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Review

Electrode placement in electrocardiography smart garments: A review

Azadeh Soroudi *, Niina Hernández, Lena Berglin, Vincent Nierstrasz

Textile Materials Technology, Department of Textile Technology, Faculty of Textiles, Engineering and Business, University of Boras, 501 90 Boras, Sweden

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ABSTRACT

Wearable Electrocardiography (ECG) sensing textiles have been widely used due to their high flexibility, comfort, reusability and the possibility to be used for home-based and real-time measurements. Textile electrodes are dry and non-adhesive, therefor unlike conventional gel electrodes, they don't cause skin irritation and are more user-friendly especially for long-term and continuous monitoring outside the hospital. However, the challenge with textile electrodes is that the quality and reliability of recorded ECG signals by smart garments are more sensitive to different factors such as electrode placement, skin humidity, user activities and contact pressure. This review will particularly focus on the research findings regarding the influence of electrode placement on the quality of biosignal sensing, and will introduce the methods used by researchers to measure the optimal positions of the electrodes in wearable ECG garments. The review will help the designers to take into account different parameters, which affect the data quality, reliability and comfort, when selecting the electrode placement in a wearable ECG garment.

Introduction

Wearable electronics are a kind of smart garments in which monitoring devices are often embedded into clothing in order to sense, measure, monitor, and report human vital signals, for example, heart or muscle signals can be recorded by ECG or EMG garments respectively [1,2]. The wearable ECG and EMG garments have been tested on hospital patients for example to monitor movements and physiological signs in order to detect and differentiate seizures in epilepsy [3,4], or to quantify activity and upper limb function in stroke patients [3]. Unlike conventional gelled electrodes, textile electrodes used in ECG garments are more comfortable and user-friendly especially for continuous monitoring of cardiac conditions. The conventional gelled electrodes together with the electrode adhesive can create rash or skin reaction, and even lead to bacterial growth [5], have limited storage time (less than one year), and skin abrasion is usually required to remove the dead skin cells from the surface of the skin [6]. Furthermore, gelled electrodes are applicable on skin only for a few days because they will dry eventually which in turn increases the electrode contact impedance and generates noise and errors in the measured signals [7]. Textile electrodes can indeed overcome the mentioned limitations especially in long-term monitoring [8,9]. For example, Gonzales et al. [10] embedded silver woven conductive fabric as electrodes into a T-shirt, which was worn by patients for 24-h to detect heart abnormalities during daily life, or Di Rienzo et al. [11] developed a smart garment using silver-coated conductive fabric for heart monitoring and other vital signs during sleep in space missions. However, wearable monitoring is also challenging because the quality of textile-based ECG electrodes are significantly depended on different factors such as skin-textile contact, humidity [12], contact pressure [13–15], electrode placement, user's movements, and muscle activity [16]. On the other hand, a medical quality electrocardiogram (ECG) signal is necessary for short and long-term heart monitoring [17], therefor dry textile electrodes show limitations when very small signals must be recorded, or they create doubts about the signal quality [18–21]. Apart from the mentioned challenges such as a proper electrode placement, there are two other important problems with smart garments: improper fit, and wearing discomfort. Improper fit and electrode displacement lead to signal errors and an unreliable data collecting system, and if a garment is not comfortable, it is likely that a user do not wear the garment at all [22,23]. There are other types of wearable ECG for non-invasive long term monitoring, such as commercially available Nuubo which is a dynamic, wireless and remote ECG worn like a sports bra. Electrodes are automatically positioned tightly but comfortably in the right locations against the skin to enable high quality data gathering. The wireless remote ECG Nuubo platform consists of biomedical bra (or shirt), electronic device and software package [24–27].

It should be also mentioned that for a proper ECG recording, apart from the above mentioned parameters such as proper skin contact and correct electrode placement, the right technical parameters should be applied to obtain a recording with the maximum quality possible, such as adding high-pass and low-pass filters to electrocardiograph devices. Such filters can reduce or prevent unwanted signals in the form of noise or interferences which are produced by muscle activity, breathing, small movements by the patient, or coming from alternating current [28–31]. The use of low-pass, high-pass and band-pass filters have been reported in textile based ECG electrodes [32,33].

* Corresponding author.
E-mail address: azadeh.soroudi@hb.se (A. Soroudi).

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Electrode placement in conventional and disposable electrodes

Inaccurate ECG lead placement can lead to increased level of noises and errors, and even wrong diagnoses, for example poor wave progression [34]. Most of the studies to date are regarding the electrode placement in conventional ECG measurements performed in the hospitals. However, the results can be an inspiration for electrode placement in developing ECG garments. According to Nedios et al. [35], there is a strong positive relation between electrode distance, and ECG signal-amplitude. The highest signal amplitude for the shortest distance was obtained for an 8 cm distance between electrodes (bipolar leads) on a heart-aligned axis and over the relevant heart-chamber. It was also reported that a distance of 5 or 7 cm would give a signal with at least 20% lower amplitude than those at 8 cm [35]. Kabir et al. [36] have shown the optimal configuration of ECG adhesive patches for continuous monitoring of orthogonal ECGs similar to orthogonal Frank ECGs. The BioStamp Research Connect™ (MC10, Inc., Lexington, MA) patch is a mobile telemetry device for continuous recording of high resolution ECG and electromyography signals and body movements, based on epidermal electronics technology. It was reported that artefacts on Y-lead could be mislabeled if this would be the only ECG patch as shown in Fig. 1. The patches were claimed to be usable for monitoring of long-term vector cardiogram (VCG) parameters such as QRS-T angle, spatial QRS and Tvector characteristics.

An assessment tool to compare various ECG lead configurations for long-term patient monitoring has been suggested by Drew et al. [37], however needs more study to reach standardization of electrode placement. The tool is based on scoring (0–20 points, with 20 as perfect score) and considers 5 factors that are clinically important: equivalency to the standard ECG (6 points), patient comfort (4 points), giving less noise (4 points), non-interference with clinical interventions (clinical interventions should not interfere with ECG electrode sites) (3 points), and identifiable anatomical landmarks for accurate electrode placement (3 points) [37]. For 12-Lead ECG Monitoring, different lead systems can be used such as EASI™ Lead System using 5 electrodes, Mason-Likar Placement using 10 or 5 electrodes, or conventional electrocardiograph 10-electrode [38]. All the investigated lead systems for the standard 12-lead ECG are sensitive to electrode placement error [39]. However, it is shown by Finlay et al. [40] that the EASI leads are less sensitive to electrode misplacement (up to $\pm$5 cm in their study), than the standard Precordial leads. It is recently reported that ECG electrodes position on the surface of body was well localized using 3D photography, and it was in good agreement with CT/MRI imaging methods (computed tomography/magnetic resonance imaging). Therefore, reconstruction of torso geometry can be done accurately using 3D photography [41]. The application of this method is for non-invasive electrocardiographic imaging, ECGi, which is still in developing stage as an alternative for currently used ECG. The proper registration of the ECG electrode positions on the body surface is necessary to minimize the errors in ECGi method [41]. Recently, a novel single lead ambulatory ECG monitor, Cardiostat™, has been introduced where recording is made through 2 electrodes positioned in a lead 1-like configuration. Nault et al. have validated its detection accuracy compared to a 12-lead ECG [42].

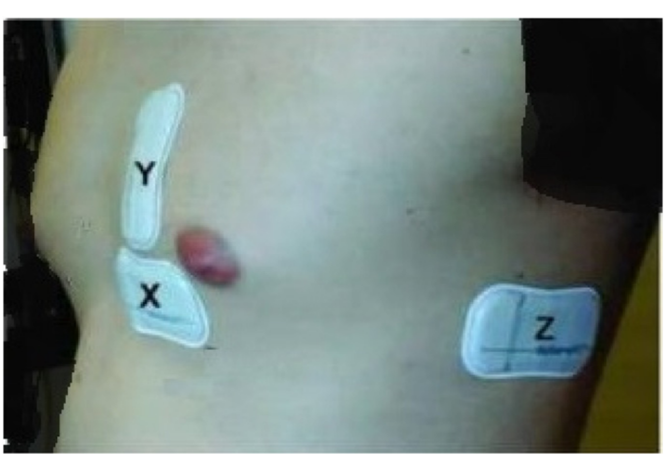

Fig. 1. Optimal configuration of ECG patches [23].

Electrode placement in ECG smart garment

A few studies have been done when it comes to electrode placement in smart garments and wearable electronics. As mentioned before, a proper fit and wearing comfort should be also considered in this context [22,23], because according to Hakyung et al. [23], in contact-type ECG monitoring garments, the main factors affecting the motion artefacts are: 1-the lack of contact between the human skin and the electrode due to improper fit, and 2-the improper location of the electrode on a garment which makes the electrode to shift from its position when wearer moves. The second parameter leads to electrical errors, such as errors in the apparatus arrangement [23]. It is necessary to minimize motion artefacts by improving skin-electrode contact for example, by applying pressure [15,43], or finding proper electrode placement [44].

The easiest way to obtain a good contact between textile sensor electrodes and skin without using adhesive would be to increase the garment pressure to the body, to avoid a sliding between electrodes and skin, and minimize the signal artefacts. The pressure, however, can be increased up to a point to maintain the comfort of the wearer. To obtain good signal quality and high comfort at the same time, a proper selection of conductive and elastic fibers, garment structure, and cut play an important role [45]. In WearItMed smart shirt for people with neurological disorders [3,46], three electrodes were used; two electrode zones were selected to be under breast and one in forearm, all needed to be tight and under pressure in order to have a better skin contact and minimize motion artefacts as shown in Fig. 2. A previous study by the same project showed that wearables need to be user- friendly, have an attractive design, and show clinical efficacy in improving disease management [47]. In a study by Di Rienzo et al. [11], the position of the electrodes was selected to be in right and left side under the breast and under a pressure zone, based on their previous study to assess the thorax and the garment deformations during specific movements [11,45]. In a recent study [48], the conventional 12-lead configuration is used to print electrodes on a smart shirt, to form six electrodes at the Wilson Monopolar Precordial lead monitoring sites [49]. In the same study, they report that for obtaining viable electrocardiograms, either the stratum corneum moisture should be high enough, or they should press the electrodes against the skin using elastic band, with a contact pressure of 5.0 to 6.0 kPa [48]. Apart from pressure and moisture, the size of active contact area can change the noise level in textile electrodes [19,50,51].

Finding a proper electrode placement has been less studied than the effect of other factors for example, applying pressure and humidity; especially if we think about a systematic method which can be used for a

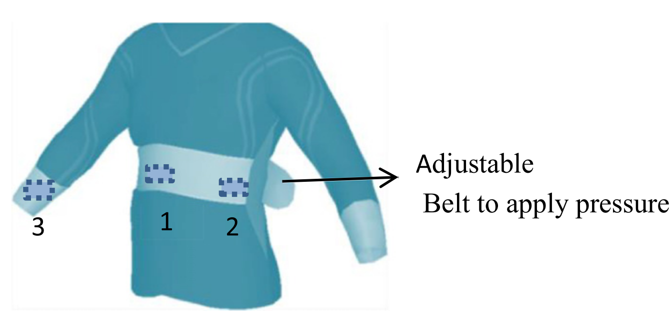

Fig. 2. Electrode position (1, 2 and 3) in WearItMed [32] health monitoring shirt.

wide range of individuals and groups. According to Tong et al. [16], when the patient is walking, the sensing quality by textile electrodes can be strongly affected by the electrode placement. Furthermore, textile electrodes which were placed on areas having fewer muscles could record better signal quality. A method to measure the displacement of a body sensor embedded in a garment is reported by Dunne et al. [52]. Such measured movements are expressed as “error” or “movement noise”. The method of the measurement is based on motion-capture of garments worn by a robotic running mannequin. The method is so that the “error” that sensor experiences due to poor mechanical coupling to skin can be characterized with regard to the difference in 3-dimensional position between the sensor and a corresponding “true” body location, by assuming that the aim of the embedded sensor is to mimic as closely as possible the characteristics of the body surface. Therefore, measuring of the variability of the sensor position relative to the true body location can be used to trace the amount of “error” experienced by sensor. However, measuring movement over the surface of a robot is not exactly the same as measuring a human body due to being rigid, a difference in the coefficient of friction, etc.

3D body scanning is another interesting alternative to evaluate smart garments. 3D body scanning has been initially made for clothing industry to make a digital copy of the outside of the human body instead of manual size measurement [53]. In health care section, the body's size and shape have been traditionally measured by hand to assess health status. Computed-tomography (CT) scanners have been also used recently to produce 3D internal images of a patient's body [54,55] and most recently, 3D body-surface scanners are transforming the ability to measure body size, shape, and skin-surface area of the individuals accurately. The advantages of 3D scanners are their low cost, non-invasive character, and being user-friendly making them interesting for clinical applications [56]. For example, a novel 3D body scanner for healthcare applications has been developed by Grazioso et al. [57], to provide an accurate body measurement and visualize anatomical structures for diagnosis, treatment and monitoring applications.

3D body scanning has been also reported as a fit model for smart wearable garments [22,58]. According to Mahendran et al. [22], 3D body scanning could provide two distinct sets of information for smart garment design; creating a 3D form representing a special group of people to simulate sensor placements and (b) evaluating variations in the landmarks on human body. Optimal sensor placement for respiratory band and ECG sensors was obtained by quantification of variations in the measurements for each of the groups; the method was also claimed to be applicable for improving fit and comfort [22]. Hakyung et al. [23] used a case selection approach based on key torso measurements derived from 3D body scanned data. They studied effects of 56 electrode positions by sectioning the surface of the garment into grids with 6 cm intervals in the front and back of the bodies. Then ECG measurements were collected from 10 participants at every electrode position in the garment while the wearer was in motion. Four locations were identified to be least affected by wearer movement, and finally they suggested a design of the garment-formed ECG monitoring platform showing the optimal positions of the electrode.

Flexible dry electrodes were screen-printed by Yokus et.al [59] and the effect of electrode placement and electrode area on the ECG signal was studied using a standard General Electric bedside monitor. A dry electrode was placed at the center of chest as right electrode, while the left dry electrode was placed to the level of second rib on the chest and close to the left arm. This area of chest was selected to meet high user compliance and less sensitivity to body movements. ECG measurements were analyzed for electrode pair distance of 2, 4, 6, 8, 10 and 12 cm. It was observed that the placement of electrode pairs on body surface changed the amplitude of ECG signal, since body surface potential variation is location-dependent.

Biosignal sensing without direct skin contact as an alternative method is attracting interest and can be used to record various electrical biosignals such as ECG or EMG [60,61]. In this method, a thin layer of insulator is placed between the human skin and an electro-conductive sensing electrode. This structure, forms a capacitance that conveys the signal from the body to the sensor [62]. Babusiak et al. [63] made capacitive textile electrodes and placed pair of ECG electrodes on the upper waist, back side of person, and DRL (Driven Right Leg) electrode on the front side. The DRL circuit was used to decrease the main noise (50 Hz). Even for capacitive measurements, having a close contact between the electrodes and the skin is critical, and using a rubber band to press the electrodes onto the body is an option [63].

Conclusion

To obtain good quality ECG signals, high comfort and wearability at the same time, different factors should be considered simultaneously when designing an ECG garment: a proper selection of conductive and elastic fibers, garment structure and cut, proper fit, and a proper electrode placement. The electrode placement on the other hand should be selected based on the sensitivity to body movements (for example fewer-muscle zones), electrode distance, the comfort, the possibility to apply pressure, and the body surface potential variation. The optimal positions of the electrodes considering the body movements have been measured by different methods such as a method based on motion-capture of garments worn by a robotic running mannequin [52], and 3D body scanning [22,23]. Since a successful ECG monitoring garment needs a multi factor design, a good strategy would be a cooperative design using techniques and experiences provided by medical experts, textile and garment designers, as well as material and electronic professionals.

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