

## REVIEW ARTICLE

# Flexible sensors in smart textiles and their applications

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### ABSTRACT

Sensors are the core part of intelligent smart textiles, and flexible sensors play an important role in wearable smart textiles because of their softness, bend ability and stretch ability, and excellent electrical properties. Based on the working principle of sensors, the research progress of flexible sensors for smart textiles in recent years is reviewed, and the sensing mechanism, sensing materials and application status of different sensors are introduced respectively; the main research directions of flexible sensors for smart textiles are summarized: physiological parameter detection, pressure detection and motion detection, and the applications of the three research directions are reviewed. On this basis, the problems of intelligent flexible sensors and their development prospects are pointed out.

**Keywords:** wearable technology; smart textiles; flexible sensors; smart textile materials

Smart textiles refer to the integration of electronics, computers, biology, materials and other high technologies into textile garments, so that textile garments can simulate living systems with dual functions of sensing and reacting<sup>[1,2]</sup>, etc., in which sensors are a key component of smart textiles that can sense and feedback changes in the external environment. With the increasing requirements for smart textiles, the expectations for the range, accuracy and stability of sensor measurements have been gradually increased, and it is also hoped that the sensors can also be flexible, ductile, easy to carry and fold. In recent years, the development of wearable flexible sensor technology has become a major hotspot in the research field of smart textiles<sup>[3]</sup>, and the combination of flexible sensors and textile materials makes smart textiles intelligent while maintaining the softness and comfort of the

fabric<sup>[4]</sup>, which plays an important role in medical health monitoring, fitness sports, military, aerospace and other fields<sup>[5]</sup>. In this paper, the existing flexible sensors are classified into flexible pressure-electrical sensors and flexible strain-electrical sensors according to different sensing mechanisms, and the research progress of these two types of sensors and their latest applications in human physiological parameters, pressure, and motion monitoring are presented.

## 1. Classification and characteristics of flexible sensors

Smart textiles usually consist of three parts: Sensors, actuators, and control units<sup>[6,7]</sup>. As a wearable flexible monitoring device, the sensor needs to be embedded in the textile and can fully contact

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with the human skin surface to monitor a wide range of signs data without affecting the normal human activities and maintaining a certain wearing comfort. At present, there are many types of flexible sensors for smart textiles, with different classification methods. For example, according to the classification of signal conversion mechanism, flexible sensors mainly include capacitive, resistive, inductive, fiber optic flexible sensors<sup>[8]</sup>; according to the classification of fabric structure, flexible sensors mainly include flexible sensors based on knitted structure<sup>[9]</sup> and flexible sensors based on woven structure<sup>[10]</sup>.

Effective conversion of external stimuli into electrical signals is a key technology for flexible sensor applications. According to the different electrical signal conversion mechanisms and operating principles of sensors, the common sensors with relatively mature technologies and a wide range of applications can be classified into four categories: Pressure-electrical-based flexible sensors, strain-electrical-based flexible sensors, flexible fiber-optic sensors, and flexible gas-sensitive sensors.

### **1.1. Flexible pressure-electrical sensors**

Flexible pressure-electrical sensors include flexible capacitive sensors, flexible piezoresistive sensors, flexible piezoelectric sensors, etc., which indirectly detect changes in external pressure through changes in capacitance, current or voltage of the measured object under pressure. Flexible pressure-electrical sensors are widely used because of their high testing sensitivity and accuracy.

Flexible capacitive sensors generally use flexible materials (conductive films, fibers, yarns, fabrics, etc.) as capacitor pole plates and foam, rubber, etc. as spacer layers, and according to the principle of capacitor operation, the sensor will sense the amount of change in pressure or shear force to the user<sup>[11]</sup>. This flexible sensor can be combined with textiles to prepare smart textiles that can sense changes in external forces, have a simple structure, high sensitivity and are soft and easily deformable, and its greatest advantage is that it can achieve the detection of small static external forces.

Compared to capacitive sensors, flexible piezoresistive sensors are characterized by small size, various forms, high resolution and easy integration with textiles. Piezoresistive sensors are sensors made based on the piezoresistive effect of materials as well as integrated circuits<sup>[12,13]</sup>, which, when subjected to pressure, generate electrical conductivity due to the transfer between metal particles within the sensing material, and infer the magnitude of the applied pressure by measuring the change in resistance. This sensor usually uses a composite material with a high sensitivity coefficient and good piezoresistive properties, such as a carbon-based material or graphene, as the piezoresistive material. Combining this sensor with textiles can be used to measure parameters such as pressure and acceleration acting on the fabric. However, pressure sensors based on piezoresistive and capacitive signal mechanisms suffer from problems such as signal crosstalk, which affects their measurement accuracy.

Flexible piezoelectric sensors are sensors made by applying pressure to piezoelectric materials to produce a piezoelectric effect<sup>[14]</sup>. The piezoelectric material is a special material that can generate an electrical charge under mechanical pressure, and currently most of the conductive material composite piezoelectric film with high piezoelectric coefficient and high sensitivity or bi-polyvinyl fluoride (PVDF) film. Intelligent textiles made of piezoelectric films can detect the pressure generated by the bending of human body parts, or detect the stability of human foot gait, etc. They have the advantages of high sensitivity, simple structure design and stable performance. Since the output is a voltage signal, the flexible piezoelectric sensor is relatively simple in circuit design and signal acquisition, with high sensitivity and high signal-to-noise ratio; however, these sensors can produce charge leakage and poor DC responsiveness of the output.

### **1.2. Flexible strain-electrical sensors**

Flexible strain-electrical sensor is a kind of sensor with “strain-resistance effect”, such as

pull-resistive sensors. Flexible tension-resistance sensors, also known as flexible strain sensors<sup>[15]</sup>, are based on the same principle as piezoresistive sensors, i.e., the electrical signal of the sensor itself changes when the material or fabric is subjected to mechanical stress, which converts the local deformation of the object under test into an intuitively measurable electrical change. These sensors have low preparation costs, and the test principle and acquisition method are simple, with the advantages of good comfort and high sensitivity. In the field of smart textiles, these sensors are usually classified according to the preparation method and include mainly flexible coated strain sensors and flexible inlaid strain sensors.

The coated strain sensors are represented by polypyrrole-coated flexible sensors<sup>[16]</sup>, which are made by coating the fabric surface with conductive polymers in the form of coating process (e.g., textile printing, collage). The coating material usually selects the carbon composite coating<sup>[17]</sup>, and this polymer conductive coating has good adhesion on the fabric, as well as good sensitivity and linear correlation; however, there are problems such as coating process difficulties and easy to cause rough cracking of the surface coating.

The embedded strain sensor uses conductive fiber and yarn material as the main sensing element, and the corresponding conductive textile can be prepared by interweaving in woven or knitted form. The measurement is achieved by the deformation of the yarn coil structure under the action of the strain force, which affects the change in resistance. Commonly used textile conductive fiber materials include three types: metal conductive fibers, carbon fibers and organic conductive fibers<sup>[18]</sup>. Among them, the composite organic conductive fiber is the conductive properties of the yarn and other yarns through the core yarn and other composite conductive yarn, its comprehensive performance is the most excellent. The strain sensors prepared from conductive fiber yarns have the advantages of excellent sensitivity, easy measurement, and high wearing comfort; however, due to the special characteristics

of the coil structure, the wash ability and repeatability for wearable textiles still need further improvement.

### 1.3. Flexible fiber optic sensors

The measured physical quantity is converted into a sensor for the change of optical characteristics<sup>[19]</sup>. Among the optical properties include characteristic parameters such as the amplitude, phase, and wavelength of the light wave. Compared with the traditional flexible resistive sensors, flexible optical fiber sensors have the advantages of light weight, high accuracy, fast response, good repeatability as well as high stability and low cost. The current domestic and international literature explores the weaving of optical fibers into textiles to constitute fiber optic sensors. In addition to sensing signals such as pressure, temperature, velocity, vibration and angle, fiber optic sensors can be used to measure tensile stress as well as changes in displacement. Such embedded fiber-optic flexible sensors can be used to measure small strain situations<sup>[20]</sup>, such as measuring bending changes in human elbows and finger joints, or subtle strain signals associated with breathing.

### 1.4. Flexible gas sensitive sensors

Flexible gas sensors, also known as flexible gas sensors<sup>[21]</sup>, are based on the measurement principle that when the sensor is in a gaseous environment, the conductivity of the sensor changes with the concentration and type of the gas being measured in the air, responding to the contact gas and converting it into an electrical signal. This sensor is widely used in environmental pollution detection, public safety and other fields, but also for medical diagnosis. The new gas-sensitive sensors currently used for wearable are generally constructed on a flexible stretchable substrate with polymer complex thin-film sensors, which have high gas-sensitive performance, small size, light weight, good stability, flexible and stretchable. The integration of flexible gas-sensitive sensors for detecting different gas types on textiles can be used to make smart textiles, such as clothing

and multifunctional masks.

## **2. Application of flexible sensors**

In the future development of wearable devices, flexible sensors will play a pivotal role. At present, the research of flexible sensors for smart textiles mainly focuses on the detection of human health conditions, such as the detection of basic human physiological parameters, pressure detection and motion recognition. The research on flexible sensors for smart textiles mainly focuses on the detection of human health conditions, such as the detection of basic physiological parameters, pressure detection and motion recognition.

### **2.1. Physiological parameters testing**

Respiration, heart rate and pulse are important physiological parameters of the human body, which play an important reference value in the daily life monitoring of the human body. Therefore, when selecting sensors, try to choose flexible sensors with excellent sensitivity, high accuracy and high elasticity of the substrate.

The skin surface is deformed by stretching when the human body breathes, and physiological data such as respiratory rate and depth can be measured indirectly by detecting this deformation, so the sensors that can fit the skin, are portable and have high sensitivity and repeatability have obvious advantages. De Jonckheere et al.<sup>[22]</sup> made fiber-optic sensors by crocheting optical fibers into elastic fabrics to compensate for the effect of metallic materials on the detection signal in MRI in medicine. The stretching motion of the abdomen and chest caused by respiration leads to deformation of the fiber optic position in the fabric, and the change of the optical signal is measured to monitor the patient's respiratory status. Guo et al.<sup>[23]</sup> used six different materials of conductive yarns to embed the sensor into a seamless specimen in the form of partial yarn addition, and simulated the skin deformation caused by human respiration and heartbeat by performing tensile recovery experiments

with different sizes of specimens at constant elongation. Huang et al.<sup>[24]</sup> studied three main factors affecting the fabric sensor: Yarn structure, textile structure, and fabric structure, and the detection of human respiration rate can be achieved by using single and double conductive yarns wrapped around the core fibers and woven into the fabric. In addition, due to the extended movement of human respiration, it makes the mutual pressure effect between the body surface and the intimate garment, and the respiratory changes can be easily detected by the pressure sensor. Kang et al.<sup>[25]</sup> used silver-plated elastic fabric and silver-plated non-elastic fabric as the two parallel pole plates of a capacitor, and through the contraction and deformation of the electrode plate under the action of external pressure, resulting in the capacitance between the two parallel pole plates. The change in capacitance between the two parallel plates was caused by the contraction and deformation of the electrode plates under external pressure, which indirectly monitored the human respiratory condition.

Due to the irregular and complex surface structure of the human body, the detection of weak heart rate and pulse signals requires sensors that are thin, light and extremely sensitive. In recent years, fiber optic sensors have been widely used to develop a variety of pulse, heart rate, respiration and other detection devices. Tian et al.<sup>[26]</sup> proposed a pulse detection method based on fiber Bragg grating sensor, which is implanted into the air layer of the fabric by cross-machine weaving, and uses the change in wavelength and amplitude of the reflection center of the fiber grating caused by heart vibration to achieve real-time online acquisition and analysis of pulse signals. Yang et al.<sup>[27]</sup> designed a new fiber-optic microbending sensor based on the fiber-optic microbending effect, using multimode optical fibers clamped to parallel strips to form a microbending structure, which is sewn together on an elastic base fabric for measuring human heartbeat and respiration rate when standing and sitting. In addition, fabric-based temperature sensors can also be used to sense human temperature changes, such as the use of wire cores in the weft direction and

fabric integration to prepare a wearable temperature monitoring system, temperature sensors sense temperature, conductive yarn transmission data, so that the signal of body temperature changes can be obtained<sup>[28]</sup>.

In practical applications, in order to optimize the sensitivity of the sensor, reduce the signal shift, and seek a more stable sensor structure, Peng et al.<sup>[29]</sup> improved the sensitivity of the contact resistance by coating silicone at the contact points between the wire yarns to increase the signal repeatability. However, the reliability and stability of flexible sensors are easily affected by external mechanical friction and water washing during the process of providing long-term sensing and feedback on human health conditions. Although Cai et al.<sup>[30]</sup> studied the performance stability of flexible sensors under a certain number of washes as well as temperature, they have not really been able to meet the performance requirements of actual consumers in their daily lives and work.

## 2.2. Pressure testing

Flexible pressure sensors have a wide range of applications in smart clothing and other applications, where they are mainly used to detect the pressure distribution generated by textiles on the human body.

The sensor resistance-strain principle was used to indirectly calculate the pressure values of various parts of human dressing. Wang<sup>[31]</sup> explored the relationship between the equivalent resistance of the flexible sensor and the tensile strain by analyzing the relationship between the equivalent resistance of the flexible sensor and the tensile strain of the knitted fabric, and integrated the correlation between the garment pressure and the tensile strain of the knitted fabric. According to the change of sensor resistance, the undergarment pressure distribution in the main parts of the human body and the influence of garment margin on the undergarment pressure were objectively evaluated. In addition, the flexible pressure sensor can be used to conduct static garment pressure test directly. Wang<sup>[32]</sup> prepared PVDF nanofiber membrane by electrostatic spinning

method and designed and developed a flexible pressure sensor that can be used for human garment pressure testing and monitoring, and the complex human garment pressure can be measured realistically using its piezoelectric effect. Yi et al.<sup>[33]</sup> produced a conductive knitted fabric coated with carbon-based conductive composites with good piezoresistive properties and high sensitivity when the non-conductive surface is in contact with the indenter, which can be used as a sensitive element of the sensor for garment pressure and flexible human platform pressure measurement. Pang et al.<sup>[34]</sup> used a flexible pressure sensor to design and build a pressure sock pressure test platform, and the test obtained the pressure change values and pressure distribution on multiple parts of the circumference such as ankle and calf. In addition, in the study of dynamic pressure contact between clothing and human skin, Tang et al.<sup>[35]</sup> built a dynamic pressure testing system for sportswear based on flexible piezoresistive sensors, signal conditioning modules and graphical programming language to achieve the acquisition, processing and display of human dynamic pressure data.

In addition to measuring the distribution of garment pressure on the human body as well as the size of the intimate apparel, flexible pressure sensors can also be used to detect the distribution of plantar pressure<sup>[36]</sup>. Jin et al.<sup>[37]</sup> developed a piezoelectric test insole using PVDF piezoelectric film, and proposed the use of a multilayer sense core structure to improve the signal response of the sensor and improve the elastic hysteresis of the flexible sensor, which can record the distribution of plantar pressure under different states of motion, in response to the common frequency response problem of flexible sensors. In other textile manufacturing fields, Lee et al.<sup>[38]</sup> developed a textile structured fiber optic pressure sensor for car cushions, in which polymer optical fibers and yarns are cross-woven into a mesh structure, and the optical fibers produce bending deformation when the cushion is subjected to a large pressure load.

Flexible pressure sensors can be used not only

in textiles directly, but also in the inspection of garment ready-to-wear. Jin<sup>[39]</sup> combined flexible pressure sensors with airbags and proposed an intelligent hanger as well as a mathematical model and control method to attach the flexible pressure sensor to the hanger, which can more directly detect the target deformation and eventually display the degree of fit of the clothes and the hanger, providing a fast and accurate method for garment inspection. In recent years, the research and development of flexible robotic pressure-sensitive skin further realized the intelligence of robots, and Tian et al.<sup>[40]</sup> integrated carbon black conductive material with a flexible substrate to develop a flexible robotic pressure capacitive sensor skin with a 3-layer composite structure, which can be attached to a robot hand for grasping, lifting and gripping application operations.

### **2.3. Motion detection**

Currently, flexible sensors combined with existing wireless transmission technologies are widely used in the detection of human motion behavior. In addition to detecting subtle movements of the chest as well as the neck during breathing or speaking in human motion, the sensors can be used to capture a wide range of motion, such as the bending motion of hands, arms and legs.

Xie<sup>[41]</sup> used weft knitting technology to knit silver-plated nylon conductive yarn into a flexible knitted sensor, analyzed the electrical-mechanical properties of the sensor under bi-directional stretching and established a related theoretical model, and applied it to the recognition and monitoring of limb movements in a monitoring suit. Helmer et al.<sup>[42]</sup> tied a strain knitted sensor to the knee, and measured various movement postures of athletes' lower limbs when they played soccer at different times and with different movement amplitudes and speeds. Tognetti et al.<sup>[43]</sup> developed a strain sensor based on single-layer and double-layer knitted piezoelectric fabric KPF for measuring limb movement stretching and bending. The device measured knee movements at rest and in motion, respectively, and compared the measurements with

those of a standard phase indicator, and the experiments confirmed the better performance of the double-layer knitted piezoelectric sensor. Zhang et al.<sup>[44]</sup> prepared three types of polypyrrole conductive fabrics by in situ polymerization method, and used these three conductive fabrics as sensing elements to fabricate posture monitoring fabric sensors, and performed quasi-static tests of upper limb motion states, respectively. By observing the changes of tensile resistance of polypyrrole conductive fabrics and their directional differences, the bending, rotation and their compound movements of the upper limbs could be accurately reflected.

In addition to the use of strain sensors to detect the deformation changes generated by the bending motion of the human body, Shi et al.<sup>[45]</sup> also proposed a pressure sensor-based human motion recognition method, which placed pressure-sensitive sensors in the insole and obtained the distance and time of human motion as well as the number of exercises based on the changes of the collected pressure data, and also extracted the motion intensity data such as the difficulty of the motion. Yang et al.<sup>[46]</sup> demonstrated the application of piezoelectric thin-film flexible sensors in table tennis motion detection by attaching DT1-028K piezoelectric film to the elbow of a table tennis suit, and when the paddle is swung, the elbow bends to make the voltage change between the two electrodes of the piezoelectric film, which can detect the number of single hits, frequency and total number of hits in real time.

With the rapid development of human-computer interaction and emotion technology, Su et al.<sup>[47]</sup> first proposed the concept of expression recognition through multi-channel analysis of piezoresistive flexible wearable electronic sensors. By attaching the flexible sensor to the human body skin, the response of human facial expressions under different environmental and psychological conditions can be monitored in real time.

At present, the data monitored by the flexible sensors applied to human motion detection is relatively single, mainly based on basic human flexion

and extension movements, and the data analysis in the medical or fitness field is not fully matched with the actual needs, and the data mining, comprehensive analysis and utilization needs to be continuously improved. In addition, motion detection is a long-time output and feedback process, especially as a module to collect and transmit data information, the working mode of the sensor is often constrained by the battery energy, insufficient energy supply will affect the accuracy and stability of data acquisition.

### 3. Conclusions

Compared with traditional wearable sensors, flexible sensors have the characteristics of lightness and softness, outstanding electrical performance, good comfort and high integration, which influence the functional design and development direction of future wearable devices. However, the rapid development of intelligent flexible sensors is accompanied by some problems.

The current research and development of flexible sensors to conductive fabrics as the main sensing element, these sensors usually have a poor feel of the coating, the lack of wash ability, complex processing technology and processing costs and other shortcomings, cannot meet the design goals and use the performance requirements, it is difficult to adapt to the future of flexible sensors, large-scale, low-cost and high-efficiency production mode. In addition, the energy consumption and self-drive of flexible sensors is an important condition to ensure the stability of signal transmission, while the existing energy supply of sensors and the actual demand still exists a large gap.

The real development and application of flexible sensors also need to rely on more advanced research and development of new materials and the development of computer technology, with the recent years of printed electronics and 3D printing technology has received widespread attention to flexible sensors as the representative of the new printed electronic components, with its efficient and

environmentally friendly, convenient and more customized advantages, and gradually to the advanced manufacturing of intelligent and flexible wearable products.

In terms of energy supply, considering the popularity of wireless charging technology in electronic products, it is possible to use relevant technologies or accept energy from the electromagnetic field in the environment or in the form of electromagnetic waves and convert it into electrical energy as a charging source. As far as battery technology is concerned, the development of electrochemical batteries with high energy and small size is a topic that researchers need to focus on.

While measuring the basic physical quantities of human daily physiology as well as activities, flexible sensors should also broaden the scope of their detection and combine with the data recording and feedback functions of mobile communication devices to meet consumers' needs for customization and personalization of smart textiles and adapt to different people and occasions. The integration of nanotechnology can integrate flexible sensors with different functions as well as other sensors in wearable textiles to realize highly integrated, tiny and diversified measurement functions of smart textiles.

### Conflict of interest

The authors declare no conflict of interest.

### References

1. Yang D. Intelligent materials and intelligent systems. Tianjin: Tianjin University Press; 2000. p. 24–37.
2. Li X. An overview of intelligent fiber and intelligent textiles (in Chinese). *Cotton Textile Technology* 2009; 37(6): 62–64.
3. Shi M, Xiao H. The present state and perspectives of the smart textiles (in Chinese). *Hi-Tech Fiber and Application* 2010; 35(4): 5–8.
4. Cochrane C, Koncar V, Lewandowski M, et al. Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite. *Sensors* 2007; 7(4): 473–492.

5. Qian X, Su M, Li F, et al. Research progress in flexible wearable electronic sensors (in Chinese). *Acta Chimica Sinica* 2016; 74(7): 565–575.
6. Yin J, Wang Y, Ju G. Introduction to functional materials. Harbin: Harbin Institute of Technology Press; 1999. p. 256–258.
7. Liu M, Zhuang Q. The application and development foreground of smart flexible sensor (in Chinese). *Progress in Textile Science and Technology* 2009; (1): 38–40, 42.
8. Ma Y, Liu Q, Liu W. Research progress of flexible sensor for smart textiles (in Chinese). *Transducer and Microsystem Technologies* 2015; 34(4): 1–3, 7.
9. Atalay O, Kennon WR, Husain MD. Textile-based weft knitted strain sensors: Effect of fabric parameters on sensor properties. *Sensors* 2013; 13(8): 11114–11127.
10. Li L, Ding Y. Design and analysis of woven structure-based flexible strain sensor (in Chinese). *Chinese Journal of Sensors and Actuators* 2008; 21(7): 1132–1136.
11. Wilson JS. *Sensor technology handbook*. Holland: Butter-Worth-Heinemann; 2005.
12. Pang W, Liu T, Li Y, et al. Review on fabric-based sensor (in Chinese). *Technical Textiles* 2012; 30(6): 1–7.
13. Fan Q, Zhang X, Qin Z. Preparation of polyaniline/polyurethane fibers and their piezoresistive property. *Journal of Macromolecular Science, Part B(Physics)* 2012; 51(4): 736–746.
14. Wang Q, Wu B, Song Y, et al. Design of a signal conditioner circuit for the PVDF piezoelectric transducer (in Chinese). *Chinese Journal of Scientific Instrument* 2006; 27(Sup.2): 1653–1655.
15. Wu S, Liu W, Liu X. Research progress of flexible fabric strain sensor (in Chinese). *Transducer and Microsystem Technologies* 2017; 36(12): 1–3.
16. Liu H, Chen T, Zhao L, et al. Research progress on the fabric with ppy-coating (in Chinese). *China Textile Leader* 2018; (3): 64–67.
17. Liu T, Zou F. Structural design and sensing performance of conductive knitted fabrics of carbon coated fibers (in Chinese). *Journal of Textile Research* 2014; 35(9): 31–35, 46.
18. Li Y, Chen T, Yang X. Conductive fibers for textile and its applications (in Chinese). *Technical Textiles* 2010; 28(4): 32–35.
19. Rothmaier M, Luong MP, Clemens F. Textile pressure sensor made of flexible plastic optical fibers. *Sensors* 2008; 8(7): 4318–4329.
20. Guo X, Yang K, Zhang C. Research progress of flexible textile sensors (in Chinese). *Wool Textile Journal* 2018; 46(8): 86–91.
21. Gao Z. Fabrication of distinguishable target gas based on flexible gas sensor wearable mask [PhD thesis]. Changchun: Jilin University; 2017.
22. DeJonckheere J, Narbonnean F, Kinet D, et al (editors). *Optical fiber sensors embedded into technical textile for a continuous monitoring of patients under magnetic resonance imaging*. 30<sup>th</sup> Annual International Conference of the IEEE Engineering in Medicine and Biology Society; Vancouver BC: IEEE; 5266–5269.
23. Guo Q. Development of smart seamless garments integrating different conductive materials with knitted flexible sensors [PhD thesis]. Shanghai: Donghua University; 2017.
24. Huang C, Tang C, Lee M, et al. Parametric design of yarn-based piezoresistive sensors for smart textiles. *Sensor and Actuators A (Physical)* 2008; 148(1): 10–15.
25. Kang T, Merritt C, Karaguzel B, et al (editors). *Sensors on textile substrates for home-based healthcare monitoring*. 1<sup>st</sup> Distributed Diagnosis and Home Healthcare (D2H2) Conference; 2006; Virginia: IEEE; p. 5–7.
26. Tian X, Yang K, Zhang C. Design of pulse sensing fabric based on fiber bragg grating (in Chinese). *Journal of Textile Research* 2016; 37(10): 38–41.
27. Yang X, Chen Z, Elvin CSM, et al. Textile fiber optic micro bend sensor used for heartbeat and respiration monitoring. *Sensors Journal IEEE* 2015; 15(2): 757–761.
28. Ozdemir, HO, Kilinc S. Smart woven fabrics with portable and wearable vibrating electronics. *Autex Research Journal* 2015; 15(2): 99–103.
29. Peng X, Yang X, Hu J. Study on respiration monitoring piezo-resistive sensors based on embroidery (in Chinese). *Journal of Donghua University (Natural Science Edition)* 2014; 40(6): 712–717, 727.
30. Cai Q, Chen W, Wang J. Effect of washing and heat setting on electric conduction of flexible sensors (in Chinese). *Advanced Textile Technology* 2017; 25(1): 23–27, 55.
31. Wang J. Electrical-mechanical properties of conductive knitted flexible sensors and pressure testing of underwear [PhD thesis]. Shanghai: Donghua University; 2013.
32. Wang Y. Research on the pressure performance of elastic knitted fabrics and the design of testing system and development [PhD thesis]. Shanghai: Donghua University; 2010.
33. Yi W, Zheng R, Gu Y. The piezoresistive performance of conductive knitted fabric under small pressure (in Chinese). *Knitting Industries* 2014; (9): 12–14.
34. Pang X, Fang Y, Li X. Pressure testing of compression stockings based on flexible pressure sensor (in Chinese). *Journal of Zhejiang Institute of Science Technology University (Natural Sciences)* 2017; (6): 759–764.
35. Tang Q, Xiao J, Wei Q. Establishment and evaluation of dynamic pressure measurement system for sports wears (in Chinese). *Journal of Textile Research* 2009; 30(9): 123–126.
36. Gao M, Zhang Y, Hong C, et al. Application of flexible sensors in the plantar pressure measurement



- system (in Chinese). *Journal of Clothing Research* 2018; 3(4): 301–307.
37. Jin M, Ding X, Gan Y, et al. A sensing insole for measuring plantar pressure distribution (in Chinese). *Journal of Textile Research* 2010; 31(9): 114–117.
  38. Lee TH, Kim ES, Kim TH, et al. Simple pressure sensor for a vehicle seat using a woven polymer optical-sheet. *Journal of the Korean Physical Society* 2015; 67(11): 1947–1951.
  39. Jin X. Research and application of intelligent clothes rack based on multi-objective collaborative optimization algorithm application [PhD thesis]. Shanghai: Donghua University; 2017.
  40. Tian H, Liu P, Guo X, et al. Flexible pressure/temperature composite perceptual system based on conductive rubber (in Chinese). *Transducer and Microsystem Technologies* 2015; (10): 100–103.
  41. Xie J. Bi-directional extension electro-mechanical properties of knitted fabric sensors and limb movement monitoring [PhD thesis]. Shanghai: Donghua University; 2015.
  42. Helemer RJN, Farrow D, Ball K. A pilot evaluation of an electronic textile for lower limb monitoring and interactive biofeedback. *Procedia Engineering* 2011; 13(1): 513–518.
  43. Tognetti A, Lorussi F, Mura GD, et al. New generation of wearable goniometers for motion capture systems. *Journal of Neuro Engineering and Rehabilitation* 2014; 11(1): 56–73.
  44. Zhang X, Li G, Hu J, et al. Mechanic-electronical property characterization of ppy-coated conductive woven fabric for human upper limb motion monitoring (in Chinese). *Chinese Journal of Biomedical Engineering* 2015; 34(6): 670–676.
  45. Shi X, Xiong Q, Lei L. Study on human motion recognition method based on pressure sensor (in Chinese). *Chinese Journal of Scientific Instrument* 2010; 31(6): 1429–1434.
  46. Yang H, Dong W. Design of elbow motion detection system on piezoelectric thin film sensor (in Chinese). *Electronic Engineering and Product World* 2017; (1): 41–43.
  47. Su M, Li F, Chen S, et al. Nanoparticle based curve arrays for multi-recognition flexible electronics. *Advanced Materials* 2016; 28(7): 1369–1374.