engineering proceedings

Proceeding Paper

Development and Evaluation of a Wearable ECG Monitoring System †

Abreha Bayrau Nigusse *, Benny Malengier and Lieva Van Langenhove

Department of Materials, Textiles and Chemical Engineering, Ghent University, 9000 Gent, Belgium; benny.malengier@ugent.be (B.M.); lieva.vanlangenhove@ugent.be (L.V.L.)

* Correspondence: abrehabayrau.bayraunigusse@ugent.be; Tel.: +32-467-68-8045

† Presented at the 5th International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles, Ghent, Belgium, 14–16 November 2023.

Abstract: A wearable ECG monitoring system was developed by integrating embroidered electrodes, and the collected ECG waveforms were comparable to those obtained using gelled Ag/AgCl electrodes. The R-peak amplitude was 2.09 mV with a 42.9 dB SNR for signals acquired using embroidered electrodes. The ECG signal quality was observed to improve with an increase in electrode size and holding pressure. ECG signals were recorded while the subject was in a walking condition, resulting in detectable waveforms with no missing R-peak and a 30.13 dB SNR which were comparable to signals acquired using standard gelled electrodes under the same conditions. Overall, these results are promising for developing an applicable wearable ECG monitoring system.

Keywords: ECG; ECG electrodes; textile electrodes; wearable ECG monitoring

Citation: Nigusse, A.B.; Malengier, B.; Van Langenhove, L. Development and Evaluation of a Wearable ECG Monitoring System. *Eng. Proc.* **2023**, *52*, 9. https://doi.org/10.3390/engproc2023052009

Academic Editors: Paula Veske-Lepp, Frederick Bossuyt, Steve Beeby, Kai Yang and Russel Torah

Published: 15 January 2024

1. Introduction

Portable biosignal monitoring devices allow individuals to record their health status in their homes without going to a hospital [1,2]. However, most of these technologies require trained experts for implementation, and cumbersome wires make them inconvenient for long-term use [3,4]. To overcome this problem, several wearable physiological monitoring systems have been developed over the past two decades to continuously monitor patients' health status (e.g., heart performance) while they are outside the hospital in their environment. Wearable sensing systems aid the daily acquisition and processing of multiparametric health data, providing early detection of physiological activities and other health indicators without intervening in the patient's daily life. Wearable ECG monitoring devices can be used as an affordable substitute solution for health monitoring. They can reduce the cost of medical services in hospitals as people can perform ECG measurements in their homes without the presence of medical staff, in addition to promoting and improving the quality of life for people with disabilities and chronic illnesses, as well as for aged persons [5].

Wearable health monitoring products may comprise various types of sensors that can be integrated into watches, wristbands, belts, different garments, and textiles or directly into the skin [6–8]. Textile-based wearable sensors have been gaining strong interest as they are suitable for long-term and large-scale monitoring. Textile electrodes and cables are among the most common applications of wearable sensors, offering advantages because they can be integrated unobtrusively into clothing, are comfortable to wear, and can be used in long-term measurements. The integration of textile-based sensors and interconnection tracks into textile clothing can be carried out at different stages [9,10].

In this study, embroidered textile electrodes were developed, and a wearable ECG monitoring system was created by integrating textile ECG electrodes into a commercially available shoulder strap (position corrector). The effects of electrode size, holding pressure (tightness of the shoulder strap), electrode position, and electrode structure on the ECG detection performance of the electrodes were studied, and the results were compared with signals collected using gelled silver/silver chloride (Ag/AgCl) electrodes.

2. Materials and Methods

2.1. Materials and Electrode Development

A fully silver-plated polyamide thread (Madeira HC-40) was used as the embroidery yarn, and a gray woven fabric with a yarn density of 37 ends/cm and 17 picks/cm was used as the base material to develop embroidered textile electrodes. Gray woven fabric was selected as a base material for embroidery to minimize the shirking effect and damage to the fabric during machine embroidery. The electrodes were designed using Ink/Stitch software (v3.0.1), an embroidery plugin for the vector drawing program Inkscape, and created using a computerized embroidery machine. The design was uploaded to a computerized embroidery machine (Brother PE800). The electrodes were developed with a stitch length of 1.5 mm, and the total yarn consumption for each electrode was 3.6 m.

In all the developed textile electrodes, a metallic snap button was attached to connect to the wires of an ECG recording module; during all ECG tests the connecting track of the electrode was shielded with plastic tape to prevent contact with the skin, and only the active part of the electrode was in contact with the skin.

2.2. ECG Measurements

A wearable ECG monitoring system was developed by integrating embroidered ECG electrodes into a commercially available shoulder strap. The pressure exerted on the human body varies from point to point. The selection of the best position for the placement of the electrodes that can ensure conformal skin-electrode contact is very important [11]. In this study, we collected signals from around the armpit.

ECG signals were collected from persons wearing shoulder straps with embroidered electrodes, using a portable PC-80B easy ECG monitor. The measuring electrodes (right arm and left arm) were placed on the right and left armpit, and the third ground electrode was placed around the lower chest in a lead I configuration, where the electrodes were embedded inside a shoulder strap with Velcro to hold the electrodes in place with uniform skin-electrode contact (12 mmHg) during any body movement. We also collected ECG signals using standard electrodes (Ag/AgCl) for comparison with asynchronous ECG recording methods.

The effect of electrode size on ECG signal quality was also studied. To study the effect of the electrode dimensions, electrodes of three different sizes (12 cm^2, 8 cm^2, and 4 cm^2) were developed, as shown in Figure 1. The P, R, and T peaks' visibility and amplitude, as well as signal intervals such as the PR, QT, and QRS intervals, were used to analyze the collected signals. Since the viewer lacks an export option, the ECG viewer manager program (V5.2.0.1) was used to calculate the amplitude of each peak and noise from 33 consecutive cardiac cycles for each sample. By calculating the size of the highest and lowest deflections, the amplitude of peaks and sounds was measured. The signal-to-noise ratio (SNR) of the measured voltage was calculated as the ratio of the QRS amplitude to the amplitude of the noise [12].

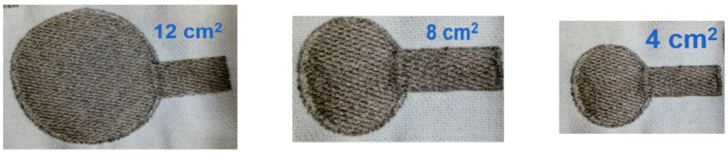

Figure 1. Developed ECG electrodes in different three sizes.

3. Results and Discussions

The ECG signal was collected using the developed wearable system with textile electrodes from the armpit while the subject was in a sitting position and signals were taken using gelled Ag/AgCl electrodes from the same position for comparison. Figure 2a,b show ECG signals collected using embroidered electrodes (8 cm^2 size) at a holding pressure of 12 mmHg (0.15 N/cm^2) and gelled Ag/AgCl electrodes, respectively.

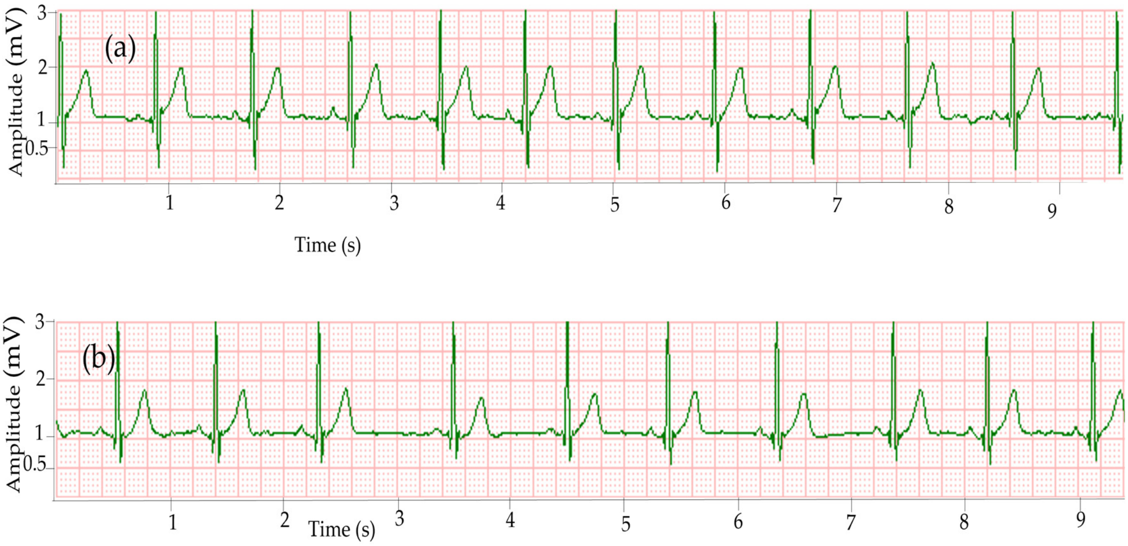

Figure 2. ECG signals taken from the armpit using: (**a**) the wearable system with embroidered electrodes; and (**b**) Ag/AgCl electrodes.

The results show that the three major waveforms, i.e., P, QRS, and T waves which are very crucial in ECG signals are visible in all the ECG signals. The quality of the signal taken by embroidered electrodes is comparable to the signal collected using gelled electrodes (Figure 2b). The P wave amplitude was almost similar in all signals which were 0.08 mV. The R-peak amplitude was 2.09 mV and 1.99 mV for signals taken using embroidered and gelled Ag/AgCl electrodes, respectively. It was observed that both ECG signals showed lower fluctuation in R-peak amplitude and a higher signal-to-noise ratio (SNR) which was 42.90 dB and 42.47 dB for signals taken using embroidered and gelled Ag/AgCl electrodes, respectively. Pearson correlation coefficient was calculated to compare the similarity of the signal collected using the textile electrodes and standard gelled Ag/AgCl electrodes based on the amplitude of the major waveforms. The correlation between the signals was very high, i.e., ~0.90. The average HR was 75 bpm and 68 bpm for signals acquired using embroidered and gelled Ag/AgCl electrodes, respectively. The expected value for HR is 60–100 bpm [13].

ECG signals collected while the subject was walking at 12 mmHg holding pressure (results not shown here) have recognizable major peaks, but the signals contain motion artifacts and the SNR was lower, for instance, the SNR of the signals acquired using embroidered electrodes was 30.13 dB which is lower than signals taken under static conditions which were 42.90 dB. ECG signals collected at a contact pressure of 18 mmHg and 12 mmHg holding pressure also provided cF8lear signals with distinguishable waves in all cardiac cycles with better amplitude compared to signals taken at 6 mmHg.

Table 1 presents the amplitude of the major waveforms in millivolt (mV), the duration of signal intervals in milliseconds (ms), the average heart rate (HR), and the signal-to-noise ratio (SNR) of the acquired signals. The P wave amplitude of the acquired signals was approximately the same while the mean amplitude of the T wave shows some increase in amplitude as the electrode size becomes large. A significant difference was noticed between the T wave amplitude of the signals from small-size electrodes compared to the other electrodes (p-value < 0.001, alpha = 0.01), but the signals from large and medium-size electrodes do not show a significant difference. The standard value for normal T wave amplitude is 0.1–0.5 mV and all the results were in this range. The R-peak amplitude was significantly higher. The SNR was relatively high compared to previously reported results [12,14].

Table 1. Comparison of signals from large (12 cm^2), medium (8 cm^2), and small (4 cm^2) electrodes.

Waveforms and Intervals	Electrode Size		
	12 cm^2	**8 cm^2**	**4 cm^2**
P (mV)	0.08 ± 0.01	0.08 ± 0.02	0.08 ± 0.02
R-peak (mV)	2.12 ± 0.07	2.09 ±0.08	1.99 ± 0.06
T (mV)	0.88 ± 0.03	0.85 ± 03	0.73 ± 0.04
PR (ms)	162 ± 5	158 ± 7	142 ± 7
QRS (ms)	96.31 ± 4.15	96.15 ± 4.16	96.69 ± 3.04
QT (ms)	349.85 ± 6.73	356.69 ± 5.25	359 ± 3.77
SNR (dB)	43.53	42.90	41.96
HR (bpm)	72	73	69

4. Conclusions

In this study, we developed a wearable ECG monitoring system by incorporating embroidered electrodes into a shoulder strap. We collected ECG signals while the subject was wearing the shoulder strap in both static and dynamic conditions, with electrodes placed in the armpit area. We then compared these results with signals obtained from traditional gelled Ag/AgCl electrodes. The ECG waveforms collected while the subject was in a seated position using textile electrodes were clearly visible in all signals and exhibited a level of comparability with signals gathered using gelled Ag/AgCl electrodes.

The R-peak amplitude was 2.09 mV with a 42.9 dB SNR for signals taken using embroidered electrodes. It was observed that ECG signal quality improves with an increase in electrode size and holding pressure. ECG signals were acquired while the subject was in a walking condition, resulting in detectable waveforms with no missing R-peak. The SNR of the signals acquired using embroidered electrodes was 30.13 dB. Overall, the results are promising for the development of an applicable wearable ECG monitoring system.

Author Contributions: A.B.N. designed and conducted the experiment, analyzed results, and wrote the paper; B.M. analyzed experimental results and edited the paper; and L.V.L. supervised and administered the project. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the ReCure project and IIE-SRF.

Institutional Review Board Statement: The measurements were conducted following the approved protocol of the Institutional Review Board at EiTEX, Bahir-Dar University, on 19 March 2020, with Reference Number EITEX-PGPDO/37/2020.

Informed Consent Statement: Before they decided to participate in this study, each participant was given ample opportunity to thoroughly read the information sheet. They were encouraged to discuss any uncertainties or seek additional information with the study team or other individuals. This crucial step is referred to as the "informed consent form". Subsequently, upon deciding to participate, participants were requested to sign the consent form.

Data Availability Statement: Data is contained within the article.

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

References

1. Ramasamy, S.; Balan, A. Wearable Sensors for ECG Measurement: A Review. *Sens. Rev.* **2018**, *38*, 412–419. [CrossRef]
2. Miao, F.; Cheng, Y.; He, Y.; He, Q.; Li, Y. A Wearable Context-Aware ECG Monitoring System Integrated with Built-in Kinematic Sensors of the Smartphone. *Sensors* **2015**, *15*, 11465–11484. [CrossRef]
3. Abu-Saude, M.; Morshed, B. Characterization of a Novel Polypyrrole (PPy) Conductive Polymer Coated Patterned Vertical CNT (PvCNT) Dry ECG Electrode. *Chemosensors* **2018**, *6*, 27. [CrossRef]
4. Ribeiro, D.M.D.; Fu, L.S.; Carlos, L.A.D.; Cunha, J.P.S. A Novel Dry Active Biosignal Electrode Based on an Hybrid Organic-Inorganic Interface Material. *IEEE Sens. J.* **2011**, *11*, 2241–2245. [CrossRef]

5. Jung, H.C.; Moon, J.H.; Baek, D.H.; Lee, J.H.; Choi, Y.Y.; Hong, J.S.; Lee, S.H. CNT/PDMS Composite Flexible Dry Electrodesfor Long-Term ECG Monitoring. *IEEE Trans. Biomed. Eng.* **2012**, *59*, 1472–1479. [CrossRef] [PubMed]
6. Das, P.S.; Kim, J.W.; Park, J.Y. Fashionable Wrist Band Using Highly Conductive Fabric for Electrocardiogram Signal Monitoring. *J. Ind. Text.* **2019**, *49*, 243–261. [CrossRef]
7. Lee, J.-W.; Yun, K.-S. ECG Monitoring Garment Using Conductive Carbon Paste for Reduced Motion Artifacts. *Polymers* **2017**, *9*, 439. [CrossRef] [PubMed]
8. Zhu, Z.; Liu, T.; Li, G.; Li, T.; Inoue, Y. Wearable Sensor Systems for Infants. *Sensors* **2015**, *15*, 3721–3749. [CrossRef] [PubMed]
9. Tseghai, G.B.; Malengier, B.; Fante, K.A.; Nigusse, A.B.; Van Langenhove, L. Integration of Conductive Materials with Textile Structures, an Overview. *Sensors* **2020**, *20*, 6910. [CrossRef] [PubMed]
10. de Mulatier, S.; Nasreldin, M.; Delattre, R.; Ramuz, M.; Djenizian, T. Electronic Circuits Integration in Textiles for Data Processing in Wearable Technologies. *Adv. Mater. Technol.* **2018**, *3*, 1700320. [CrossRef]
11. Cho, G.; Jeong, K.; Paik, M.J.; Kwun, Y.; Sung, M. Performance Evaluation of Textile-Based Electrodes and Motion Sensors for Smart Clothing. *IEEE Sensors J.* **2011**, *11*, 3183–3193. [CrossRef]
12. Nigusse, A.B.; Malengier, B.; Mengistie, D.A.; Tseghai, G.B.; Van Langenhove, L. Development of Washable Silver Printed Textile Electrodes for Long-Term ECG Monitoring. *Sensors* **2020**, *20*, 6233. [CrossRef] [PubMed]
13. De Capua, C.; Meduri, A.; Morello, R. A Smart ECG Measurement System Based on Web-Service-Oriented Architecture for Telemedicine Applications. *IEEE Trans. Instrum. Meas.* **2010**, *59*, 2530–2538. [CrossRef]
14. Kannaian, T.; Neelaveni, R.; Thilagavathi, G. Design and Development of Embroidered Textile Electrodes for Continuous Measurement of Electrocardiogram Signals. *J. Ind. Text.* **2013**, *42*, 303–318. [CrossRef]