DOI: 10.19884/j.1672-5220.202402001

Review on Development and Application of Fabric Electrodes in Electrocardiogram Monitoring Garments

XIE Yutong[1, 2*], ZAKARIA Norsaadah[1]
1. School of Design, Taylor's University, Subang Jaya 47500, Malaysia
2. Clothing and Design Faculty, Minjiang University, Fuzhou 350108, China

Abstract: Cardiovascular disease persists as the primary cause of human mortality, significantly impacting healthy life expectancy. The routine electrocardiogram (ECG) stands out as a pivotal noninvasive diagnostic tool for identifying arrhythmias. The evolving landscape of fabric electrodes, specifically designed for the prolonged monitoring of human ECG signals, is the focus of this research. Adhering to the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement and assimilating data from 81 pertinent studies sourced from reputable databases, the research conducts a comprehensive systematic review and meta-analysis on the materials, fabric structures and preparation methods of fabric electrodes in the existing literature. It provides a nuanced assessment of the advantages and disadvantages of diverse textile materials and structures, elucidating their impacts on the stability of biomonitoring signals. Furthermore, the study outlines current developmental constraints and future trajectories for fabric electrodes. These insights could serve as essential guidance for ECG monitoring system designers, aiding them in the selection of materials that optimize the measurement of biopotential signals.

Key words: fabric electrode; electrocardiogram (ECG) monitoring; conductive material; fabric structure; meta-analysis

CLC number: TS941.48 **Document code:** A

Article ID: 1672-5220(2024)05-0482-10

0 Introduction

Cardiovascular diseases stand as the primary cause of human mortality and the reduction of healthy life expectancy, holding the top position in the global burden of diseases. Electrocardiogram (ECG) aims to capture potential changes in the systolic and diastolic manifestations of heart cells on the body's surface. This provides crucial data for medical diagnosis and treatment, aiding in the prevention and management of cardiovascular diseases. Presently, conventional ECG stands as the predominant non-invasive tool for diagnosing cardiac arrhythmias in clinical practice[1]. Currently, conventional ECG holds the status of the most widely employed noninvasive diagnostic tool for arrhythmias.

The silver/silver chloride (Ag/AgCl) gel electrode has been widely utilized in ECG signal measurement, suitable for both clinical and portable devices[2]. The electrolyte gel is utilized to decrease skin-electrode interface impedance, ensuring effective electrical contact between the electrode and the skin, resulting in high-quality signals[3]. Nevertheless, the Ag/AgCl gel electrode is often used as a disposable electrode, and coated with conductive adhesive that may irritate sensitive skin. Prolonged use of such electrode not only induces skin allergy symptoms but also alters skin-electrode impedance, diminishing both the signal sensitivity and the signal-to-noise ratio, thereby rendering it unsuitable for extended wear[4].

The fabric electrode, a rapidly evolving flexible dry electrode in recent years, is a kind of sensor featuring textile structures capable of detecting bioelectrical signals on human skin surface[5]. This kind of electrode is soft and breathable, and can collect human electrical signals without using conductive paste, which can well solve the problem of irritation and allergy to human skin caused by traditional electrodes.

Various types of fabric electrodes were developed for long-term monitoring of human ECG signals. Bin Ahmad et al.[6] developed a multi-functional application for ECG signal monitoring cotton fabric flexible circuits. Cai et al.[7] designed a continuous, non-invasive and comfortable ECG signal monitoring intelligent clothing. Liu[8] made a square plain woven fabric ECG electrode with a side length of 4 cm using silver-plated nylon yarns, and designed and released an ECG monitoring wearable with the function of ECG signal acquisition, processing and storage. Lin et al.[9] designed the ECG monitoring system, which mainly included the fabric ECG electrode, the signal acquisition front-end circuit,

Received date: 2024-02-01

* Correspondence should be addressed to XIE Yutong, email: xieyutong03@taylors.edu.my

Citation: XIE Y T, ZAKARIA N. Review on development and application of fabric electrodes in electrocardiogram monitoring garments[J]. *Journal of Donghua University (English Edition)*, 2024, 41(5): 482-491.

the power supply and the Bluetooth transmission system; the fabric ECG electrode used for the ECG signal acquisition was woven with silver fibers and conventional yarns.

Based on the above situation, this research summarizes the materials commonly used in fabric electrodes and their structural characteristics through a comprehensive literature review and analysis. In past studies, the design of fabric electrodes mainly includes two aspects: electrode materials and structures. Based on the previous research on fabric electrodes, the relationship between fabric electrode materials and structures, electrode comfort and monitoring signal stability are discussed. To exclude the influence of different monitoring methods of other physiological data on the comfort and stability of detection signals, relevant studies on the monitoring of physiological signals such as respiration, body temperature and heartbeat are not included in this review. In addition, since the goal of this research is the feasibility of ECG monitoring in daily life, the discussion of invasive electrodes is excluded.

Databases searched include the science citation index (SCI) in Web of Science, IEEE, Taylor & Francis, ProQuest, Wiley, SpringerLink, PubMed, MDPI and SAGE. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement were used to guide the systematic review of relevant literature[10-11]. Following the PRISMA statement guideline, 794 papers were screened, resulting in a comprehensive systematic review and meta-analysis of 81 pertinent studies from the databases. This review is expounded on the aspects of research materials, research methods, challenges and limitations, which provides a reference for the design and development of fabric electrodes.

1 Components of Fabric Electrode

Fabric electrodes typically consist of two main components: the base material and the conductive material. They are often combined by different combination methods.

1.1 Base material

The base material, i. e. the substrate, serves as the foundation or backing for fabric electrodes, providing the structural support and enabling the integration of conductive materials, thereby imparting conductive properties to the fabric. Commonly used substrates include woven fabrics, nonwoven fabrics and knitted fabrics, each offering unique characteristics that influence the overall performance of the electrode. The choice of the substrate affects the flexibility, durability and comfort of the electrode. Various techniques are employed to attach conductive materials to the substrate[12], which will be discussed in detail in the following sections.

1.2 Conductive material

The conductive material is responsible for collecting and transmitting ECG signals and thus is crucial for the functionality of fabric electrodes. The conductive materials can be metals, conductive polymers, carbon allotropes such as graphene, or innovative solutions like highly conductive liquids. The integration of these materials with the substrate is achieved through various methods, including coating, weaving and embedding.

Silver and silver-based polymers are the most commonly used conductive materials due to their excellent conductivity and chemical stability. They are often applied to the substrate via chemical deposition or coating techniques[13]. Graphene, known for its superior electrical and thermal conductivity, is another promising material, particularly for flexible and wearable electronic devices. When combined with nylon or other fabric substrates, graphene can significantly enhance the performance of fabric electrodes[14].

Recent research efforts have focused on developing ternary composites combining carbon materials, metal oxides and conductive polymers. This ternary composites combination approach aims to leverage the synergistic effects of these components to maximize the performance of fabric electrodes[15]. For instance, electrodes based on activated carbon and manganese oxide coated on cotton woven fabrics have been investigated for their enhanced electrochemical properties[16].

1.3 Combination methods

Common combination methods of the base material and the conductive material are shown in Fig. 1. The first method is to weave conductive materials and base materials together to get woven electrodes[17], knitted electrodes[18], embroidered electrodes[19] and nonwoven electrodes[20]. The second method is to apply conductive materials onto base materials through various techniques, such as electroplating, physical vapor deposition, chemical polymerization, dip-coating and printing. This ensures that the conductive material is uniformly covered on the substrate, forming a continuous conductive surface. The selection of the combination method depends on the desired electrode performance, comfort and manufacturing scalability. With this combination, fabric electrodes can achieve efficient collection and conduction of bioelectrical signals while maintaining softness and adaptability.

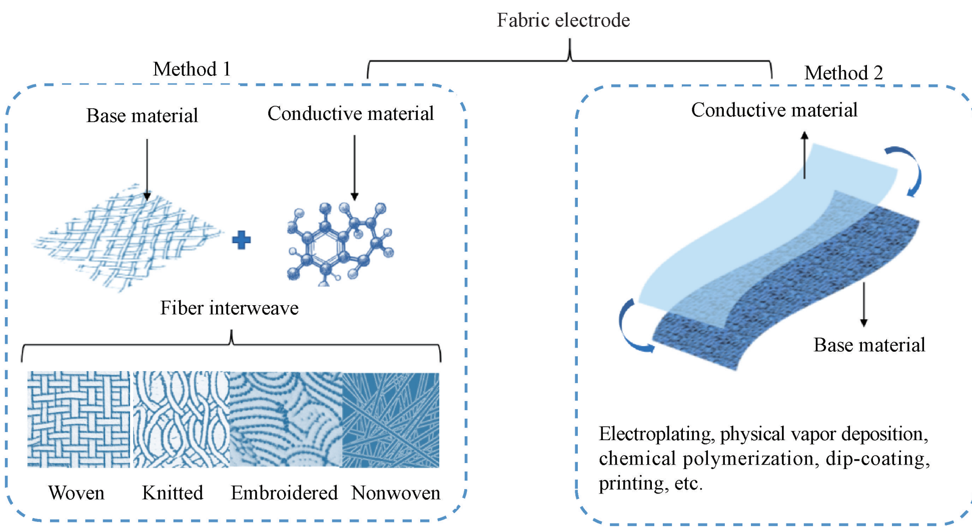


Fig. 1 Combination methods of base materials and conductive materials in fabric electrode

2 Fabric Structure

The fabric structure not only affects the firmness between the conductive material and the base material, but also affects the stability of signal acquisition and the comfort of wearing[12]. According to the interweaving mode, the common textile structures are woven structure, knitted structure, embroidered structure and nonwoven structure (Fig. 1).

2.1 Woven structure

The woven structure refers to the fabric structure formed by the interweaving of warp yarns and weft yarns, which is stable and has good conductive uniformity[21]. Based on different woven structures and parameters, various conductive fabrics can be produced. Figure 2 shows the plain woven and honeycomb woven fabric electrodes used for ECG monitoring reported in Ref. [22].

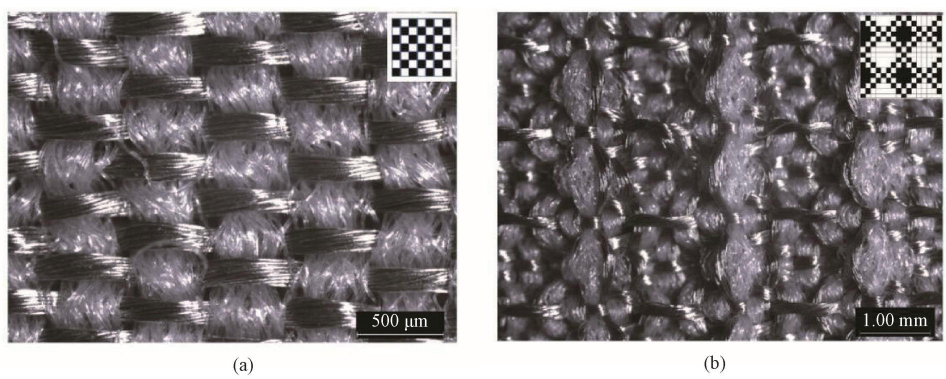


Fig. 2 Woven fabric with conductive weft yarns and non-conductive warp yarns[22]: (a) plain woven; (b) honeycomb woven

Furthermore, the jacquard fabric is also a type of woven structure textile produced by a jacquard loom to control the arrangement of warp yarns and weft yarns, creating intricate patterns and designs. This complexity distinguishes the jacquard fabric from other common woven fabrics in terms of functionality and design. The jacquard structure enables precise pattern design, allowing for specific functional or conductive distribution in the electrode area[23].

2.2 Knitted structure

Knitting refers to the creation of a fabric structure composed of a series of interconnected loops, where each row of loops is formed from a continuous yarn. Each row of loops is connected to the loops above and below it. This results in a connected area of the conductive yarns, allowing current to flow within the yarns as well as between the yarns[18]. Figure 3 shows a physical demonstration of electrodes with a knitted structure[24]. Knitted fabric electrodes are usually produced by using silver-plated yarns as the basic material. They produce large deformation during use and reduce the continuity of conduction, and their dimensional stability is not as good as that of woven fabric electrodes[25]. However, the knitted structure can better adapt to human skin and deform with it, helping to reduce the adverse effects of noise caused by friction between the skin and the electrode[4].

Fig. 3 Knitted fabric electrode[24]

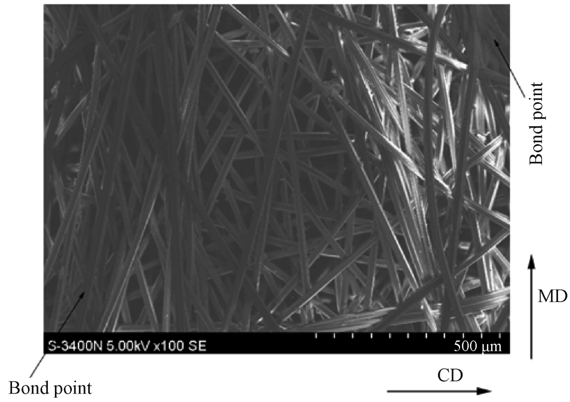
2.3 Embroidered structure

The embroidered fabric electrode refers to the electrode made by embroidering the conductive yarns or threads onto the fabric surface[26]. The design of embroidered structures can be customized according to application needs. The pattern design can range from something as simple as a single conductive thread to something as complex as multiple connection points or sensor networks. For instance, in fabric electrodes, the embroidered structure can be designed in specific shapes for ECG sensors, allowing for precise placement on key areas of the human skin[27]. Logothetis et al.[28] optimized the design of embroidered fabric electrodes for bioelectrical impedance analysis by examining the impact of various embroidery characteristics on electrode performance, demonstrating their potential for integration into wearable health monitoring systems. Figure 4 shows the embroidered fabric electrode with the snap fastener parts reported in Ref. [28].

Fig. 4 Embroidered fabric electrode sample with snap fastener parts[28]

2.4 Nonwoven structure

The nonwoven structure refers to a structure of the fabric made without traditional weaving or knitting techniques. Instead, the fabric is formed by directly bonding fibers together (Fig. 5[29]) through thermal bonding, chemical bonding, mechanical entanglement, etc., so it lacks the distinct warp-weft structure typical of woven fabrics. Nonwoven fabrics exhibit commendable mechanical properties, including the tensile strength and the elongation at break[30]. This structure generally offers good air permeability, moisture absorption and softness, making it widely applicable in medical, filtration and disposable products.



MD—machine direction; CD—cross direction.
Fig. 5 SEM image of a nonwoven fabric[29]

3 ECG Monitoring Signal Quality Analysis

3.1 Effect of fabric electrodes with different materials on ECG signals

In the development of novel electrode materials for ECG signal monitoring, the signal quality is a crucial metric for electrode accuracy and is significantly influenced by both materials and electrical characteristics. Numerous researchers have investigated how various materials impact the quality of ECG signals. Yapici et al.[14] integrated graphene with textiles, creating a graphene-coated conductive fabric electrode. The experimental results demonstrated that the signal from this electrode exhibited a 97% correlation with that of conventional Ag/AgCl electrodes, indicating a high degree of consistency. Zhang et al.[31] polymerized polypyrrole (PPy) in situ on goat skin to create a wearable flexible dry electrode that was biodegradable and breathable. Gauthier et al.[32] mixed multi-arm carbon nanotubes and polyethylene vinyl acetate (PEVA) into a composite material with high viscosity, and then used a syringe to extrude continuous fibers with a radius of 1.6 mm and a length of 3–6 cm. A long composite fiber with a length of 2 cm was selected and fixed on the skin of the subjects with a stretchable viscoelastic cotton strip to measure the ECG performance, and a good ECG signal could be obtained.

3.2 Effect of fabric electrodes with different structures on ECG signals

Many researchers have evaluated ECG signals for different fabric structures, as shown in Table 1.

Table 1 Analysis of ECG signals across varied fabric structures

No.	Author	Fabric structure	Experiment	Result
1	Dong et al. [33]	Woven	Four kinds of fabric electrodes based on silver-plated polyamide and polyester blend interwoven plain and satin structures were studied.	The pure conductive satin fabric had better air permeability and more comfort than the plain fabric, but plain fabric electrodes showed better ECG signal quality at a comfortable wearing pressure (2.5 kPa).
2	Pan et al. [34]	Woven	Fabric electrodes were prepared with silver-coated conductive filaments and polyester filaments as raw materials, and the change of conductivity of fabric electrodes was studied only when the fabric structure was changed.	On the surface, the specific resistance of the plain grain structure fabric electrode was the largest. That of the satin structure and the honeycomb structure fabric electrodes were small and thus had good electrical conductivity.
3	Song et al. [35]	Woven (jacquard technology)	A jacquard fabric electrode was designed, and its quality for ECG signal monitoring was studied. The fabric electrode employed a double-sided woven method, with a layer of silvered yarns woven into the weft direction.	The fabric electrode demonstrated good stability. Under static conditions, it maintained good ECG signal quality even after three consecutive monitoring sessions.
4	Lin et al. [9]	Woven (jacquard technology)	Double-sided fabric electrodes were prepared by interweaving with other fabrics through jacquard technology. Among them, the structural yarn and the warp yarn were made of chemical fiber filaments, the sensing layer and the weft yarn were made of silver-plated yarns, and the double-layer structure was formed in the weft yarn direction.	The ECG signals monitored by this electrode were of good quality, and compared with the traditional Ag/AgCl electrode, its durability, washable property, softness, human biocompatibility and integrability were greatly improved.
5	Catrysse et al. [36]	Knitted	Knitted fabric electrodes were woven to monitor ECG signals in children.	The electrode did not stimulate the skin and was easy to integrate into clothing or bandages. The disadvantage was that the knitted fabric could appear curly and loose, and the skin-electrode impedance was also high.
6	Zhang et al. [37]	Knitted	Two kinds of conductive yarns, namely silver-plated nylon yarns and 2-ply stainless steel fiber yarns, were used as raw materials. The electrode fabric structure was selected as plain weave, 1×1 rib, and 1×2 rib, and four circular electrode sizes were designed, resulting in 24 types of weft-knitted electrodes.	Comparative studies revealed that the factors influencing conductivity were ranked in the order of raw material > structure > size. Additionally, the fabric electrode made from 2-ply stainless steel fiber yarns exhibited a superior transverse conductivity, while the electrode made from silver-plated nylon yarns demonstrated a better longitudinal conductivity.

(Table 1 continued)

No.	Author	Fabric structure	Experiment	Result
7	Liu et al. [38]	Knitted	The composite electrode material supported by graphene/MnO_2 on the knitted fabric was prepared by two-step electrodeposition.	The electrochemical performance of the composite electrode material was obviously better than that of the single MnO_2-loaded electrode material. The specific capacitance was significantly improved, and the effect was best when the electrodeposition lasted for 24 min. Because the electrode material was based on the knitted fabric, it had excellent resistance to bending and folding.
8	Lu et al. [39]	Embroidered	The Ag-AgCl conductive yarn was prepared by electroplating, and the embroidered loop fabric ECG electrode was prepared by the embroidery method.	The brush-like structure formed by the abundant loops on the electrode surface allowed for close contact with the skin, improving skin adherence. This resulted in lower impedance when measuring ECG signals, enabling more accurate ECG signal monitoring.
9	Zhang et al. [40]	Embroidered	The fabrics with different structures were woven using silver-coated yarns, and then their electrical resistance was tested and analyzed at different tensions, as well as after tension was released. These tests were conducted both in a dry state and after complete immersion in a simulated sweat, so as to compare the fabric structures' electrical stability under tension conditions.	The Tatami stitch embroidered fabric displayed similar trends in resistance changes under two different conditions, with only minor variations in resistance values, indicating that its electrical properties were not significantly affected by the tensile force. This made it a suitable candidate for use as a fabric electrode.
10	Hu et al. [41]	Embroidered	The effect of the AgCl content on electrochemistry and ECG signal acquisition of the embroidered fabric electrode was investigated by the electrodeposition method.	The electrochemical performance of the embroidered fabric electrode after 90 s electrodeposition and the practical performance of collecting ECG signals reached the best.
11	Wang et al. [42]	Embroidered	The stitch density was selected from 0.2 mm to 0.6 mm, a total of 20 kinds of circular samples were made, and each sample had two needle patterns. The performance of the computer-embroidered flexible electrode based on conductive stainless steel yarn was tested.	The Tatami stitch embroidered fabric electrode features evenly distributed contact points and thread spacing, which effectively reduced the resistance of the embroidered fabric electrode and significantly lowered the impedance at the interface between the embroidered fabric electrode and the human skin.

In general, the electrical performance of fabric electrodes is significantly influenced by the specific structure and the pattern. For embroidered structures, the distribution of the needle-like yarn contact points and the thread spacing can vary based on the embroidery pattern. When the distribution is uniform, these electrodes can provide more stable resistance variations and lower the impedance at the skin-electrode interface, making them suitable for prolonged ECG monitoring.

The fabric electrodes with woven structures, especially those created with jacquard technology, tend to offer enhanced stability, durability, washability, softness and biocompatibility compared to traditional Ag/AgCl electrodes. This makes them ideal for applications that demand long-term wear and consistent performance under varying conditions.

The fabric electrodes with knitted structures excel in flexibility and bending resistance, which makes them easy to integrate into wearable garments. However, they are prone to curling and loosening, which leads to the increased skin-electrode impedance and the reduced overall effectiveness for precise ECG signal monitoring. The higher impedance and potential structural instability of knitted fabric electrodes make them less ideal for applications where stable skin contact and low impedance are critical.

4 Discussion

4.1 Key considerations for fabric electrode design

The results of this research will guide the designer of the ECG monitoring system to choose the material for the product.

1) The fabric electrode needs to be in close contact with the human skin. This can be achieved not only by increasing the thickness and the volume of the electrode itself but also by utilizing the elasticity of the fabric, which helps to improve the contact level between the fabric electrode and the skin[43].

2) The knitted fabric electrodes exhibit excellent folding ductility, while the jacquard and the embroidered fabric electrodes demonstrate relatively stable resistance, leading to more reliable and higher-quality ECG signal acquisition.

3) The size and the shape of the fabric determine the size of the limited area and the current density of the electrode in contact with the human body during the monitoring process, so the change of the size and the shape will have a great impact on its performance. Furthermore, the washable fastness and the reusability of the fabric electrode are essential, so it is necessary to determine the optimal fabricating parameters and washing conditions for the fabric electrode's reusability through extensive washing tests to ensure the accuracy of signal monitoring. These are the next key research directions of the fabric electrode design field[44-45].

4.2 Challenges and limitations

In recent years, dry fabric electrodes have attracted much attention due to their ease of use, comfort and portability. However, there are some challenges and limitations that need to be addressed before they can be widely adopted in ECG and other electrogram monitoring applications.

1) Despite fabric electrodes offering superior comfort to traditional wet electrodes, eliminating the impact of motion artifacts and mitigating crosstalk and interference from external sources during biological data reception remains challenging.

2) Prolonged monitoring poses challenges for fabric electrodes in sustaining consistent skin contact during subject movement. The poor skin contact compromises signal accuracy. Additionally, the long-term durability of fabric electrodes necessitates further refinement[46].

3) Currently, fabric electrodes lack a standardized evaluation criterion, highlighting the need for specific and uniform assessment and measurement standards tailored to long-term usage and development[47].

4) In the state of exercise, the skin in various parts of the limbs is stretched to different degrees. When the skin is stretched violently, the interface between the fabric electrode and the skin has a complex impedance problem, which affects the detection of the ECG signal. This is a problem that still needs to be solved in the development of fabric electrodes[48-49].

5 Conclusions

The fabric electrode is a critical component in the advancement of wearable ECG monitoring systems due to its superior comfort and ease of integration into everyday garments. This study highlighted the potential of fabric electrodes to replace traditional Ag/AgCl electrodes, especially in long-term monitoring applications where comfort and reusability are essential.

However, challenges remain, including the management of motion artifacts, interference from surrounding devices and ensuring stable signal reception amidst pressure changes at the skin-electrode interface. Furthermore, the lack of standardized evaluation criteria for fabric electrodes presents a barrier to their widespread adoption.

This research has provided valuable insights into the relationship between fabric electrode materials and structures and the quality of ECG signals. Future studies should focus on optimizing electrode design parameters, such as the placement, the size and the fabric properties, to enhance both comfort and signal accuracy. Additionally, long-term usability and washability standards need to be established to ensure the practical application of these electrodes in real-world settings.

In conclusion, fabric electrodes hold significant promise for improving the accuracy and reliability of bioelectrical signal monitoring, making wearable medical devices more user-friendly and cost-effective. Continued research and innovation in this field will be key to realizing their full potential.

References

[1] ROTH G A, MENSAH G A, JOHNSON C O, et al. Global burden of cardiovascular diseases and risk factors, 1990–2019: update from the GBD 2019 study[J]. *Journal of the American College of Cardiology*, 2020, 76(25): 2982-

3021.
[2] NIGUSSE A B, MENGISTIE D A, MALENGIER B, et al. Wearable smart textiles for long-term electrocardiography monitoring: a review[J]. *Sensors*, 2021, 21(12): 4174.
[3] LEE J W, YUN K S. ECG monitoring garment using conductive carbon paste for reduced motion artifacts[J]. *Polymers*, 2017, 9(9): 439.
[4] ZHANG C, WEI D J, CAO H. Research progress on fabric electrode technologies for electrocardiogram signal acquisition[J]. *Journal of Biomedical Engineering*, 2018, 35(5): 811-816. (in Chinese)
[5] SONG J Z, YAN H, GONG G Q, et al. Research progress of textile electrode technologies applied in electrocardiogram signal acquisition [J]. *Transducer and Microsystem Technologies*, 2015, 34(10): 4-7. (in Chinese)
[6] BIN AHMAD M A S, HARUN F K C, WICAKSONO D H B. Hybrid flexible circuit on cotton fabric for wearable electrocardiogram monitoring [C]//2017 International Electronics Symposium on Engineering Technology and Applications (IES-ETA). New York: IEEE, 2017: 217-222.
[7] CAI Z P, LUO K, LIU C Y, et al. Design of a smart ECG garment based on conductive textile electrode and flexible printed circuit board[J]. *Technology and Health Care*, 2017, 25(4): 815-821.
[8] LIU J J. Wearable wireless ECG monitoring system design[D]. Xi'an: Xi'an Polytechnic University, 2016. (in Chinese)
[9] LIN S D, ZHU J J. Wearable ECG monitoring system based on textile electrodes[J]. *Chinese Journal of Sensors and Actuators*, 2017, 30(6): 944-949. (in Chinese)
[10] MOHER D. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement [J]. *Journal of Chinese Integrative Medicine*, 2009, 7(9): 889-896. (in Chinese)
[11] LIN X, ZAKARIA N, RUZNAN W A N. Review on development of pressure injury prevention fabric [J]. *Journal of Donghua University (English Edition)*, 2023, 40(4): 364-369.
[12] LIU Z, LIU X X. Progress on fabric electrodes used in ECG signals monitoring[J]. *Journal of Textile Science and Technology*, 2015, 1(3): 110-117.
[13] GRANCARIĆ A M, JERKOVIĆ I, KONCAR V, et al. Conductive polymers for smart textile applications[J]. *Journal of Industrial Textiles*, 2018, 48(3): 612-642.
[14] YAPICI M K, ALKHIDIR T, SAMAD Y A, et al. Graphene-clad textile electrodes for electrocardiogram monitoring[J]. *Sensors and Actuators B: Chemical*, 2015, 221: 1469-1474.
[15] XU Y X, XIAO Q. Research progress of fabric based composite electrode materials[J]. *Tianjin Textile Science & Technology*, 2023(6): 72-76. (in Chinese)
[16] PALEO A J, STAITI P, ROCHA A M, et al. Lifetime assessment of solid-state hybrid supercapacitors based on cotton fabric electrodes [J]. *Journal of Power Sources*, 2019, 434: 226735.
[17] ARQUILLA K, DEVENDORF L, WEBB A K, et al. Detection of the complete ECG waveform with woven textile electrodes[J]. *Biosensors*, 2021, 11(9): 331.
[18] EULER L, GUO L, PERSSON N K. Textile electrodes: influence of knitting construction and pressure on the contact impedance[J]. *Sensors*, 2021, 21(5): 1578.
[19] WANG T Y, XIAO X L, WANG A, et al. Durability study of embroidery electrode made of stainless steel blended yarn[J]. *Electronics*, 2022, 11(20): 3266.
[20] LEE B M, EOM J J, BAEK G Y, et al. Cellulose non-woven fabric-derived porous carbon films as binder-free electrodes for supercapacitors [J]. *Cellulose*, 2019, 26(7): 4529-4540.
[21] LI H Z. Effect of fabric structure parameters on the electrical conductivity of conducting fabrics [D]. Shanghai: Donghua University, 2014. (in Chinese)
[22] XIAO X L, PIRBHULAL S, DONG K, et al. Performance evaluation of plain weave and honeycomb weave electrodes for human ECG monitoring[J]. *Journal of Sensors*, 2017, 2017: 7539840.
[23] KIM J K, PARK S, CHO H S, et al. Conditions for textile electrode sensors to monitor cardiac activity in daily life[J]. *Journal of Electrical Engineering & Technology*, 2022, 17(5): 3045-3055.
[24] SHAHIDI A M, HUGHES-RILEY T, OLIVEIRA C, et al. An investigation of the physical and electrical properties of knitted electrodes when subjected to multi-axial compression and abrasion [C]//International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles. Basel: MDPI, 2021, 68: 2.
[25] LIU Z, LIU X X. Research progress of myoelectric signal collecting with fabric electrode [J]. *Cotton Textile Technology*, 2017, 45(1): 80-84. (in Chinese)
[26] PANG L N, WANG C H, WANG H Q. Research progress of fabric ECG electrodes[J]. *Technical Textiles*, 2021, 39(5): 1-6. (in Chinese)

[27] KANNAIAN T, NEELAVENI R, THILAGAVATHI G. Design and development of embroidered textile electrodes for continuous measurement of electrocardiogram signals [J]. *Journal of Industrial Textiles*, 2013, 42 (3): 303-318.

[28] LOGOTHETIS I, FERNANDEZ-GARCIA R, TROYNYKOV O, et al. Embroidered electrodes for bioelectrical impedance analysis: impact of surface area and stitch parameters [J]. *Measurement Science and Technology*, 2019, 30 (11): 115103.

[29] GAO X P, WANG L P. Finite element modelling for tensile behaviour of thermally bonded nonwoven fabric [J]. *Autex Research Journal*, 2015, 15(1): 48-53.

[30] XIAO X L, DONG K, HE W T, et al. Research progress of fabric electrodes in wearable electronic clothing [J]. *Wearable Technology*, 2021, 2(2): 27-34.

[31] ZHANG K, KANG N W, ZHANG B, et al. Skin conformal and antibacterial PPy-leather electrode for ECG monitoring [J]. *Advanced Electronic Materials*, 2020, 6(8): 2000259.

[32] GAUTHIER N, ROUDJANE M, FRASIE A, et al. Multimodal electrophysiological signal measurement using a new flexible and conductive polymer fiber-electrode [C]//2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC). New York: IEEE, 2020: 4373-4376.

[33] DONG K, ZHANG L, FAN J X, et al. Action mechanism of wearing pressure on electrocardiogram monitoring of woven fabric electrodes [J]. *Journal of Textile Research*, 2019, 40(9): 75-82. (in Chinese)

[34] PAN D N, MA W W, ZHANG X C, et al. Weave design and performance characterization of conductive fabric [J]. *Journal of Textile Science and Engineering*, 2020, 37 (4): 9-14. (in Chinese)

[35] SONG H Y, LEE J H, KANG D, et al. Textile electrodes of jacquard woven fabrics for biosignal measurement [J]. *Journal of the Textile Institute*, 2010, 101(8): 758-770.

[36] CATRYSSE M, PUERS R, HERTLEER C, et al. Towards the integration of textile sensors in a wireless monitoring suit [J]. *Sensors and Actuators A: Physical*, 2004, 114 (2/3): 302-311.

[37] ZHANG J H, WANG J P. Electric conduction and resistance theory model of circular weft knitted electrodes [J]. *Journal of Textile Research*, 2020, 41(3): 56-61. (in Chinese)

[38] LIU Y J, ZHAI Y Y, ZHAO R, et al. Preparation and properties of knitgoods-based graphene/MnO_2 composite electrode material [J]. *China Dyeing & Finishing*, 2020, 46(12): 8-13, 30. (in Chinese)

[39] LU L B, ZHANG H, XIE G Y. Research progress of the textile-structured flexible ECG electrodes [J]. *Synthetic Fiber in China*, 2015, 44(11): 34-38. (in Chinese)

[40] ZHANG Y T, ZHANG H, XIE G Y. Research on the fabric used for ECG electrode [J]. *Synthetic Fiber in China*, 2016, 45(1): 48-53, 55. (in Chinese)

[41] HU Y. Design and application of flexible textile electrode for bioelectric signal measurement [D]. Tianjin: Tianjin Polytechnic University, 2018. (in Chinese)

[42] WANG T Y, WANG A, CAO S J, et al. Effect of embroidery processing on structure and performance of metal-based textile electrodes [J]. *Chinese Journal of Sensors and Actuators*, 2023, 36(10): 1522-1530. (in Chinese)

[43] RU D Q. Research on fabric electrode based on ECG [D]. Beijing: Beijing Institute of Fashion Technology, 2021. (in Chinese)

[44] MAROZAS V, PETRENAS A, DAUKANTAS S, et al. A comparison of conductive textile-based and silver/silver chloride gel electrodes in exercise electrocardiogram recordings [J]. *Journal of Electrocardiology*, 2011, 44(2): 189-194.

[45] KRASTEVA V T, PAPAZOV S P. Estimation of current density distribution under electrodes for external defibrillation [J]. *Biomedical Engineering Online*, 2002, 1: 7.

[46] CHO S, CHANG T, YU T H, et al. Smart electronic textiles for wearable sensing and display [J]. *Biosensors*, 2022, 12(4): 222.

[47] RUCKDASHEL R R, KHADSE N, PARK J H. Smart e-textiles: overview of components and outlook [J]. *Sensors*, 2022, 22(16): 6055.

[48] VIDHYA C M, MAITHANI Y, SINGH J P. Recent advances and challenges in textile electrodes for wearable biopotential signal monitoring: a comprehensive review [J]. *Biosensors*, 2023, 13(7): 679.

[49] LE K, NARAYANA H, SERVATI A, et al. Electronic textiles for electrocardiogram monitoring: a review on the structure-property and performance evaluation from fiber to fabric [J]. *Textile Research Journal*, 2023, 93(3/4): 878-910.

织物电极在心电监测服装中的发展与应用综述

谢雨彤[1, 2*]，ZAKARIA Norsaadah[1]

1. 泰莱大学 设计学院，雪兰莪州 梳邦再也 47500，马来西亚

2. 闽江学院 服装与艺术工程学院，福建 福州 350108，中国

摘　要：心血管疾病仍然是导致人类死亡的主要疾病，显著影响了健康预期寿命。常规心电图（electrocardiogram，ECG）作为一种重要的无创诊断工具，在识别心律失常方面具有重要作用。该研究重点关注专为长期监测人类 ECG 信号而设计的织物电极的发展动态。依据 PRISMA 声明，基于权威数据库的 81 项相关研究的数据，系统综述和荟萃分析了现有文献中纺织电极的材料、织物结构和制备方法，评估了各种纺织材料和结构的优缺点，阐明了它们对生物监测信号稳定性的影响。此外，该研究概述了当前织物电极发展的限制及未来发展方向。这些见解可为心电监测系统设计者提供指导，帮助他们选择能够优化生物电位信号测量的材料。

关键词：织物电极；心电监测；导电材料；织物结构；荟萃分析