coatings

Article

Fabric Electrode Monitoring of Dynamic and Static ECG Signal and Comfort Performance

Jinli Zhou [1,2,3], Yazhou Zhang [1], Hongying Yang [1,*], Qingxia Liu [1], Ming Wang [4,5], Fan Xiong [1], Dongyi Chen [1] and Lixin Du [3]

1 College of Textile, Zhongyuan University of Technology, Zhengzhou 450007, China
2 College of Chemistry, Chemical Engineering and Materials Science, Soochow University, Suzhou 215021, China
3 Luthai Textile Co., Ltd., Zibo 255100, China
4 Key Laboratory of Science & Technology of Eco-Textile, Donghua University, Shanghai 201620, China
5 College of Chemical and Dyeing-Printing Engineering, Henan University of Engineering, Zhengzhou 450007, China
* Correspondence: 5721@zut.edu.cn; Tel.: +86-371-62506973

Abstract: To monitor dynamic ECG for a long time, fabric electrodes must have excellent comfort and electrical properties. In addition, the quality of the collected ECG should be as free as possible from interference by motion artifacts due to dry skin and body movement. This study explores the comfort of four different materials and structures of silver-plated fabric electrodes, analyzing the acquisition effect of ECG signals under dynamic and static conditions. To obtain fabric electrodes with good comfort levels and stable ECG signal monitoring under dynamic and static conditions, four kinds of electroless silver-plated conductive fabrics were selected and assembled into fabric electrodes. Permeability, electrochemical impedance spectrum, static opening voltage, and dynamic static electrocardiogram were tested and evaluated for each of the four fabric electrodes; additionally, the comfort of the four fabric electrodes and the mass of ECG monitored under dynamic and static conditions were assessed. The results showed that the highly hygroscopic knitted fabric electrode showed better comfort than the other three samples. The electrochemical impedance spectrum curve of the highly hygroscopic knitted fabric electrode was relatively smooth and stable, and it had lower impedance than the other electrodes; moreover, the static open-circuit voltage changed more stably with the increase of processing time compared to the other samples. The four kinds of fabric electrodes all collected clear and stable ECG in the resting state. However, in dynamic conditions, only the highly hygroscopic knitted fabric electrodes collected stable ECG under the conditions of seven daily life actions, clearly distinguishing between the P-wave, QRS wave group, and T-wave. The knitted fabric electrode has a high correlation with the ECG measured by a disposable gel electrode, meeting the standards needed to monitor ECG during the human body's daily activities.

Keywords: fabric electrode; comfort; impedance spectrum; ECG signals

check for updates

Citation: Zhou, J.; Zhang, Y.; Yang, H.; Liu, Q.; Wang, M.; Xiong, F.; Chen, D.; Du, L. Fabric Electrode Monitoring of Dynamic and Static ECG Signal and Comfort Performance. *Coatings* **2023**, *13*, 289. https://doi.org/10.3390/coatings13020289

Academic Editor: Arūnas Ramanavičius

Received: 8 December 2022
Revised: 9 January 2023
Accepted: 16 January 2023
Published: 27 January 2023

1. Introduction

In recent years, even with the improvement of living standards, incidence of cardiovascular disease has increased. More importantly, cardiovascular disease has the characteristics of "long-term, cumulative, and occasional", so it is essential to continuously monitor patient ECG data and make a quick and accurate diagnosis [1–3]. The early prevention and diagnosis of cardiovascular disease can be achieved by monitoring physiological parameters such as ECG, blood pressure, blood oxygen saturation, body temperature, and heart rate. The measurement of ECG is essential. Clinically, the collection of ECG is usually achieved by one-time pasted wet electrode silver/silver chloride (Ag/AgCl). In order to make good contact between the skin and the electrode, a conductive gel needs to be pasted on the skin during the measurement process. The measured ECG has good fidelity and stability, and it has been widely recognized by medical diagnosis. However, in some cases, due to the long-term use of gel-based "wet" electrodes, there have been reports of skin irritation and allergic reactions. In addition, due to the drying of the gel, the electrode performance decreases over time [4,5]. Therefore, researchers have been working to develop gel-free "dry" electrodes, which are more suitable for long-term monitoring applications and can provide the required comfort. Among them, the dry electrode developed based on conductive textiles is ideal for the construction of wearable health-monitoring equipment [6]. Textile structure electrodes are soft and comfortable in texture, can be washed and reused, and are easy to integrate with clothing without making the wearer feel uncomfortable [7–11]. In order to enable the prepared textile structure electrodes to be used for long-term monitoring of ECG signals, different preparation methods have been studied, including screen printing technology [12–14], metal fiber wire weaving [15,16], in situ polymerization to coat conductive polymers to the surface of fibers or fabrics [17], physical vapor deposition metal coating [18], graphene-coated textiles [5,19], and electroless nano-silver plating [20,21]. Zhang et al. polymerized the conductive polymer polypyrrole (PPy) in situ on goat leather and used the obtained conductive leather as a wearable dry electrode to come into contact with human skin and collect electrophysiological signals for daily health monitoring. The results show that due to its own surface structure, the electrode can form conformal contact with the skin and reduce the noise during electrical signal acquisition. In addition, PPy-leather electrodes have good antibacterial properties and are more breathable and comfortable than medical Ag/AgCl gel electrodes [22]. Weder et al. developed a silver/titanium embroidered textile electrode from polyethylene terephthalate yarn, which is plasma-coated with silver for electrical conductivity and with an ultrathin titanium layer on top for passivation. The results showed that the combination of silver, titanium, and water vapor produced excellent electrode chemistry and prolonged monitoring of electrocardiograms both at rest and during exercise [6].

Textile electrodes, which are integrated into clothing and worn on the body, do not cause skin irritation. However, when in use, there is a gap between the electrode and the skin that is susceptible to interference from external noise, resulting in large electrode-skin contact impedance and poor ECG signal stability [23,24]. ECG-monitoring clothing is mostly worn close-fitting, putting electrodes in direct contact with the skin. Most wearable systems introduce additional components distinct from the clothing itself, which can cause discomfort during long-term wear [25]. In the process of dynamic electrocardiogram monitoring, the daily movements of the human body will inevitably produce limb movement, resulting in relative slippage or deformation of the fabric electrodes and, ultimately, the formation of a "motion artifact" effect, affecting the collection of ECG signals [26–29].

To reduce the bodily discomfort and movement artifacts generated by physical activity, it is necessary to select distinct fiber materials and structures to design and prepare fabric electrodes, so as to improve the wearer's comfort and to monitor the dynamic and static ECG signals. This paper uses four conductive fabric electrodes of different materials and structures, prepared under the same electroless silver plating process, to explore both the comfort and electrochemical performance of the four fabric electrodes and the influence of different electrodes on the quality of the collected dynamic and static ECG signals. The goal is to obtain fabric electrodes that are comfortable, effective at monitoring stable and dynamic ECG signals, and attachable to wearable ECG clothing.

2. Materials and Methods

2.1. Materials and Instruments

Materials: insulation shielding cloth, double-sided adhesive conductive foam, space cotton, double-sided hot-melt seamless adhesive, metal concealed buckle; electroless silver-plated conductive fabric (plain cotton conductive fabric, plain polyester conductive fabric, corduroy conductive fabric, high-hygroscopicity conductive knitted fabric).

Instruments: YG461E-III automatic air permeability meter (Ningbo Textile Instrument Factory, Ningbo, China), W3/031 water vapor transmittance tester (Jinan Languang Mechanical and Electrical Technology Co., Ltd., Jinan, China), electrochemical workstation (model: CHI660E, produced in Shanghai Chenhua Co., Ltd., Shanghai, China), BIOPAC MP160 (BIOPAC, Goleta, CA, USA) multichannel (16 channels) physiology recorder (BIOPAC, Goleta, CA, USA).

2.2. Fabric Electrode Design and ECG Belt Assembly

In this experiment, plain cotton fabric, plain polyester fabric, corduroy fabric, and high-hygroscopicity knitted fabric were used as the base materials for the electrode fabric. Four different silver-plated conductive fabrics were prepared using the same electroless silver plating process, and, finally, fabric electrodes of the same structure as shown in Figure 1a below were prepared based on the four conductive fabrics. The fabric electrodes were stitched onto the elastic bandage to prepare four different fabric ECG belts with adjustable pressure, used for ECG monitoring. The main body of the central electrical band is a physiotherapy-grade elastic bandage with a width of 6 cm and a total length of 76 cm. The distance between a pair of electrodes is 10 cm, and the distance between the metal concealed buckles is 7 cm. The structure of the fabric ECG belt is shown in Figure 1b below.

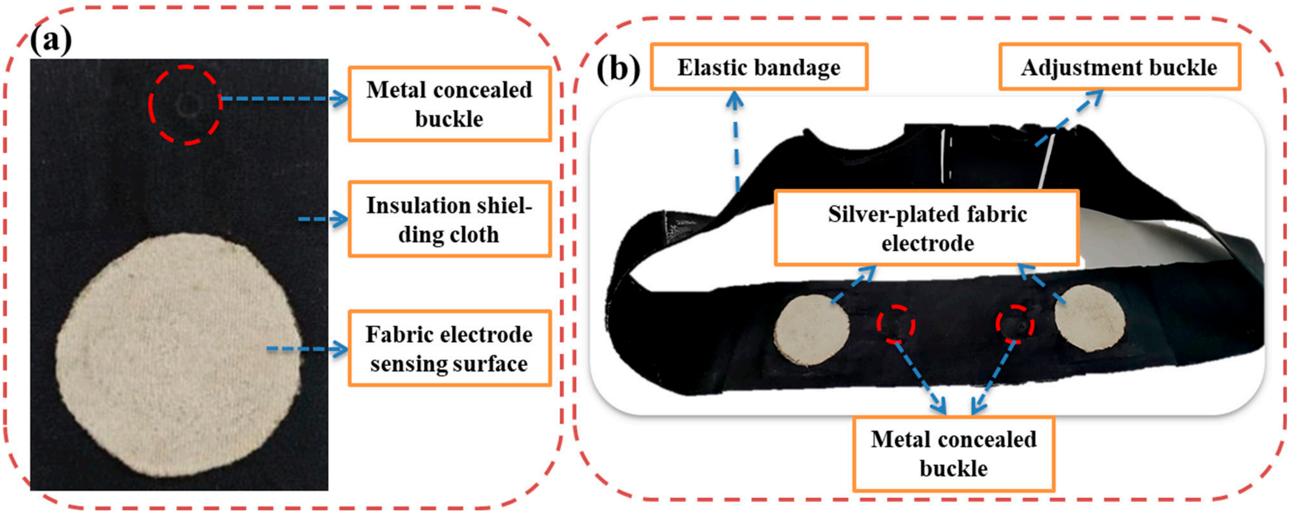

Figure 1. (**a**) Fabric electrode structure diagram. (**b**) Fabric ECG belt structure diagram.

2.3. Fabric Electrode Comfort Performance Test

When fabric electrodes collect ECG signals, they need to be in close contact with the skin for a long time. Therefore, comfort level at the place where the electrode touches the skin is an important factor in a patient's suitability for long-term ECG signal monitoring [28]. This experiment is mainly a comfort test of the fabric conductive sensing layer of the electrode. Four silver-plated conductive fabric sensing layers of different materials were prepared, and the breathable and moisture-permeable properties of the silver-plated conductive fabric were measured by different instruments to objectively evaluate the comfort properties of the conductive sensing material on the electrode substrate of the fabric.

The breathable and moisture-permeable performance of the fabric is an important indicator of the comfort of long-term wear. The thermal, humidity, and air flow transmission performance of the fabric also greatly impact comfort [30]. In this experiment, a YG461E-III automatic air permeability meter was used to measure the air permeability. Before the test, the differential pressure was set to 100 Pa, and the sample area was cut to 20 cm^2. After that, the sample was clamped on the sample round table. The system automatically selects the appropriate nozzle aperture according to the sample specifications, measuring the air flow through the sample. Different parts of each sample were selected, and the test was repeated at least 10 times [31].

When the human body dissipates heat and sweats, moisture permeability plays an important role in maintaining the thermal balance between heat production and heat dissipation; therefore, the fabric's moisture permeability is closely related to clothing comfort [31]. The W3/031 water vapor transmittance tester was used to measure the moisture permeability of the fabric electrode. Before the test, samples with an area of 33.18 cm^2 were first cut and placed on the moisture permeability cup of the fabric water vapor transmittance tester, and then set in a moisture permeability box with a temperature of 38 °C and a relative humidity of 50%. After 1.5 h, the moisture permeability of the fabric was calculated according to the following formula. The process was repeated 3 times for each sample.

$$WVT = \frac{\Delta m}{A \cdot t} \quad (1)$$

In the formula: WVT is the moisture permeability, g/(m^2·24 h); Δm is the weight differential of the moisture permeability cup, g; A is the effective area of the sample, m^2; t is the test time in hours.

2.4. Fabric Electrode Electrochemical Performance Test

Fabric electrode materials have an important impact on the performance of electrocardiogram electrodes. At present, among the materials used in the preparation of fabric electrodes, Ag/AgCl composite architecture electrodes have very low polarization impedance and good physiological compatibility. Both of these qualities can reduce noise and other phenomena in the signal collection process, making the materials popular for electrical signal testing in professional medical centers [32]. Moreover, in addition to being more stable, the Ag/AgCl composite electrode's equilibrium potential is lower than that of silver [32,33]. A large number of researchers have attempted to use silver-plated fabrics for electroplating by forming a silver-plated silver chloride composite system as the fabric ECG electrode to measure ECG electrical signals. In this experiment, after electroless silver plating, four conductive fabric samples were electroplated to form Ag/AgCl composite architecture electrodes. The electrochemical impedance spectra and open-circuit voltages of the four fabric electrodes after electroplating were analyzed and compared.

The device shown in Figure 2 was used to test the electrochemical impedance spectrum and open-circuit voltage of the electrode. It consists of a working electrode, a counter electrode, and a reference electrode to form a three-electrode system. The working electrodes are composed of the four kinds of silver-plated conductive fabrics, platinum electrodes, and the Ag/AgCl reference electrodes made in this experiment. During the test, all three electrode pads were placed in a solution containing a concentration of 0.9% NaCl. The initial voltage and scanning frequency parameters were set to 10 mV and 0.1~10,000 Hz, respectively, the chlorination treatment voltage was set to 1.5 V, and the time elapsed was 30 s.

2.5. Measuring Human ECG Signals

As shown in Figure 3a, the elastic ECG band was bound to a specific position on the surface of the body before the test, and a pair of disposable gel electrodes was affixed below the corresponding position. When the central electrical belt was in use, the position of the fabric electrode was located about 10 cm under the clavicle. A and B shown in Figure 3a correspond to the fixed position of the fabric electrode; C, D, and E correspond to the fixed position of the disposable gel electrode. During the test, the bound fabric electrode and the metal concealed buckle corresponding to the disposable gel electrode were connected to the ECG signal collector (BIONOMADIX, BIOPAC Systems Inc., Goleta, CA, USA), and then wirelessly transmitted to the BIOPAC® MP 160 system with an ECG amplifier module (ECG100C) to collect human ECG signals (Figure 3b).

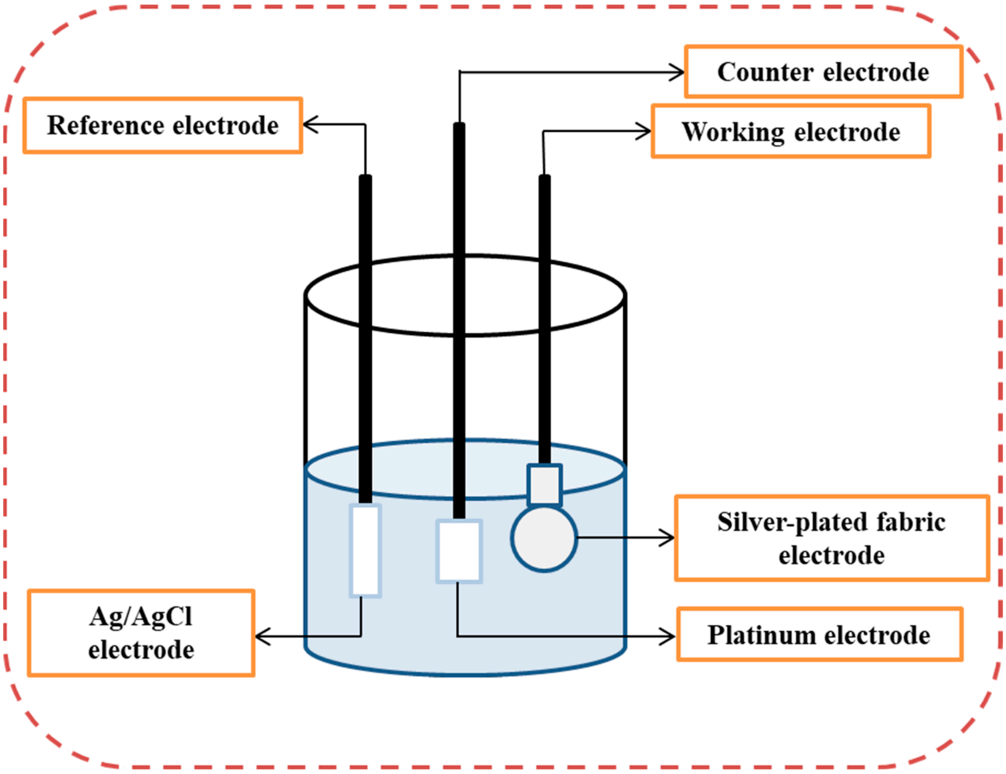

Figure 2. Schematic diagram of electroplating process device.

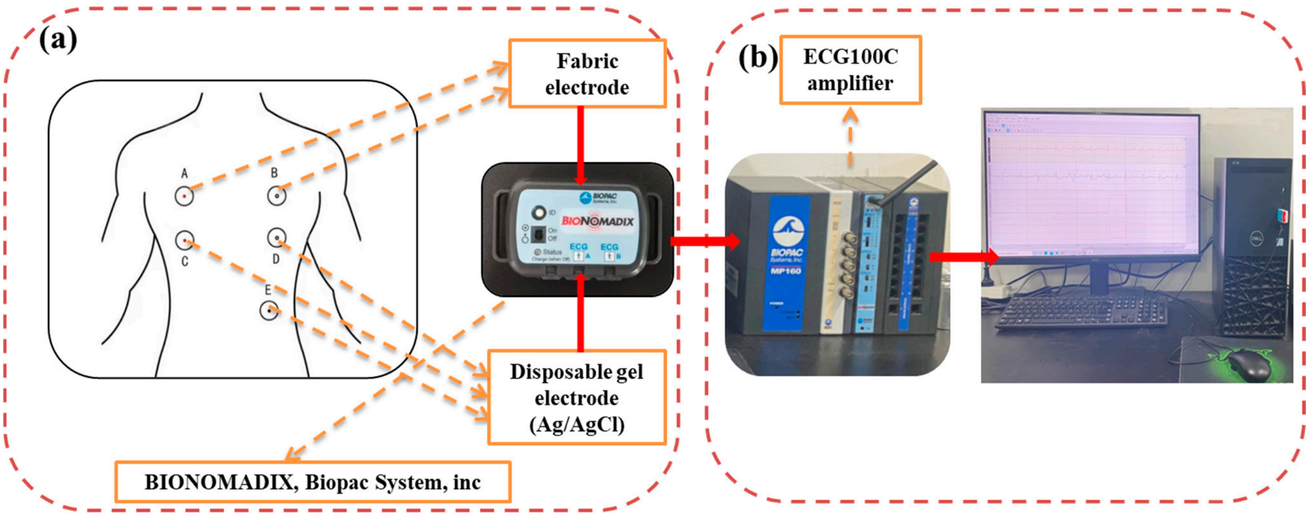

Figure 3. (**a**) Schematic diagram of human ECG test. (**b**) Diagram of ECG collection device.

When measuring ECG under the dynamic conditions of the human body, the body's movement impacts the collected ECG signals. To ensure that the pressure of different ECG belts was consistent under dynamic conditions, the belt's tightness was modified by adjusting the buckle. The electrode was fixed in the central position of the torso during testing of the influence of fabric electrodes of different structures on the measurement of dynamic and static ECG signals. According to the daily exercise activities explored in reference [29], in this experiment, the human body's motion modes were sorted into seven movements: sit down and stand up, sit and bend over, walk in place, stand and bend over, right arm up, twist the waist, and expand the chest. The movements were repeated at a normal daily life speed, each movement for 60 s, resting for 20–30 s between movements. Static ECG was recorded in the first 10 s.

3. Results and Discussion

3.1. Fabric Electrode Comfort Performance

The breathability test results of the original and silver-plated conductive fabrics for each of the four different fabrics are shown in Figure 4. The base fabrics corresponding to 1#, 2#, 3#, and 4# are plain cotton fabrics, plain polyester fabrics, corduroy fabrics, and highly hygroscopic knitted fabrics, respectively. As can be seen from Figure 4, before electroless silver plating, 1# plain cotton fabrics had the best breathability, followed by 4# highly hygroscopic knitted fabrics, and 2# plain polyester fabrics had the worst. The cotton fibers contained in the 1#, 3#, and 4# fabrics are natural fibers, which have good moisture absorption and better breathability than synthetic fibers. The 1# plain cotton fabric is a plain-weave structure, which creates a moderate gap between the yarns, making breathability good. The breathability of the four fabrics decreased after silver plating because the dense silver layer negatively affects breathability. Among the four types of silver-plated conductive fabrics, 4# highly hygroscopic conductive knitted fabrics had the best breathability, followed by 3# corduroy conductive fabrics, and 2# plain polyester conductive fabrics had the worst. The yarn used in the 4# fabric not only contains cotton fiber, but also has high hygroscopicity and high-hygroscopicity fiber material. The hygroscopicity of the yarn is much better than that of cotton fiber; at the same time, its knitted structure causes good breathability even after silver plating. Due to the electroless silverplating process used to form a metallic silver layer on the surface of the fabric, the silver particles are uniformly attached to the surface of the fiber, which makes it difficult for air to pass through the conductive fabric. Compared with Wang et al., the permeability of conductive yarn and textile structure electrodes woven with different fiber materials is relatively poor [26]. However, by comparing the breathability of the four silver-plated conductive fabrics under the same electroless silver plating process, it can be seen that the conductive substrate material of the highly hygroscopic fabric electrode has the best breathability.

The moisture permeability test results for both the original four fabrics and the conductive fabrics after silver plating are shown in Figure 5. Before silver plating, 4# highly hygroscopic knitted fabrics had the best moisture permeability, followed by 3# corduroy fabrics, and 2# plain polyester fabrics had the worst. Because 4# highly hygroscopic knitted fabrics contain cotton fibers and fiber materials with good hygroscopicity, and because of the knitted organizational structure, these fabrics have good moisture permeability. After electroless silver plating, the moisture permeability of the conductive fabric decreased relatively, perhaps because dense silver particles are attached to the surface of the fabric after silver plating, negatively affecting moisture permeability. However, among the four types of silver-plated conductive fabrics, 4# highly hygroscopic conductive knitted fabrics had the best moisture permeability, 1# plain cotton conductive fabrics and 3# corduroy conductive fabrics had little difference in moisture permeability, and 2# plain polyester conductive fabrics had the worst moisture permeability. Because the highly hygroscopic knitted fabrics contain not only cotton fibers but also high hygroscopic fiber material with even better hygroscopicity, the conductive fabrics after silver plating still have good moisture permeability. Both 1# and 3# silver-plated conductive fabrics have cotton fibers, so their moisture permeability is not much different. The polyester fibers in the 2# fabric are synthetic fibers, which have poor moisture absorption, so the moisture permeability of the conductive fabrics after silver plating is poor compared to other conductive fabrics. After electroless silver plating, the moisture permeability of the four conductive fabrics decreased, but due to the influence of fibrous materials and organizational structure, the moisture permeability of the four conductive fabrics was far better than that of Wang et al., in which the woven structure electrodes of different fiber materials and structures were studied [26]. This shows that the conductive fabric electrode prepared by the electroless silver plating process has good moisture permeability. The highly hygroscopic conductive fabric has a new type of highly hygroscopic fiber material, which still has good moisture permeability after silver plating and can be preferably used as the substrate material for the fabric electrode.

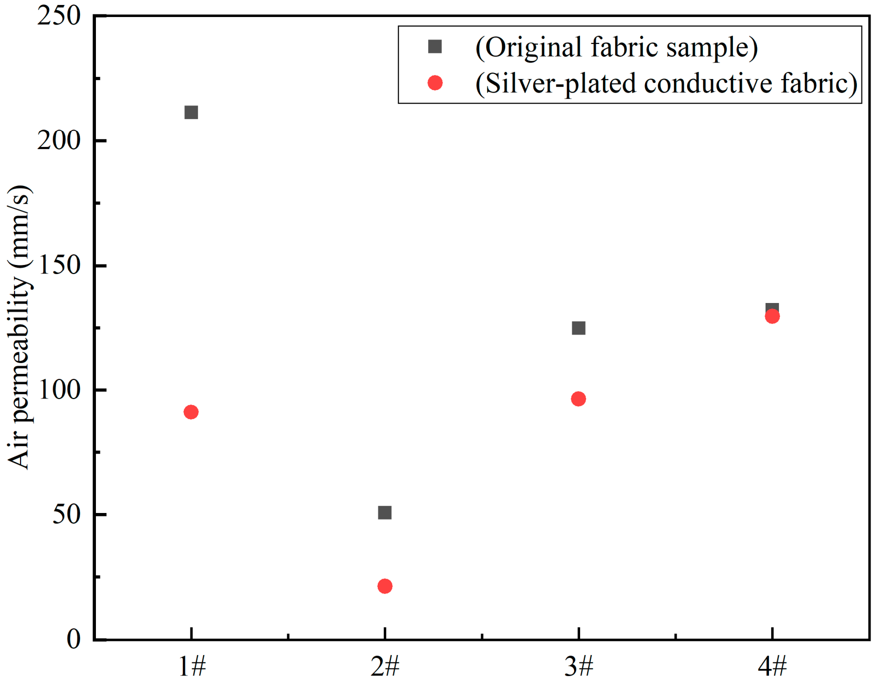

Figure 4. The original state of the four fabrics and the breathability test results of the silver-plated conductive fabrics.

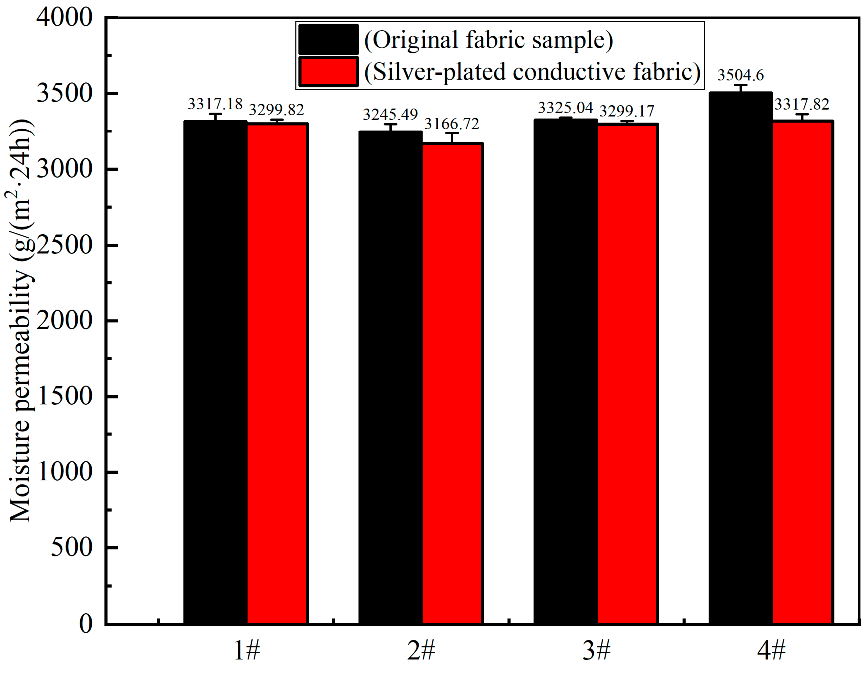

Figure 5. The original state of the four fabrics and the moisture permeability test results of the silver-plated conductive fabric.

3.2. Fabric Electrode Electrochemical Performance

3.2.1. Fabric Electrode Electrochemical Impedance Spectroscopy

The same method was used to measure the electrochemical impedance spectra of the four fabric electrode samples. The scanning frequency range was 0.1 Hz~10,000 Hz. Figure 6 shows the electrochemical impedance spectra of the fabric electrode samples under the same processing time. The electrochemical impedance of all fabric electrode samples decreased with the increase of frequency. For comparative analysis, see Xu et al. [30] and

Zhang et al. [34] The AC impedance spectra of textile structure electrodes of different developed materials show that the four silver-plated fabric electrodes prepared in this paper all exhibited lower AC impedance, which is more conducive to the application of ECG electrodes to collect stable ECG signals. The impedance of plain polyester fabric electrode samples at low frequencies (<0.5 Hz) was much higher than that of the other three samples, indicating that more silver on the surface of the electrode fiber was converted into silver chloride. Because the conductivity of silver chloride is much lower than that of silver, the impedance of the silver–silver chloride complex formed on the surface of the fabric electrode rises. On the other hand, the high-hygroscopicity knitted fabric electrode sample had lower impedance than the other samples at both high and low frequencies, and the impedance spectrum change curve was relatively stable, indicating that the silver chloride formed on the surface of the fabric electrode was more uniform. Additionally, the polarization impedance of the silver–silver chloride complex was lower, which is more conducive to the collection of stable ECG signals.

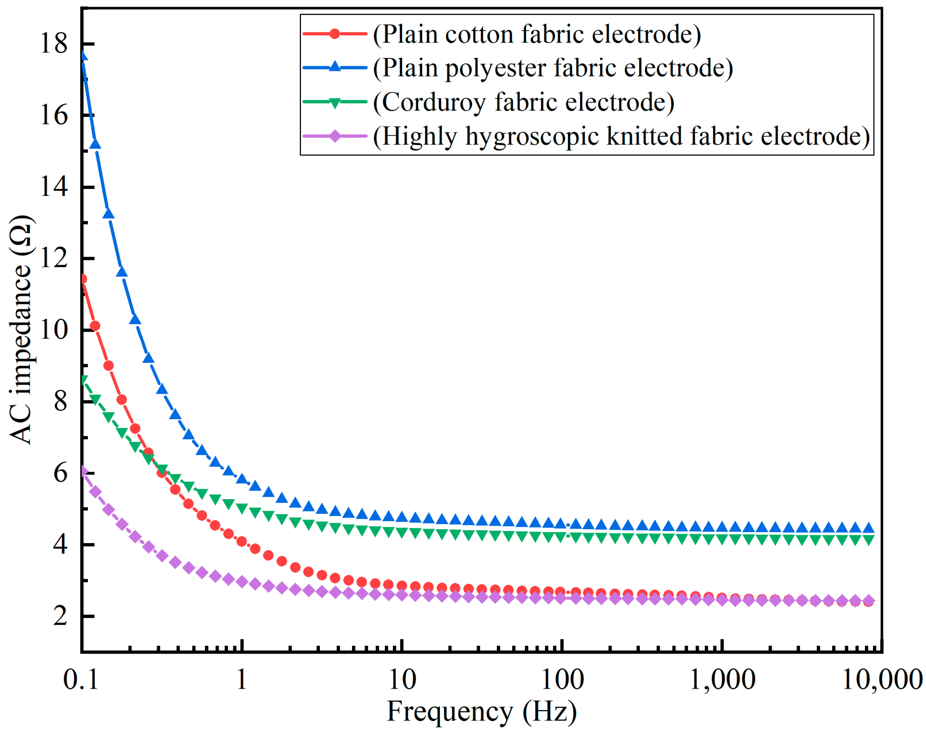

Figure 6. Electrochemical impedance spectra of four fabric electrodes.

3.2.2. Fabric Electrode Static Open-Circuit Voltage

The open-circuit voltage (OCP) of the primary battery, composed of a pair of electrodes and an electrolyte solution, can also be used to evaluate the electrochemical properties of electrodes [16]. Because the OCP is closely related to the motion artifacts generated by biological electrical signals, many researchers evaluate the electrical properties of dry electrodes by testing the OCP of the electrode–electrolyte interface. Figure 7 shows that the static open-circuit voltage (SOCP) of the four fabric electrodes under different plating treatment times was less than 100 mV. This finding demonstrates the importance of considering the variation amplitude and stability of the SOCP curve over time when evaluating the properties of fabric electrodes. With the increase in processing time, the open-circuit voltage of the plain-weave polyester fabric electrode first increased, then stabilized, but the amplitude of change was large and unstable. While the plain-weave cotton fabric electrode was slightly more stable than the polyester fabric electrode, the corduroy fabric electrode and the highly hygroscopic knitted fabric electrode had low amplitude of change and high stability. Compared with the open-circuit voltage of the textile electrodes with different structures studied by Xu et al. [30] and Zhang et al. [34], it can be seen that the open-circuit voltage fluctuation of the corduroy fabric electrode and the high-hygroscopic fabric electrode is relatively smaller and more stable. Therefore, after electrochemical deposition treatment, the electrochemical stability of corduroy fabric electrodes and highly hygroscopic knitted fabric electrodes is relatively high.

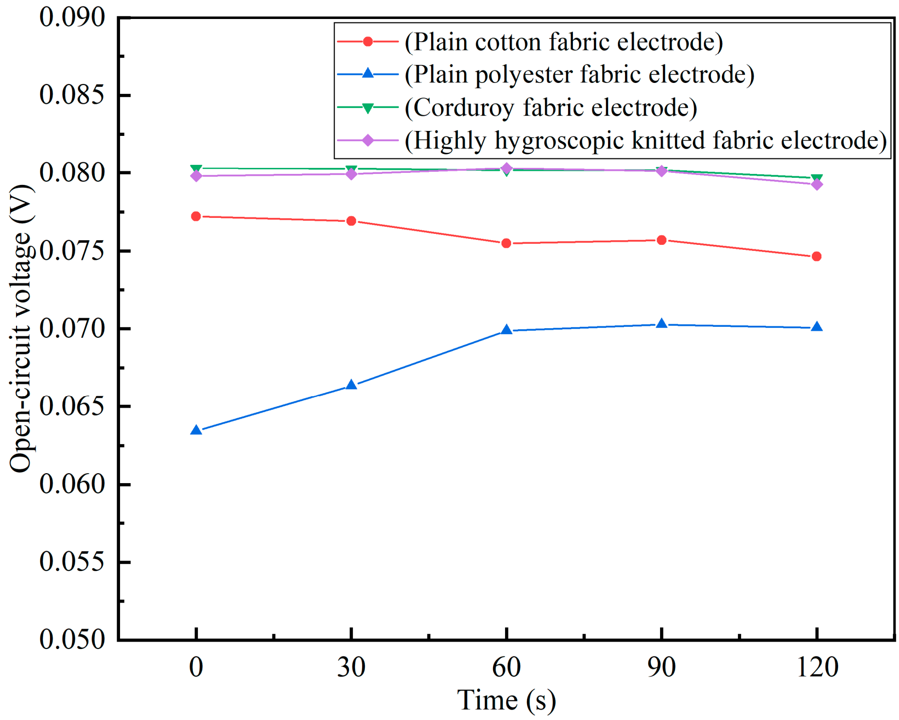

Figure 7. Static open-circuit voltage of four fabric electrodes.

3.3. ECG Static and Dynamic Analysis on Humans

Notably, fabric electrodes can both be integrated into clothing and monitor a routine dynamic electrocardiogram [9]. However, since the fabric electrode is in direct contact with the skin when used, no conductive gel is required; thus, under dynamic conditions, the electrode and the skin interact, causing motion artifacts. Figures 8–11 show ECG in different activity states, monitored by disposable gel electrodes and four fabric electrodes. The green waveform diagram represents the electrocardiogram measured by the disposable gel electrode, whereas the red represents the electrocardiogram measured by the fabric electrode. Table 1 shows the correlation coefficient between the disposable gel electrode and the ECG pattern corresponding to the four fabric electrodes.

Table 1. The correlation coefficient between the ECG pattern corresponding to the four fabric electrodes and the disposable gel electrode.

Electrode / State	Static State	Sit and Bend Over	Sit Down and Stand Up	Walk in Place	Stand and Bend Over	Right Arm Up	Twist the Waist	Expand the Chest
Cotton Fabric Electrode	0.481	0.256	0.330	0.209	0.278	0	0	−0.774
Polyester Fabric Electrode	0.890	0.690	0.594	0.488	0.556	0	0.453	0
Corduroy Fabric Electrode	0.916	0.583	0.673	0.481	0.468	0	0.326	0
Highly Hygroscopic Knitted Fabric Electrode	0.943	0.926	0.840	0.781	0.888	0605	0.713	0.703

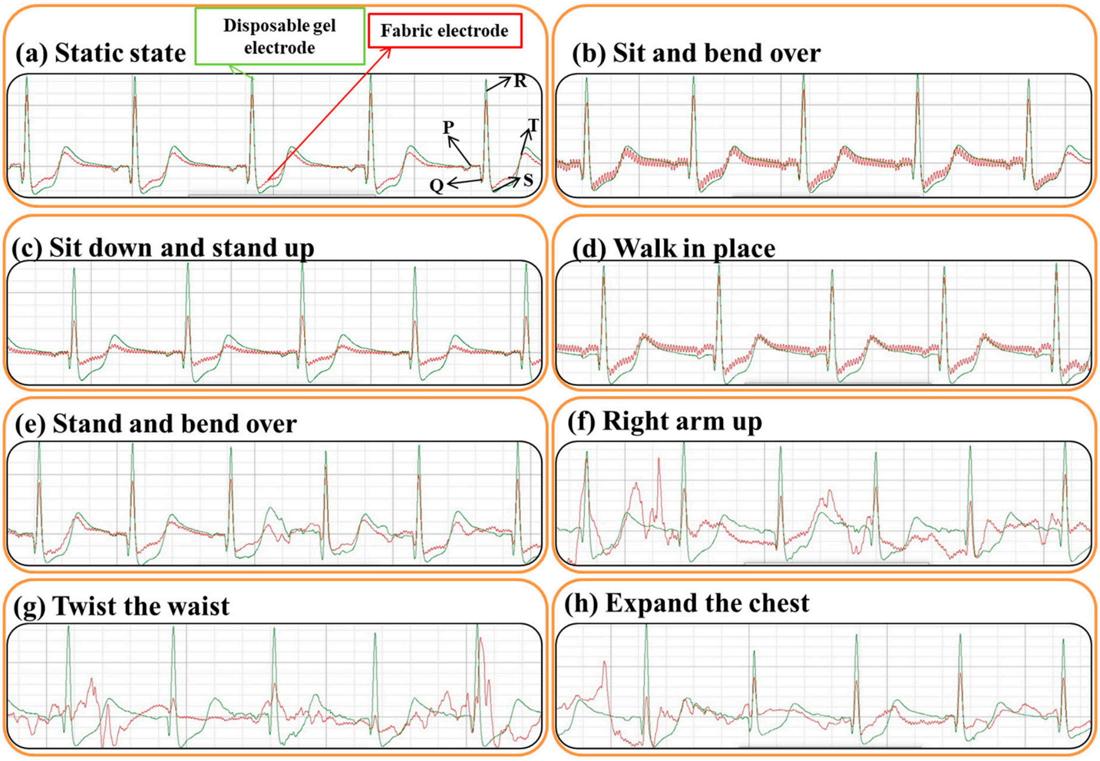

Figure 8. Cotton fabric electrodes and disposable gel electrodes monitor ECG in different states of the human body.

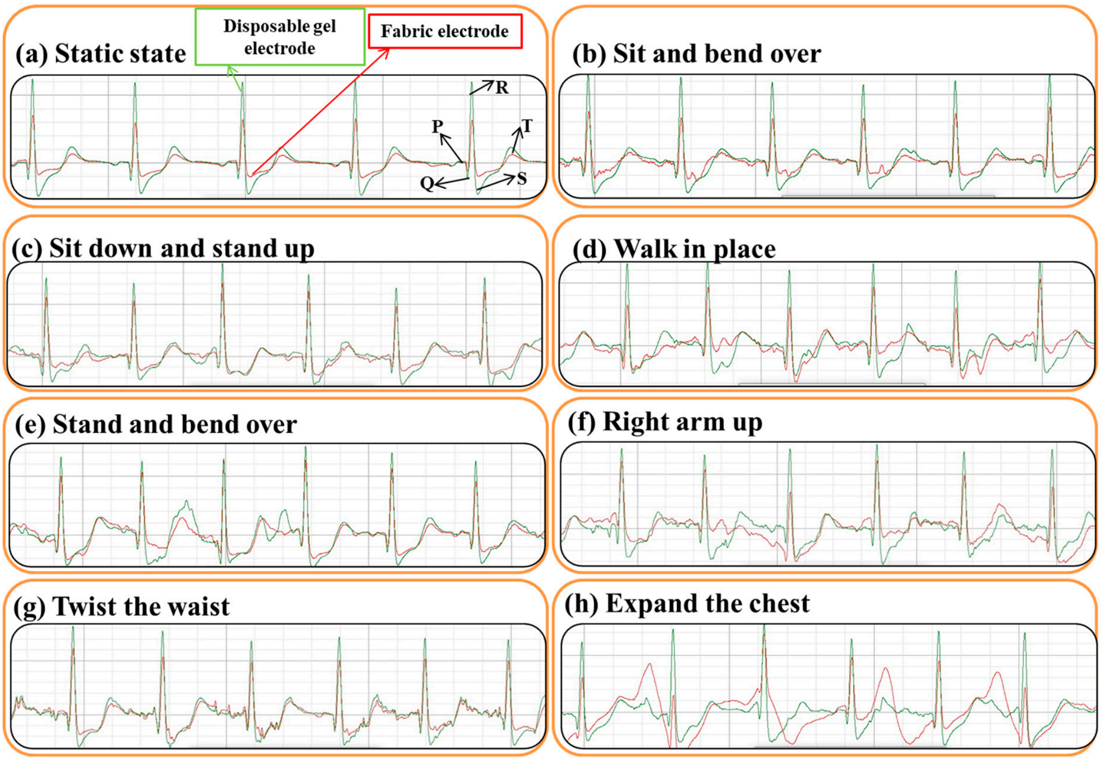

Figure 9. Polyester fabric electrodes and disposable gel electrodes monitor ECG in different states of the human body.

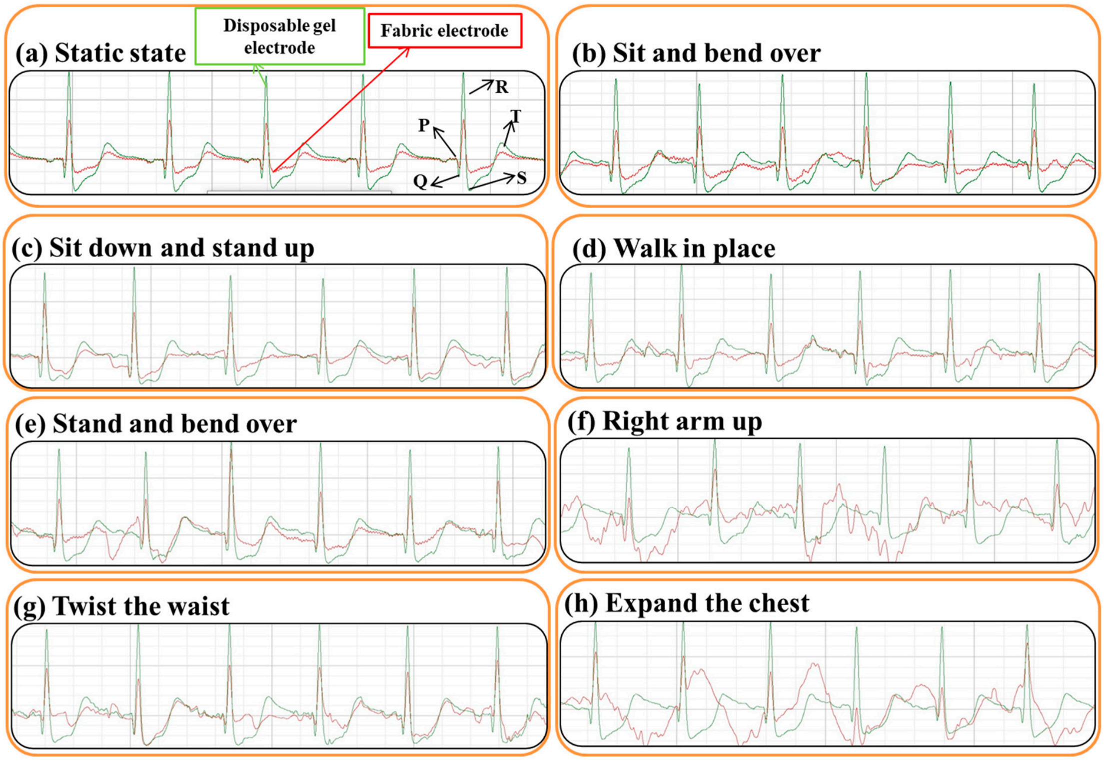

Figure 10. Corduroy fabric electrodes and disposable gel electrodes monitor ECG in different states of the human body.

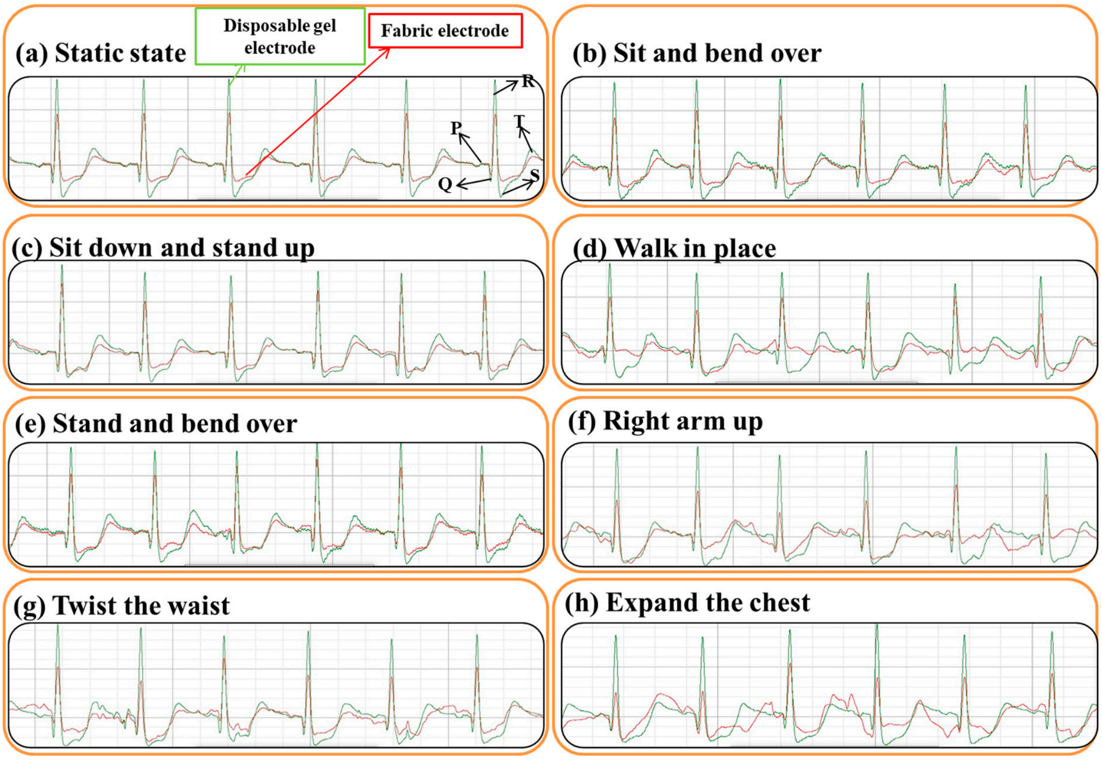

Figure 11. Highly hygroscopic knitted fabric electrodes and disposable gel electrodes monitor ECG in different states of the human body.

The correlation coefficients between Figures 8–11 and Table 1 show that the electrocardiogram measured by the four fabric electrodes under static conditions was precise.

The QRS complex of the electrocardiogram can be clearly identified (Figure 8a, Figure 9a, Figure 10a, Figure 11a). The correlation coefficients of polyester fabric electrodes, corduroy fabric electrodes, and highly hygroscopic knitted fabric electrodes are all above 0.89, which is very close to the ECG pattern of disposable gel electrodes. On the other hand, the correlation coefficient of cotton fabric electrodes is small because of the cotton fabric electrode's plain-weave structure. After electroless silver plating, the electrode surface is relatively dry and has poor adhesion to the skin, making it susceptible to noise interference.

When the four fabric electrodes collect dynamic ECG, the shape can be distinguished by the ECG collected while sitting up, sitting and bending over, walking in place, and standing and bending over. However, the ECG collected by the cotton fabric electrode has distinct noise interference and baseline drift, and its correlation with the disposable gel electrode is low. Moreover, the ECG collected by the cotton fabric electrode through the three movements of right arm upward, waist twisting, and chest expansion was subject to greater noise interference (Figure 8g,h), resulting in a long baseline drift, making it almost impossible to distinguish the characteristic waveform of the ECG; this issue also caused the disposable gel electrode to show 0, and the chest expansion exercise to show a negative correlation (Figure 8f). Similarly, the ECG collected by the polyester fabric electrode (Figure 9f,h) and corduroy fabric electrode (Figure 10f,h) under the right arm up and chest expansion movement also had obvious high-frequency noise interference, and the ECG characteristic waveform could hardly be distinguished. The slippage between the electrode and the skin during these two movements reduced the effective contact area between the fabric electrode and the skin, making the collection susceptible to external noise and other signals and causing the ECG to drift from baseline. The highly hygroscopic knitted fabric electrode can collect a clear electrocardiogram during all seven movements and can identify the P-wave, T-wave, and QRS wave groups (Figure 11). Compared with electrocardiogram collected by the disposable gel electrode, it had higher similarity, and the correlation coefficient is >0.6; this result appeared most distinctly during the three actions of right arm up, waist twisting, and chest expansion (Figure 11f–h). The characteristic waves of ECG can still be clearly distinguished despite slight baseline drift. In the process of electroless silver plating, the surface of the fabric has a more uniform and thicker silver layer so that the conductive sensing area can better fit the surface of the skin; thus, the interface state between fabric electrode and skin is stable, the relative slippage between electrode and skin is small, and the quality of the collected ECG signal is relatively high. The highly hygroscopic knitted fabric electrode can effectively monitor the ECG signal under both static conditions and daily life movements, and, to a certain extent, it can be applied to wearable ECG clothing to achieve real-time monitoring of human body ECG dynamics.

4. Conclusions

In this paper, four kinds of electroless silver-plated conductive fabrics, space cotton, double-sided adhesive conductive foam, and other materials were selected to assemble fabric electrodes. The fabric electrodes were then integrated into a physiotherapy-grade elastic bandage to prepare a fabric ECG belt. The comfort and electrochemical properties of fabric electrodes and the dynamic and static ECG measured by fabric electrodes and disposable gel electrodes were tested and analyzed. The performance of the four kinds of fabric electrodes and the quality of ECG signals monitored under dynamic and static conditions were assessed. The results show that among the four fabric electrodes prepared by the same electroless silver plating process, the high-hygroscopicity knitted fabric electrodes were better than the other three fabric electrodes in terms of breathability and moisture permeability; additionally, the high-hygroscopicity conductive knitted fabrics showed better comfort among the four fabrics. The electrochemical impedance spectrum curve of the highly hygroscopic knitted fabric electrode was relatively smooth and stable. Compared with other electrodes, this fabric had lower impedance, and the static open-circuit voltage changed more stably with the increase in processing time, making it better suited for application to ECG electrodes and collection of ECG signals. The four kinds of fabric electrodes collected clear and stable ECG when measuring the static ECG of the human body; however, when monitoring dynamic ECG, only the highly hygroscopic knitted fabric electrodes collected stable ECG under the seven daily life actions. The P-wave, QRS wave group, and T-wave were clearly distinguished, and the correlation with disposable gel electrodes was very high, meeting the standards needed to monitor ECG during daily activities. Importantly, it is necessary to study the influence of wearing pressure on comfort and dynamic ECG signals so that the fabric electrodes not only can intercept a quality ECG signal, but also are comfortable for the wearer.

Author Contributions: Literature research and discussion, Y.Z., H.Y. and J.Z.; Writing—original draft, J.Z. and Y.Z.; methodology, J.Z., Y.Z. and Q.L.; Data curation, Y.Z. and Q.L.; Writing—review & editing, Y.Z. and J.Z.; supervision, L.D., F.X., H.Y. and D.C.; project administration and funding acquisition, M.W., L.D., F.X. and D.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (2016YFB1001401), Key Laboratory of Science & Technology of Eco-Textile, Ministry of Education, Donghua University (2232021G-04), Scientific and Technological Project in Henan Province (No. 212102210550), the Science and Technology Guidance Project of China National Textile and Apparel Council (2020060), Zhongyuan University of Technology Subject Development Program for Young Master's Supervisor (No. SD202216), Zhongyuan University of Technology Advantageous Subjects Strength Improvement Plan, the Advanced Textile Equipment Technology Provincial and Ministerial Co-construction Collaborative Innovation Center, the Key Laboratory of Functional Textiles of Henan Province.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Domanski, M.J.; Fuster, V.; Diaz-Mitoma, F.; Grundy, S.; Lloyd-Jones, D.; Mamdani, M.; Roberts, R.; Thorpe, K.; Hall, J.; Udell, J.A.; et al. Next Steps in Primary Prevention of Coronary Heart Disease Rationale for and Design of the ECAD Trial. *J. Am. Coll. Cardiol.* **2015**, *66*, 1828–1836. [CrossRef] [PubMed]
2. Yan, N.N.; Zhang, H.; Deng, Y.M. Research status and development trend of wearable medical monitoring clothing. *J. Text.* **2015**, *36*, 162–168.
3. Lu, L.B.; Zhang, H.; Xie, G.Y. Research progress on flexible ECG electrodes with textile structure. *Synth. Fiber* **2015**, *44*, 34–38.
4. Marozas, V.; Petrenas, A.; Daukantas, S.; Lukosevicius, A. A comparison of conductive textile-based and silver/silver chloride gel electrodes in exercise electrocardiogram recordings. *J. Electrocardiol.* **2011**, *44*, 189–194. [CrossRef] [PubMed]
5. Murat, Y.; Tamador, A. Intelligent Medical Garments with Graphene-Functionalized Smart-Cloth ECG Sensors. *Sensors* **2017**, *17*, 875.
6. Weder, M.; Hegemann, D.; Amberg, M.; Hess, M.; Boesel, L.; Abächerli, R.; Meyer, V.; Rossi, R. Embroidered Electrode with Silver/Titanium Coating for Long-Term ECG Monitoring. *Sensors* **2015**, *15*, 1750–1759. [CrossRef] [PubMed]
7. Fernandes, M.S.; Lee, K.S.; Ram, R.J.; Correia, J.H.; Mendes, P.M. Flexible PDMS-based dry electrodes for electro-optic acquisition of ECG signals in wearable devices. In Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Buenos Aires, Argentina, 31 August–4 September 2010; Volume 20, pp. 3503–3506.
8. Yi, M. NTT invented "intelligent" textile materials. *Woolen Technol.* **2013**, *41*, 1–4.
9. Lou, C.; Li, R.; Li, Z.; Liang, T.; Wei, Z.; Run, M.; Yan, X.; Liu, X. Flexible graphene electrodes for prolonged dynamic ECG monitoring. *Sensors* **2016**, *16*, 1833. [CrossRef] [PubMed]
10. Ding, X. Design of Non-Contact Sleep ECG Measurement System Based on Conductive Fabric. Master's Thesis, University of Electronic Science and Technology, Chengdu, China, 2009.
11. Zhai, H.Y.; Wang, C.M.; Zhang, J.; Yin, J.; Qiao, L. ECG monitoring system based on fabric electrode. *J. Jilin Univ. Inf. Sci. Ed.* **2012**, *30*, 944–949.
12. Paul, G.; Torah, R.; Beeby, S.; Tudor, J. The development of screen printed conductive networks on textiles for biopotential monitoring applications. *Sens. Actuators A Phys.* **2014**, *206*, 35–41. [CrossRef]
13. Bu, Y.; Hassan, M.; Lai, D. The embedding of flexible conductive silver-coated electrodes into ecg monitoring garment for minimizing motion artefacts. *IEEE Sens. J.* **2020**, *21*, 14454–14465. [CrossRef]

14. Achilli, A.; Bonfiglio, A.; Pani, D. Design and characterisation of screen-printed textile electrodes for ECG monitoring. *IEEE Sens. J.* **2018**, *18*, 4097–4107. [CrossRef]
15. Stoppa, M.; Chiolerio, A. Wearable electronics and smart textiles: A critical review. *Sensors* **2014**, *14*, 11957–11992. [CrossRef] [PubMed]
16. Taji, B.; Shirmohammadi, S.; Groza, V.; Batkin, I. Impact of Skin–Electrode Interface on Electrocardiogram Measurements Using Conductive Textile Electrodes. *IEEE Trans. Instrum. Meas.* **2014**, *63*, 1412–1422. [CrossRef]
17. Zhou, Y.; Ding, X.; Zhang, J.W.; Duan, Y.R.; Hu, J.Y.; Yang, X.D. Fabrication of Conductive Fabric as Textile Electrode for ECG Monitoring. *Fibers Polym.* **2014**, *15*, 2260–2264. [CrossRef]
18. Silva, N.L.; Gonçalves, L.M.; Carvalho, H. Deposition of conductive materials on textile and polymeric flexible substrates. *J. Mater. Sci. Mater. Electron.* **2012**, *24*, 635–643. [CrossRef]
19. Yapici, M.K.; Alkhidir, T.; Samad, Y.A.; Liao, K. Graphene-clad textile electrodes for electrocardiogram monitoring. *Sens. Actuators B Chem.* **2015**, *221*, 1469–1474. [CrossRef]
20. Qin, H.; Li, J.; He, B.; Sun, J.; Li, L.; Qian, L. Novel wearable electrodes based on conductive chitosan fabrics and their application in smart garments. *Materials* **2018**, *11*, 370. [CrossRef]
21. Wang, L.; Pan, Y.L.; He, D.D.; Qian, L.Y.; Cao, X.H.; He, B.H.; Li, J.R. Conductive Polyester Fabrics with High Washa-bility as Electrocardiogram Textile Electrodes. *ACS Appl. Polym. Mater.* **2022**, *4*, 1440–1447. [CrossRef]
22. Zhang, K.; Kang, N.W.; Zhang, B.; Xie, R.J.; Zhu, J.Y.; Zou, B.H.; Liu, Y.H.; Chen, Y.Y.; Shi, W.; Zhang, W.N.; et al. Skin Conformal and Antibacterial PPy-Leather Electrode for ECG Monitoring. *Adv. Electron. Mater.* **2020**, *6*, 2000259. [CrossRef]
23. Coosemans, J.; Hermans, B.; Puers, R. Integrating wireless ECG monitoring in textiles. *Sens. Actuators A Phys.* **2006**, *130*, 48–53. [CrossRef]
24. Zhen, L.; Liu, X. Progress on Fabric Electrodes Used in Biological Signal Acquisition. *J. Miner. Mater. Charact. Eng.* **2015**, *3*, 204–214.
25. Yan, N.N. Research on Wearable Performance of ECG Monitoring Clothing. Master's Thesis, Xi'an Engineering University, Xi'an, China, 2015.
26. Wang, X.L.; Liang, H.; Shen, L.P.; Zhang, H. Study on the comfort of Wearable Flexible ECG electrode Fabric. *Synth. Fiber* **2016**, *45*, 32–35.
27. Paul, G.; Torah, R.; Beeby, S.; Tudor, J. Novel active electrodes for ECG monitoring on woven textiles fabricated by screen and stencil printing. *Sens. Actuators A Phys.* **2015**, *221*, 60–66. [CrossRef]
28. Xiong, F. Research on the Mechanism and Suppression Algorithm of "Motion Artifacts" Based on Fabric ECG Induction. Master's Thesis, University of Electronic Science and Technology, Chengdu, China, 2019.
29. Dong, K.; Zhang, L.; Fan, J.X.; Li, M.J.; Mei, L.; Xiao, X.L. Analysis of the mechanism of ECG signal monitoring and wearable pressure by fabric electrodes. *J. Text.* **2019**, *40*, 75–82.
30. Xu, P.J. Analysis of the Mechanical Action between the Textile Structure Electrode and the Skin Used for Surface ECG Monitoring and Dynamic Noise Research. Master's Thesis, Donghua University, Shanghai, China, 2012.
31. Yu, W.D.; Chu, C.Y. *Textile Physics*; Donghua University Press: Shanghai, China, 2003; pp. 74–75.
32. Kang, X.P. Effect of Finishing Method on Comfortable Properties of Cotton Fabric. Master's Thesis, Zhongyuan University of Technology, Zhengzhou, China, 2021.
33. Xu, P.J.; Zhang, H.; Tao, X.M. Textile-structured electrodes for electrocardiogram. *Text. Prog.* **2008**, *40*, 183–213. [CrossRef]
34. Zhang, M.; Guo, N.; Gao, Q.; Li, H.; Wang, Z. Design, Characterization, and Performance of Woven Fabric Electrodes for Electrocardiogram Signal Monitoring. *Sensors* **2022**, *22*, 5472. [CrossRef] [PubMed]