fabric matrix is light and soft, which can effectively improve the wearing comfort of traditional smart textiles, where the large strain and good stretch recov-

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ery of the knitted structure meet the requirements of smart sports health sensing monitoring[6,7]. This paper mainly summarizes the preparation method of knitted sensors, comprehensively compares the influence of knitted sensor material types, organizational structure, and tensile direction on its sensing performance, and analyzes the latest application of knitted sensors in the field of sports health. On this basis, its future development is reviewed in order to provide a reference for the research of knitted sensors in the field of sports and health clothing.

2. Preparation of knitted sensor

Knitted sensors are mainly divided into three categories: Resistive strain sensors, capacitive strain sensors and piezoelectric strain sensors, among which resistive strain sensors are the most common in the field of sports and health clothing. Resistive strain sensors mainly use the change of resistance value to characterize the physiological signals of the human body to achieve sensing. At present, there are two commonly used preparation methods: 1) Use conductive yarn to knit directly on knitting equipment; 2) Treat the surface of knitted fabrics[8].

2.1. Fabrication of sensors by knitting technology

Some conductive yarns can be directly knitted by knitting sensors on the knitting equipment. The knitting technology used mainly includes two categories: Warp knitting technology and weft knitting technology. Knitted sensors prepared by different knitting technologies have certain differences in sensing performance, wearing comfort and product appearance.

Warp knitting technology

Warp knitting technology refers to a knitting method in which one or several groups of parallel yarns are inserted into a row of knitting needles along the longitudinal direction and synchronously formed into loops. With warp knitting technology, not only that it can be used to prepare tensile sensors, but it can also be used for the preparation of pressure sensors. Since the coils of the knitted sensor prepared by the warp knitting technology are arranged along the warp direction of the knitted fabric, the product has a flat appearance, a tight weave structure with no floating thread on the back of the intarsia area, resulting in better stability and anti-separation of the fabric as compared to the weft knitted fabric. The warp knitted spacer fabric has advantages in the preparation of pressure sensors due to its good retraction. Zhu[9] studied the influence of fabric structural parameters on the compressive properties of warp knitted spacer fabrics, and the results showed that spacer fabrics with high density, large thickness and single fibre spacer have better bending resistance, which can be used to prepare knitted pressure strain sensors with good recovery. In terms of local positioning weaving, the warp knitting machine is more suitable for whole conductive fabric or strip conductive fabric. However, it offers no advantages in the preparation of small-area positioning sensors.

Weft knitting technology

Weft knitting technology mainly includes flat knitting technology and circular knitting technology.

Flat knitting technology refers to a knitting method in which one or several yarns are drawn from the yarn bobbin and placed on the corresponding knitting needles of the flat knitting machine along the weft direction to form loops. In flat knitting, the technology includes double needle bed flat knitting and four needle bed flat knitting machines. Among the two, the double needle bed flat knitting machine technology is widely used and has strong versatility. However, it has high requirements on raw materials where the yarn raw materials that match the needle type must be chosen, while the four needles bed flat knitting machine technology can be used for the preparation of one-piece molded clothing, which is more suitable for the weaving of complex fabrics. The precise positioning of the sensor can be achieved by using the intarsia function of the computerized flat knitting machine[10]. The flat knitting machine is convenient for the weaving of small knitted products. Through the design of the supporting computer software, socks, gloves, knee pads and other products can be automatically generated, and the size and product shape can be changed according to needs. **Figure 1**[11] is a fully formed sports glove that can monitor finger movement knitted on a double needle bed Shima Seiki computerized flat knitting machine. Knitted fabrics prepared by computerized flat knitting machines are inferior to warp knitting in terms of weft looping and fabric stability, especially when weft and flat fabrics are prone to crimping. Due to the coarse needle number of the general flat knitting machine, the product structure of the flat knitting machine is relatively sparse and the feel is poor.

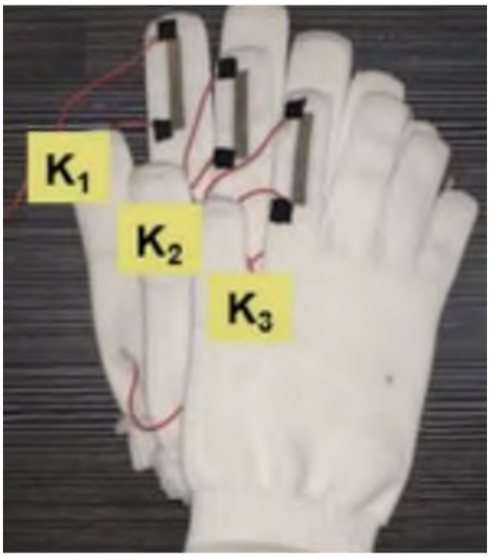

Figure 1. Fully-formed sports gloves knitted on computerized flat knitting machine using intarsia.

Circular knitting technology refers to a knitting method in which the yarns are placed on the corresponding knitting needles of the circular knitting machine in sequence along the weft direction to form loops. The circular knitting technology not only is able to achieve integral molding of knitted products, but also able to achieve the positioning and weaving of multiple sensors. Because this technology has the advantages of high rotation speed, high output, fast pattern change, good fabric quality, few processes, and strong product adaptability, it further provides advantages in the preparation of large-area knitted products and fully formed seamless sports suits. In this, weaving the whole product at one time can reduce the production process and shorten the production cycle. Thinner yarns can also be spun on a circular machine[12,13] with the obtained fabric having good stability. However, there are many floating threads on the back of the conductive area. In order to avoid mutual interference between the conductive yarns, it is generally necessary to remove the floating threads.

2.2. Surface treatment of the knitted fabric

The surface treatment of knitted fabrics is to add a certain proportion of reducing agents, dispersants and binders to conductive substances such as polypyrrole, graphene, nano-silver, etc., and treat the surface of the fabric by dipping, coating, screen printing, etc., thus forming a stable and continuous conductive network layer[14]. This processing method can improve the sensitivity of the sensor, but the overall stability of the sensor is poor. Therefore, the key to the surface treatment of knitted fabrics is to form an interface with good bonding force between the fabric and the conductive material to ensure that the conductive material has good adhesion and is not easily fallen off.

In order to improve the adhesion effect of conductive substances, Lin et al.[15] used plasma pre-treatment to increase the adhesion of polypyrrole on polyester to prevent the falling off of conductive substances and ensure the continuity and uniformity of conductive substances during stretching. Amjadi[16] covered a layer of PDMS on the surface of the nano-silver-coated fabric and prepared a stretchable sensor for finger posture monitoring.

3. Factors influencing the sensing performance of knitted sensors

The main properties of the knitted sensor include sensitivity, linearity, stability, repeatability, hysteresis, etc. The influencing factors include the type of yarn, the structure of the fabric, the direction of tensile sensing, and the interaction force between the coils.

3.1. Type of yarn

In actual production, the type of conductive yarn is a key factor affecting the performance of knitted sensors. According to the different materials, conductive yarns can be achieved in two ways: (1) Using conductive fibers to directly spin yarns; (2) Treat ordinary yarn to make it conductive. According to the actual application, it can be divided into metal conductive yarn, carbon-based conductive yarn and composite conductive yarn[17,18].

1) The difference in conductive yarn affects the sensing performance of the knitted sensor. Yarns with conductive properties such as metal and pure carbon have the characteristics of high sensitivity, but due to their high rigidity and other problems, they are prone to irreversible mechanical damage and permanent structural deformation during weaving or use, with poor stability, especially under a large strain where the rapid elastic recovery is poor, which seriously affects the stability and linearity of the sensing performance of the knitted sensor, and it is difficult to make a tensile sensor. After adding common yarns such as spandex elastic yarn and polyester yarn to the conductive yarn, not only can it increase the shape retention of the fabric, but also improve the performance of the sensor. Zhang et al.[19] used conductive yarn and ordinary yarn to weave an intarsia knitted sensor (see **Figure 2**), and the conductive yarn and ordinary yarn were connected in an intarsia manner, which improved the sensitivity and stability of the knitted sensor.

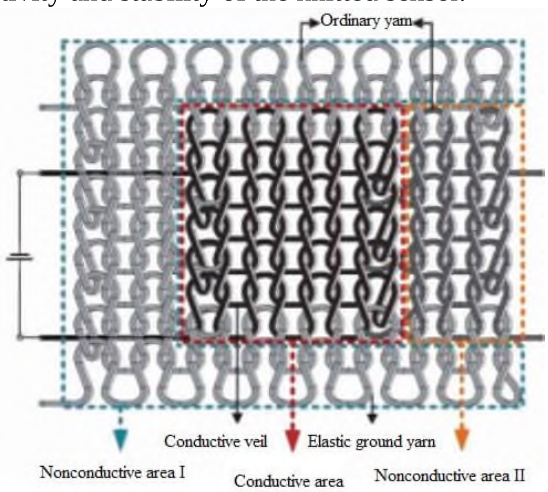

Figure 2. Intarsia stitch.

Using conductive materials such as metals to treat ordinary yarns or blending with ordinary yarns to prepare composite conductive yarns can improve the difficulties faced in knitting. However, in the weaving process, conductive coated yarns are also prone to problems such as conductive material shedding and yarn surface oxidation, which seriously affects the sensing performance. The resistance of blended yarn and the conductive core-spun yarn is relatively large, and there are also problems in sensitivity.

Many researchers have devoted themselves to the development of new conductive yarns using electrochemical methods to improve the problems of easy shedding, easy oxidation and poor sensing performance of the conductive layer on the surface of the existing conductive yarns. However, the relevant technology is not mature at present, and there are few applications in the textile field.

2) The electrical characteristics of different kinds of conductive yarns determine the effective strain range of the knitted sensor. The resistance of metal nano-silver wires is only a few to tens of ohms, which can be used for tensile strain sensors. Liu et al.[20] used 44 dtex nylon silver-coated yarns with circular knitting technology to prepare a tensile strain sensor for monitoring human arm posture. After repeated usage, it still has good sensing performance. Meanwhile, conductive yarns treated with graphene[21], polypyrrole, and conductive nanomaterials have a resistance of several thousand or even tens of thousands of ohms, with high sensitivity and can be used in piezoelectric strain sensors.

Liu et al.[22] studied the influence of parameters such as the thickness of the conductive nanofiber membrane and the material ratio on the sensitivity of the sensor. The results showed that the best sensitivity of the sensor was achieved when the mass ratio of Py monomer to nanofiber is 1:1 and the thickness of the conductive nanofiber film is 48 μm.

3.2. Structure of the fabric organization

The structural organization of the fabric has a great influence on the linearity and sensitivity of the sensor. Han et al.[23] studied the sensing performance of three kinds of weft-knitted structure sensors, and the specific results are shown in **Figure 3**. It can be seen from **Figure 3**. that under the same conditions, the weft plain needle knitted sensor has the best sensitivity and conductivity, followed by the 1 + 1 fake rib knit fabric sensor, while the 2 + 1 fake rib knit fabric sensor was the worst. The overall resistance showed a trend of first increasing and then decreasing. Therefore, the structure of the knitted stress sensor should not be too complicated, and the basic structure should be used. Han et al.[23] also studied the longitudinal electrical properties of spandex weft knitted conductive fabrics. By comparing with Zhang et al.[24], they found that the longitudinal electrical properties of spandex weft knitted conductive fabrics were similar to those of warp knitted fabrics. This shows that there is a difference in the sensing performance of warp knitted fabric and weft knitted fabric. However, both knitted fabrics shares similarity in terms of good sensitivity and linearity. Raji[25] found that the sensitivity of the rectangular sensor is higher than that of the sawtooth sensor. It can be inferred that the shape of the knitted sensor has a greater impact on its sensing performance, and the knitted sensor with a simple shape has higher sensitivity. The research results of Li, et al.[26] showed that with the increase of the number of longitudinal rows of the conductive coil, the resistance change of the sensor showed an increasing trend while with the increase of the number of rows of the conductive coil, the resistance growth trend of the sensor weakens. The resistance change of the sensor conforms to the law that the knitted fabric coils are parallel in the longitudinal direction and series in the transverse direction. Therefore, the number of horizontal and vertical coils of the coil is closely related to the sensitivity of the sensor. When the number of horizontal columns is constant, the fewer the number of vertical rows the better the sensitivity. When the number of horizontal columns is the same as the number of vertical rows, the conductivity in the vertical and horizontal directions is similar, but the sensitivity in the vertical direction is generally greater than that in the horizontal direction.

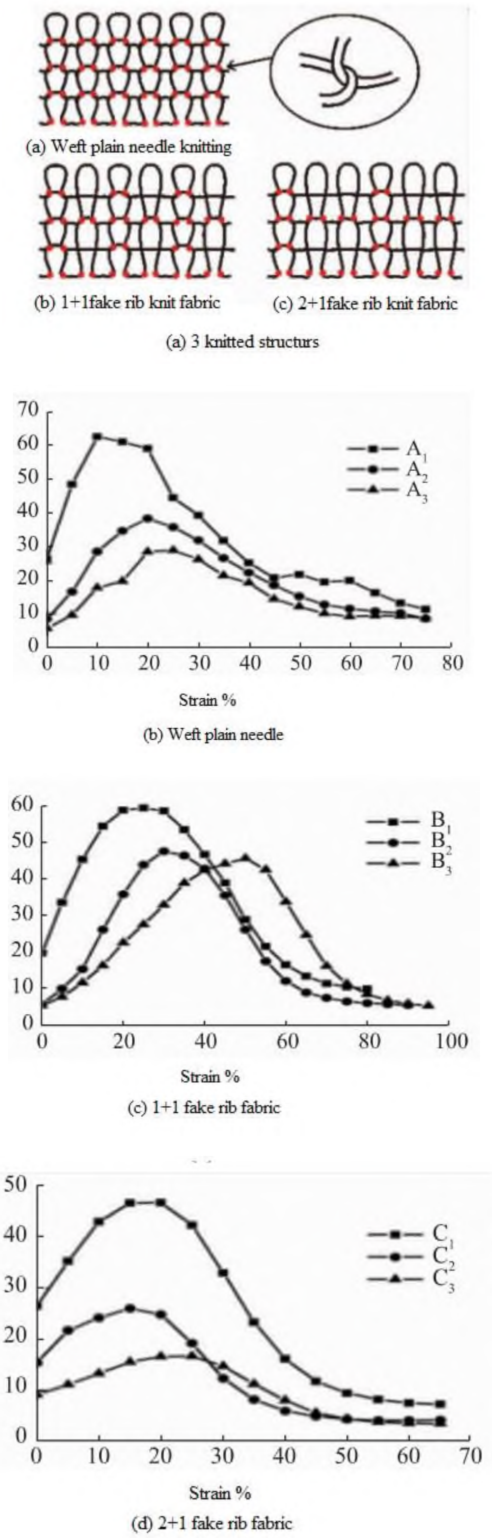

Figure 3. Distribution schematic diagrams of contact points of the three stitches.

3.3. Stretching direction of the sensors

During the actual wearing process of the sportswear, the forces incurred are mostly two-or-multi-directional tension forces from the plane, while shear and curved surface tension forces occur in the three-dimensional direction. Therefore, it is necessary to consider the sensing performance of the knitted sensor in different stretching directions.

At present, the research on the stretching direction of the sensor is mainly based on horizontal, vertical, biaxial and three-dimensional stretching which mimics the actual movement of the human body. However, there are relatively few research examples of testing electrical signal changes in multiple directions with standard experiments.

There are the following differences between horizontal and vertical stretching: (1) In terms of tensile formation, the yarn under horizontal stretching is transferred from the loop column to the loop arc where the yarn is rotated with the degree of displacement seen to be more obvious while the coiled yarn under vertical stretching moves from the loop arc to the loop column. (2) The stretching direction of the sensor is a key factor affecting the sensitivity and hysteresis of the sensor. During horizontal stretching, changes in the hysteresis of resistance between strain stretching and recovery are small while in vertical stretching, the changes in the hysteresis of resistance between strain stretching and recovery are more obvious. In most cases, the rate of change in resistance during vertical stretching is greater than that of horizontal stretching. Xie[27] studied the resistance change of the weft plain needle sensor under the condition of horizontal and vertical stretching, as shown in **Figure 4**. It can be seen from **Figure 4**. that the electrical resistance of the conductive knitted fabric in horizontal stretching shows an approximately linear growth trend with the increase of strain, while the relationship between the changes in resistance and strain increases nonlinearly in vertical stretching. (3) In terms of stretching speed, the increase of stretching speed increases the resistance of the sensor correspondingly but with a slower trend. At lower stretching speed, there is a hysteresis phenomenon that occurs in the change of resistance between strain stretching and recovery[28].

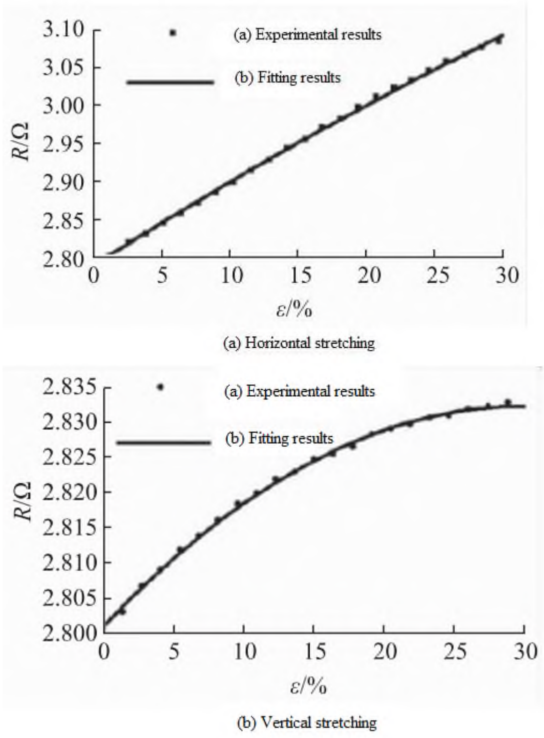

Figure 4. Relationship between resistance and strain of knitted sensor under biaxial stretching.

The three-dimensional stretching direction is closer to the actual perception of the human body when wearing the knitted sensor, and has the common characteristics of horizontal and vertical stretching.

Li et al. wrapped the fabric with small pellets to simulate the motion of the human knee joint, as shown in **Figure 5**. The sensing performance of the knitted strain sensor was evaluated using a three-dimensional curved surface. From this experiment, it was found that the strain sensing range of the three-dimensional surface was 120%, which was twice that of the two-dimensional stretching performed with the two-dimensional test method.

3.4. Interaction force between coils

The interaction force between the coils mainly affects the contact resistance of the sensor. The construction of the equivalent resistance model clarifies the sensing mechanism of the conductive fabric and is used to simplify the coil circuit, and the contact resistance directly affects the accuracy of the equivalent resistance model prediction. (1) Contact resistance is related to the contact force between coils. The interaction force between the coils, coil transfer[29] and changes in the length of the coil would result in a change in the contact resistance. Wang et al.[30] simulated the relationship between contact force and contact resistance by intertwining two silver-coated yarns with each other. From theoretical analysis and experimental research, it was known that the contact resistance decreased with the increase of the contact force. (2) In the case of a small strain, the change in contact resistance between the coils is very small, where its influence on the sensing performance of the fabric can be ignored. Conversely, in the case of a large strain, the contact resistance influences the elongation-strain linearity of the sensor. (3) The overall resistance of the sensor is small due to the close contact between the coils, where the knitted sensor is made of conductive yarn covered with ordinary yarn, and the coils are not separated from each other. If there is contact resistance, or if the exposed conductive yarn produces a small contact resistance, the overall resistance value will increase greatly.

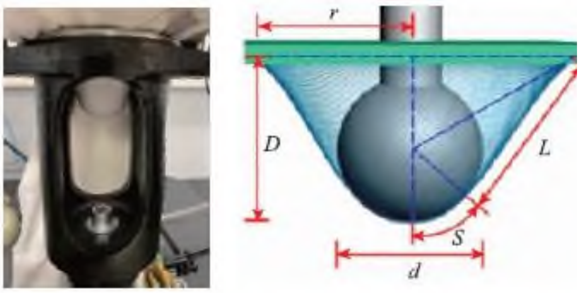

Figure 5. Three dimensional test of knitting sensor.

4. Application in the field of sports and health clothing

Knitted sensors are an important tool for collecting human motion signals. In the development of smart sports and health clothing, knitted sensors play a pivotal role. Its application scope mainly includes three aspects: daily sports protection, professional sports guidance, and sports rehabilitation guidance.

4.1. Daily sports protection

With the continuous enhancement of national health awareness, more and more people are protecting themselves through the monitoring of daily exercise. When the knitting sensor detects abnormal conditions during human movement, it will send out a warning signal to remind the athlete to rest or seek medical attention. Garcia et al[31] developed a wireless and comfortable wearable back motion monitoring system which was prepared by sewing a copper wire with a diameter of 0.14 mm into a piece of elastic fabric with a “T” shape. In addition, an inductive textile sensor was integrated into the back of the bodysuit to monitor back posture. In addition to the protection of the human body’s daily exercise, the monitoring of the human body’s physiological signals during daily exercise is a hot research topic in the field of sports health. Liu et al.[32] used graphene webbing as a substrate to be coated on elastic knitted fabrics to prepare flexible graphene sensing elastic belts. The flexible graphene sensing elastic belts have certain practicability in the collection of human body data for clothing.

4.2. Professional sports guidance

Professional exercise guidance can help athletes perform exercise assessment, improve lack of exercise, standardize exercise methods, control exercise intensity, optimize training effects and reduce physical injuries. Xie[27] used weft knitting technology to weave silver-plated nylon conductive yarns into flexible knitted fabric sensors, which were integrated into smart T-shirts and smart knee pads to monitor elbow, shoulder, abdomen and knee joints, respectively. Physiological signals are used to analyze the resistance changes under different postures, but the specific transmission method of the data collected by the knitting sensor is not clear. To this end, Li et al.[33] prepared a kind of tights that can be used to monitor the motion of the human knee joint based on a flexible sensor of silver-coated conductive yarn. The relationship between the sensors is analyzed, and a portable data module is developed for the collection and output of the sensor resistance signal. The strain resistance signal generated by a single exercise is of little significance for professional exercise guidance, but the analysis of multiple exercise signals is very important for exercise guidance. Based on this, Chow et al.[34] prepared a textile pressure sensing monitoring sock using conductive yarn to connect the communication module at the ankle joint and observe the wearer's foot movement according to the strain image.

4.3. Sports rehabilitation guidance

Exercise rehabilitation guidance can help patients recover more quickly with the scope of monitoring including families and hospitals. The current mainstream method is to achieve auxiliary rehabilitation guidance in hospitals and other medical institutions based on self-monitoring. Lorussi et al.[35] designed a smart wearable system based on the fusion of inertial sensors, fabric piezoresistive sensors and textile EMG sensors. The system is designed in a modular form and consists of separate shirts, pants, gloves and shoes to monitor human activity during post-stroke rehabilitation in daily life, which can help doctors optimize and adjust the training program of patients to assess the daily life and rehabilitation of stroke patients. Han et al.[35] designed flat knitting technology to prepare a seamless glove with sensors embedded in the fingers for finger gesture discrimination. Heo et al.[36] designed a sensing glove coated with AgNW and PDMS, and studied the electrical signal changes of different fingers under different bending conditions to guide the recovery of hand movement health.

5. Conclusions

The research of knitted sensors in the field of sports and health clothing has achieved certain results, but there are still many shortcomings, so it is difficult to be widely promoted. The future research focus and development prospects can be summarized as the following points:

1) Smart sports and health clothing should possess textile wearing quality which is similar to the performance of the sensors. At present, although there are many research results on knitted sensors, most of them were focused on the implementation of functionality, and there is still a lack of research on clothing pressure, breathability, washability and other wearability. 2) Industry standards for specifications should be established. Due to the large differences in the types and preparation methods of knitted sensors, it is difficult to unify the scope of use and data discrimination standards. Therefore, the parameters and specifications of conductive materials should be unified, and while realizing the function, the safety of sensor use should be ensured, and relevant performance, preparation and production standards should be established. In addition, in terms of data transmission standards, reliable and secure smart products can establish public trust. There are currently relevant standard protocols in the transmission mode of Bluetooth; however, as the transmission of data requires multiple transmission networks to complement each other, the security of personal information must be guaranteed. 3) Seamless connection of knitted sensors with other smart components. Limited by the development of science and technology, knitted sensors cannot be used alone at present, and the collected signals still need to be converted by circuits and data processing systems before output can be made. The use of knitting to integrate each intelligent component can effectively overcome the current limitations.

In short, with the current development and the advancement of science and technology, the research and applications of knitted sensors in the field of sports and health clothing are developing towards health comfort, functional diversification, new energy and energy storage methods, intelligent and precise information and lower pricing.

Conflict of interest

The authors declare no conflict of interest.

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