Development and Wearer Trial of ECG-Garment with Textile-based Dry Electrodes

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Abstract:

This paper presents the design and development process of ECG (electrocardiogram) garments using different textile-based dry electrodes and assesses their performance through wearer trials. To comply with the design criteria identified for such garments, sequences of sketches with modified design features, physical prototyping and trial with industry grade mannequin were first implemented before finalising a protype design with three different fabrics for chest, front and back panels. ECG electrodes were configured on the chest panel individually with following two different conductive textile materials - single jersey knitted fabric and embroidery thread – to construct two different prototypes, which were wearer-trialled with a human participant. Results show that the embroidered electrodes performed better than the knitted electrodes in ECG detection in still and active conditions within the same design and construct of garment.

Key words:

Textile, dry electrodes, knitted fabric, embroidery, ECG

1. Introduction

Continuous monitoring of body signals, such as respiratory rate, heart rate, electrocardiogram (ECG)-signals and blood oxygen levels etc., is recognised as one of the best methods for detecting and observing illness [1]. Especially ECG signals can be beneficial in long-term health monitoring due to the dominance of heart-related issues and the opportunity to investigate electrical activity of the heart by capturing episodes of arrhythmias or ischemia at relatively low cost and minimal effort [2,3]. Incorporating small sensing elements within garments can translate to minimally obtrusive and individualised health services, which in turn could improve the quality of patients' lives and avoid expensive and unnecessary hospitalisation [4,5]. Additionally, the benefits of using smart electro-clothing systems (SeCSs) go beyond the early recognition of health problems by providing increased user comfort as the systems are less physically and visually invasive than the standard Holter ECG systems [6].

The medical grade ECG systems mostly use disposable wet Silver/Sliver Chloride (Ag/AgCl) electrodes [7], wherein a hydrogel layer acts as adhesive and electrolyte on the skin-electrode interface. The adhesive gel ensures good contact between skin and electrode to facilitate unbroken flow of electricity from skin to electrode. Although the application of these electrodes in easy and secure, they may cause skin irritation and discomfort [8,9]. In case of long-term use, the hydrogel in the commercial wet electrodes can dry up over the time and lower the reliability of signal acquisition. Consequently, wet electrodes are not suitable for the application within a garment from construction and donning points of views. On the other hand, dry electrodes are configured almost similar way the wet electrodes are configured, but the only difference is the absence of an adhesive and electrolyte layer to facilitate good contact between the skin and the electrode [10].

Dry electrodes are made of flexible conductive materials, that do not irritate skin [11], use a variety of possible configurations like fabric patches, woven or knitted integrated sensors, embroidered electrodes, printed and non-fabric mounted solutions [11, 12, 13, 14-17]. They offer a stable performance throughout as there is no wet layer that could dry up and influence the electrode's performance negatively. However, when used in full garment system, dry electrodes also have a high or unstable impedance at the skin-electrode interface [13] and are susceptible to motion artifact [8]. The problems related to wearable ECG systems are the non-uniform nature of skin and movement of body. Evidently, the movement of the body and the non-rigid attachment [6] of electrode to body are problematic and results in motion artifact. This is caused by the movement of clothing by external forces and – to some degree – by relative movement between the sensor and the skin which compromises the sensor's effectiveness [18, 19]. Further causes for motion artifact are: a change of potential across the outer layer of the skin due to skin flexion and deformation, a shifting of the electrode causing changes of the contact area and a thin layer of sweat or water. Moisture can cause motion artifact as with motion the humidity changes and interrupts the ionic concertation at the skin-electrode interface [13,18]. Overall, it is difficult to address motion artifact through one method only. Whilst a tight-fitting garment can cause better contact area and sweating can improve the skin-electrode interface, motion artifact may still occur as the body is in constant movement. Moreover, there is no suitable model or generalised approach to tackle motion artifact using filtering and data processing methods [6]. Use of padding, application of pressure and tight-fitting design [12, 20] are beneficial to reduce motion artifact; however, these can influence the wearer comfort negatively.

Contemporary works [1-3, 6-18] presented different ways of addressing these challenges but in most cases by addressing one or two individual factors only but not by dealing with their combined effect in complete garment. Therefore, the goal of this paper is to tackle the contributing factors right from the fashion design stage through pattern cutting, fabric selection, prototyping, repeated fit checking using mannequin and final wear trial with human participant.

2. Materials and methods

For this work, two sleeveless men's shirts made of knitted fabrics were developed by incorporating textile-based dry electrodes. The design, prototyping and testing of these ECG-shirts are discussed in the following the sections 2.1-2.5.

2.1 Establishing design criteria

Dry electrodes suffer from high or unstable skin-electrode impedance [13] due to movement or the lack of conductive contact between skin and electrode [20]. This can be addressed by different factors such as by improving flexibility and structure of electrode [3], introducing of an electrolyte or another conductive material leading to more conformal contact [2,3,19], by applying optimum pressure [18, 21], accurate placement of sensing electrode [10,19], considering size of sensing electrodes [2,9,11], and finally by optimum incorporation of sensing electrode in garment [22].

Other than motion artifact, wearer comfort is another challenge in the development of ECG-monitoring garments. A balance between suitably tight-fitting garments and comfortable non-restrictive fit is favourable. Furthermore, as monitoring garment is to be worn as the inner most layer of a clothing system, it needs to consider moisture and temperature management to positively influence the comfort of the wearer [23]. Another way to address motion artifact is to select the optimum size of electrodes. This can also influence wearer comfort depending on the surface of the electrode and how it is incorporated within the garment [24]. A scratchy or otherwise uncomfortable electrode will inhibit the wearer to don the garment as intended over long periods of time.

Based on the understanding of the issues mentioned earlier, the follow criteria for designing an ECG-garment are established:

- ensure flexibility and appropriate structure of electrode;
- ensure application of enough pressure on skin-electrode interface;
- select appropriate placement and size of sensing electrodes;
- ensure user comfort.

2.2 Design development, fabric selection and prototyping

Fashion design and development (FDD) process includes a sequence of activities involving product research, idea generation, material sourcing, initial sketch of garment design, prototyping, design presentation, range planning, selection and finalisation of design [25]. As a first step of this process, an in-depth research on available SeCSs was conducted, which is presented in [4]. Based on extensive product research and the design criteria set out in the earlier section, several sketches of design were developed as a part of idea generation and design development before finalising a design. The technical design constitutes a three-part front (upper chest panel, chest panel and lower front panel), a two-part back (neck panel and back panel) and side panel for both left and right sides (see Figure 1).

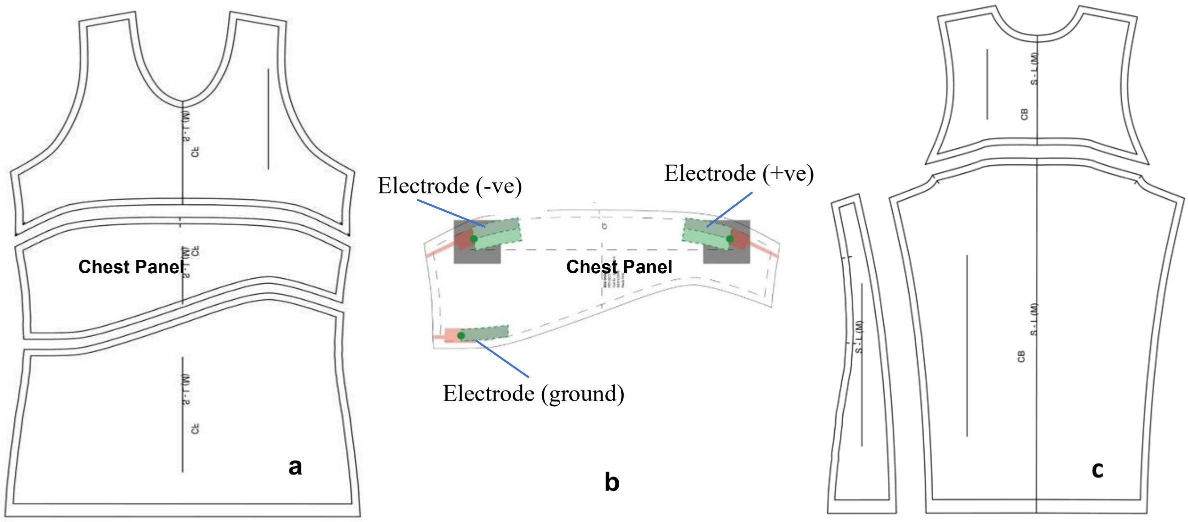


Figure 1: a) Front part including chest panel, b) Electrode position on chest panel, c) Back and side parts.

Table 1 presents the list of fabrics used for developing the garment prototypes. The chosen fabric for the upper chest, lower front and neck panels is a recycled polyamide fabric with elastane added for increased stretch-ability. A mesh fabric is chosen for the back panel to increase the moisture management and thus increase wearer comfort. The chest panel for housing dry electrodes needs to be adjustable to achieve the needed pressure of the electrodes on skin and needs to be compatible with other two fabrics. A 3D spacer fabric with compression properties, which offers cushioning for the electrodes from outside motion artefact, is chosen to press the electrode towards the body to secure the body-skin interface.

Table 1: Materials for garment prototyping

Material Specification		Compression chest panel	Main front fabric	Mesh back panel
1	**Type**	3D spacer fabric	Knitted Fabrics	Bi-elastic micro-mesh
2	**Brand Name**	XD spacer fabric Coolmax	Ln1001 black life recycled	Spider black nylon
3	**Company**	Baltex, Ilkeston, UK	Funkifabrics, Altrincham, UK	Funkifabrics, Altrincham, UK
4	**Composition**	100% Polyester	78% Nylon, 22% Lycra	80% Nylon, 20% Lycra
5	**Fabric structure**	Weft knitted spacer	Weft knitted	Warp knitted
6	**Mass/area**	350-400 g/m^2	190 g/m^2	150 g/m^2
7	**Other features**	31.04 kpa compression strength	From recycled nylon	Moisture wicking

Table 2 shows the measurements of the ECG shirt prototypes. The measurements were derived from the final prototype developed on a medium size Alvanon mannequin.

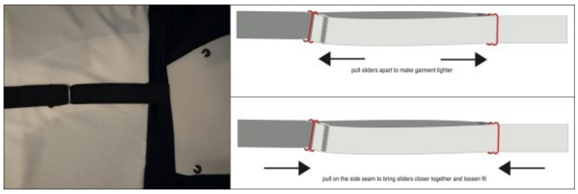
Table 2: Measurement of the ECG shirt

Place of measurements	Measurement in cm
Chest girth	87.0
Half back	14.0
Back neck to waist	40.0
Scye depth	20.0
Neck girth	50
Waist girth	83.0
Back length	66.5

Pattern pieces were drafted using the ‘Gerber AccuMark 11’ CAD system to facilitate fabric cutting. A 3-thread overlock machine and a lockstitch machine were used for stitching the panels together using stitch type 504 according to DIN 61 400/ ISO 4915 standard with the help of an Nm 120 polyester thread.

As it can be seen in the Figure 2 that the final design features an elastic strap at side seams to ensure uniform tension and pressure from both sides. The elastic band is constructed using two separate pieces of elastic and two plastic sliders, thus the elastic band can be adjusted by pulling sliders closer to the side seam. When pulling at the side seam the elastic band will become looser and the fit of the garment can easily be adjusted. Throughout the design and development phase, the fit of the prototypes was checked by trying on a medium size Alvanon Avatar.

a



b

Figure 2: a) Fit testing of Final Prototype design, b) Close up view of strap mechanism

2.4 Electrode configuration

Figure 1b presents the electrode positions on the chest panel to configure a 3-lead ECG system. The positions of electrodes on the chest panel were adapted from Einthoven triangle principle similar to commercial product [19] and contemporary research according to [21]. The dimensions of the positive and negative electrodes were 3cm x 6cm and the dimension of ground electrode was 1.5cm x 6cm. Tables 3 provides the list of materials used for dry electrode construction.

Table 3: Materials for dry electrode construction [?,?]

Materials Specifications	Conductive Fabrics	Embroidery Thread
Type	Silver plated knitted fabric	Silver plated embroidery thread
Brand Name	Shieldex® Technik-tex P130+B	HC 40 High Conductive Thread
Company	Statex, Germany	Madeira, Germany
Structure	Single Jersey	Double yarn (117 x 2 dtex)
Composition	78 % Polyamide + 22 % Elastomer, plating: 99 % Pure Silver	100% polyamid with silver plating
Dimension	Weight approx. 130 g/m², Thickness 0.55mm	Count: 290 dtex ± 6 dtex (after plating)
Resistivity / Resistance	<2 Ω/sq	< 300 Ω/m

In addition to the materials presented in the table 3, following supporting materials were used to produce the dry electrodes:

- a bobbin thread of 100% polyester (Nm 120) sourced from local market and puffy foam (thickness 1mm, composition 100% polyethylene, origin Gunold, Germany) were used together with HC 40 (Madeira) conductive embroidery thread for making the embroidered electrode.

- metal stud buttons sourced from local market was attached with the final dry electrodes to facilitate ECG measurement.

The 3D spacer fabric of the compressing chest panel (see table 1) was used as the base platform from developing the electrodes. Figure 3 shows the generic design of the electrode construction of each case.

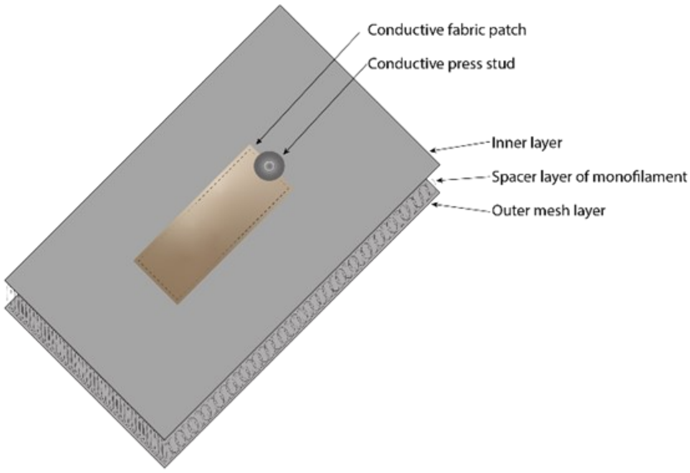
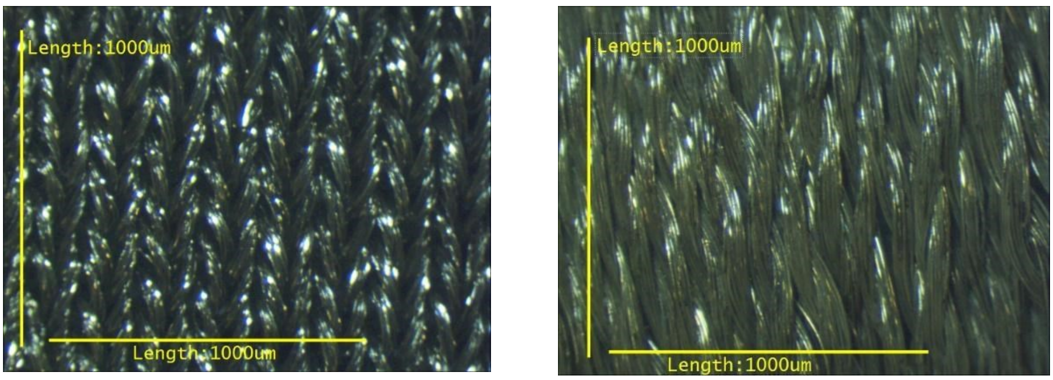


Figure 3: Generic design of the electrode construction

The electrodes are equipped with conductive press studs that facilitate the attachment of the crocodile clips of the ECG detecting unit from the outside of the garment. To obtain a true reading of the fabric patch electrodes, the press stud is covered with non-conductive clear vinyl at the back to ensure that there is no contact between skin and metal press stud.

Figure 4 present the microscopic views of the surface structures textrodes made from conductive fabric and embroidery thread.



Knitted **Embroidered**

Figure 4: Optical microscopic views of the conductive surface of the textrodes

2.4.1 Electrodes from Conductive knitted fabrics

Figures 5 illustrates the configurations of dry electrodes made from knitted fabrics. The fabric patches are hand-stitched around their perimeters to attach with the inner side of the chest panel.

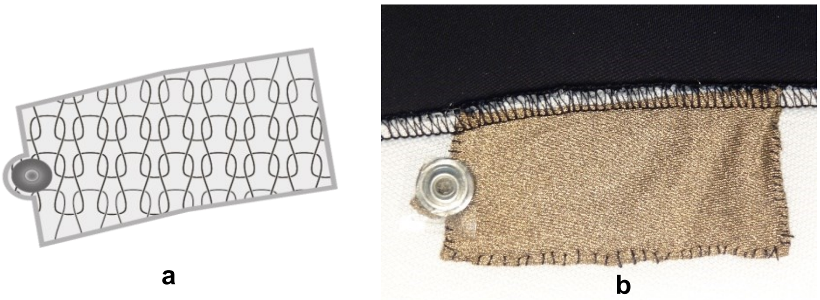


Fig 5: a) Schematic illustration of knit binding, b) Constructed electrode from knitted fabric

2.4.1 Embroidered electrode

Figure 6a illustrates the design of the ten rows of embroidery creating a raised profile. The electrodes were embroidered with a Tajima DG15 embroidery machine using HC 40 silver coated yarn from Madeira and a polyester bobbin thread (Nm 120). The border was sewn with an embroidery thread (Nm 80, from Gunhold). A non-woven stabiliser was used at the base of the embroidery and puffy foam was used as an interlining layer to ensure a raised profile (Figure 6b,c).

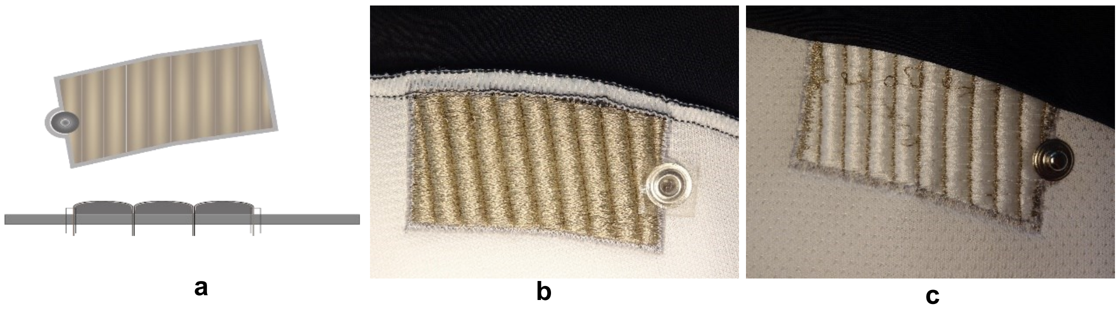


Fig 6: a) schematic design of embroidered electrode & cross section, b) Embroidered electrode, conductive side, c) Embroidered electrode, right fabric side

2.5 Wearer trial with live model and ECG capture

The prototypes of the ECG shirts were wearer-trialled with a healthy male participant of age between 30 and 35 years old, weight between 75 and 80 kg, and having the following key body measurements - chest girth 102 cm, waist girth 91.5 cm, neck girth 44 cm and scye depth 23 cm. Approved research ethics procedure (Reference Number: 0612, dated 10/04/2018) was followed to carry out the wearer trial with a live model. Each garment was donned by the model and an ECG recorder "Go Direct EKG Sensor" from Vernier (USA) was connected to it. Before collecting ECG data, the elastic strap at the back of the ECG shirt were tightened using the slider mechanism at comfortable level in discussion with the participant so that the electrodes remain in full contact with skin. The sampling rate was 200/second and 6002 data points are taken in both raw voltage as well as ECG data over a period of 30 seconds per test. Four tests for each prototype were conducted at the following four conditions - standing still with no water, standing active (arm swinging, talking) with no water, standing still with water and standing active (arm swinging, talking) with water application respectively. The prototypes were coded as

- **A**: the prototype with electrodes from single jersey knit patch
- **C**: the prototype with electrodes from conductive embroidery with puffy foam

In case of the test condition with water, about 2.5 ml of water was applied with the help of a spoon on the three electrodes of each garment.

2.6 Data Analysis and Filtering

At first, the detected ECG graphs were visually analysed against the standard PQRST-complex of an actual ECG signal, for example figure 7 shows the ECG graph from one prototype (7a) and an enlarged R-peak (the curve with the highest amplitude in the PQRST-complex) (7b) in comparison to a standard ECG signal (7c). The accumulated data is further analysed through digital filter technique and signal processing in MatLab software. For raw ECG signal, low frequency offset and high frequency noise are filtered to extract useful data. A simple signal filter technique called baseline wander filter is applied to extract ECG signal. To discard redundant elements in ECG signal, a 4th order Butterworth filter [26] is implemented. The cut off frequencies considered are 0.5Hz and 100Hz respectively. 100Hz high cut-off frequency is used to fulfil Nyquist Sampling Theorem, as sampling frequency of the acquisition is 200Hz [27]. To check bandwidth for ECG detection, the ECG measurement is transformed into frequency domain using Fast Fourier Transform (FFT). The power spectrum of majority ECG signal lies between 2Hz to 50Hz [26]. For normal ECG beats, important features such as R beats, QRS complexes and P-T waves are considered within the power spectra below 15Hz. Real challenges lie on the power spectra of motion artifact below 5Hz, at which their level is identical to normal ECG signal. This is unfilterable due to power spectra of P-T wave at similar bandwidth. In the cases, where the ECG signals have significant motion artifact in low frequency components, causing SNR of the ECG signal to be low, another adaptive technique, empirical mode decomposition (EMD), is carried out to determine ECG signals in different intrinsic modes. EMD is a widely used technique in ECG analysis and it can decompose complicated data into finite number of components, which can be described and analysed in separate terms [28-30]. With decomposed components, the low frequency motion artifact has been removed in 1st Intrinsic Mode Function (IMF) components for the cases where FFT could not provide acceptable base-line correction.

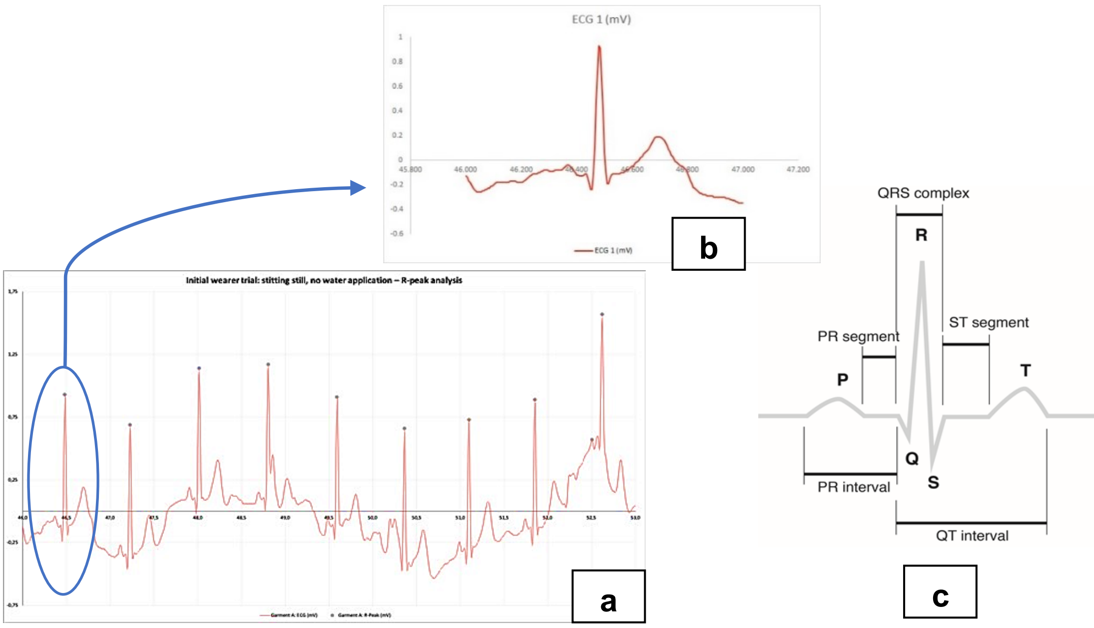


Fig 7: a) R-peak analysis, b) Enlarged version of an R-peak, c) Anatomy of an ECG signal

3. Results

The generated ECG waveform from the prototypes are analysed before and after the data filtering process. Based on the comparative assessment of the gathered peaks from the prototypes with standard constituent ECG peaks (P,Q,R,S,T), the acceptability of the data was analysed.

3.1 Prototype knitted textrode

Figures 8-11 present the ECG waveforms (raw and filtered) collected by the prototype with knitted textrode at test conditions - A1 (Standing still, no water), A2 (Standing active, no water), A3 (Standing still, with water) and A4 (Standing active, with water) respectively. The results from test A1 and A3 show characteristic P, Q, R, S and T - peaks of ECG waveform in both raw and filtered data. In case of the test A1, the baseline of the ECG waveform is shifted and not stable. Similarly, A3 also shows an unstable baseline of the ECG waveform. While the characteristics peaks Q, R, S, T are still recognizable, the stability of the baseline of the ECG waveform is important for calculating the heart rate (HR), heart rate variability (HRV), ST elevation and other characteristic markers from the waveform. These markers are critical to predict diseases and assess heart health of the wearer. The implementation of the high pass filter in the cases of A1 and A3 works very effectively to flatten the baseline without losing any significant portions of raw ECG data. The time zoomed plot of the waveform, figure 8 (c) shows the characteristic peaks of the signal after the data filtering process.

In active conditions, test A2 does not recognise any ECG characteristic peak at all, however, test A4 shows some noisy and inconclusive peaks. In both cases, the high pass filtering of the raw ECG waveform has not been effective. Figure 11 (c) shows the time zoom waveform of the ECG signal after the filtering process. The filter signal may have a pattern; however, this pattern is not recognizable when compared to the ECG unit waveform. The noise that generates during the data collection due to the active status of the wearer has larger amplitude than that of ECG signals and the generated noise spans all over frequency ranges of the ECG waveforms. The ECG data could be recovered if the noise has been generated at different frequencies (or any specific frequencies) that are separable from the bandwidth of ECG frequency.

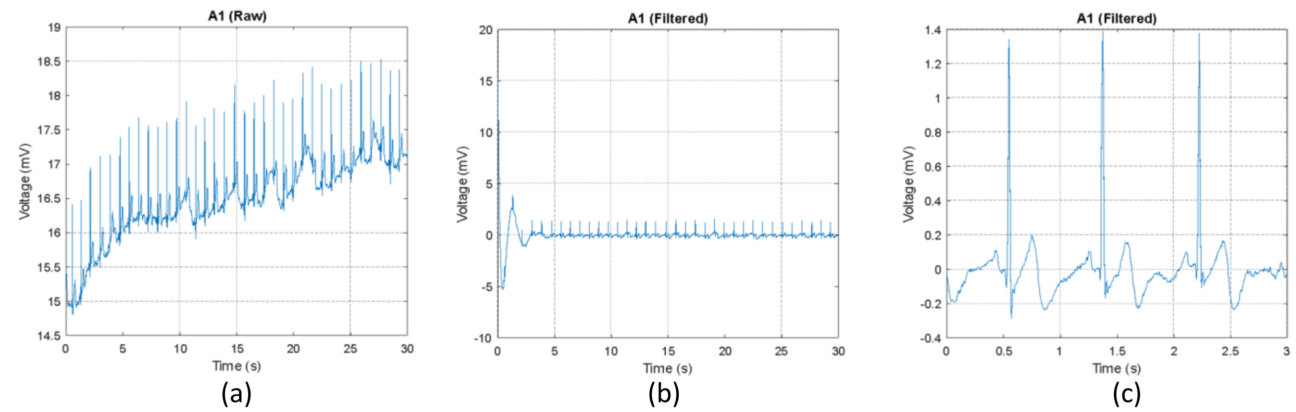


Figure 8: ECG data from test A1: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

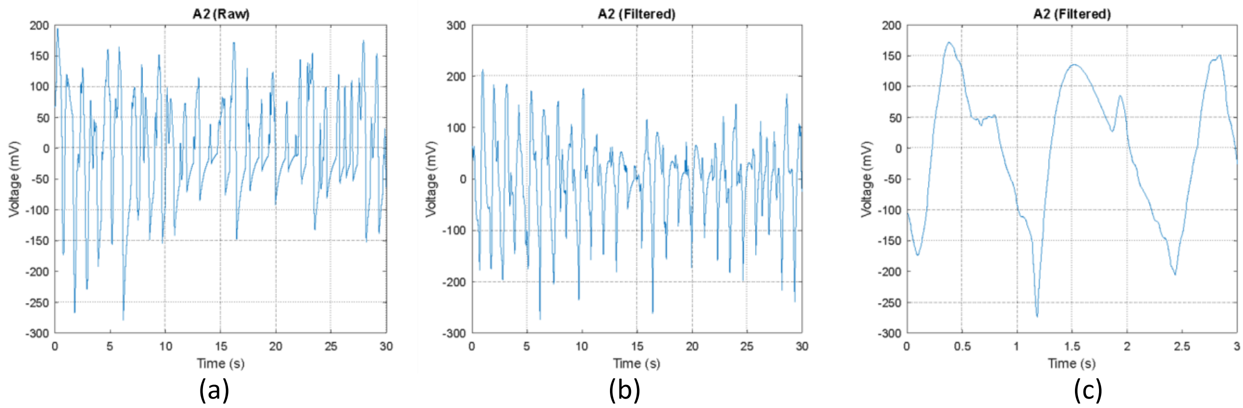


Figure 9: ECG data from test A2: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

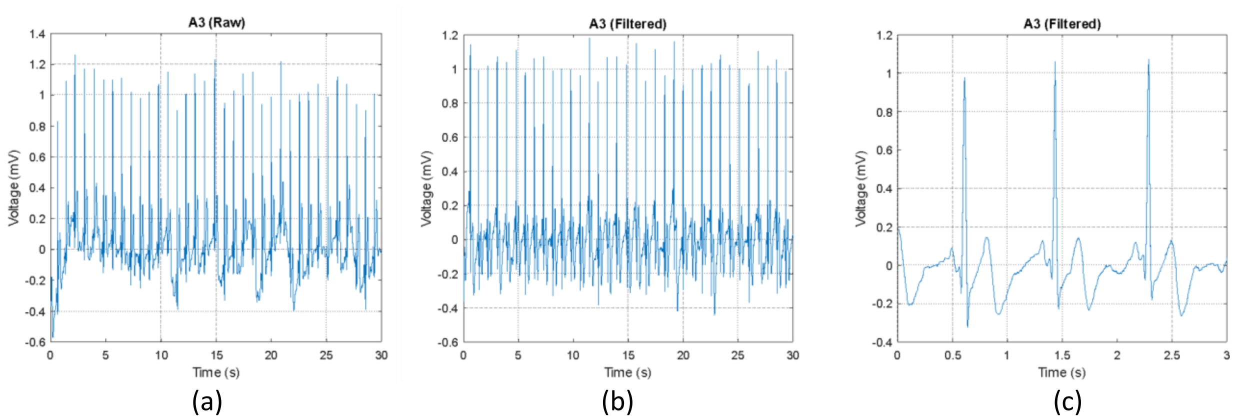
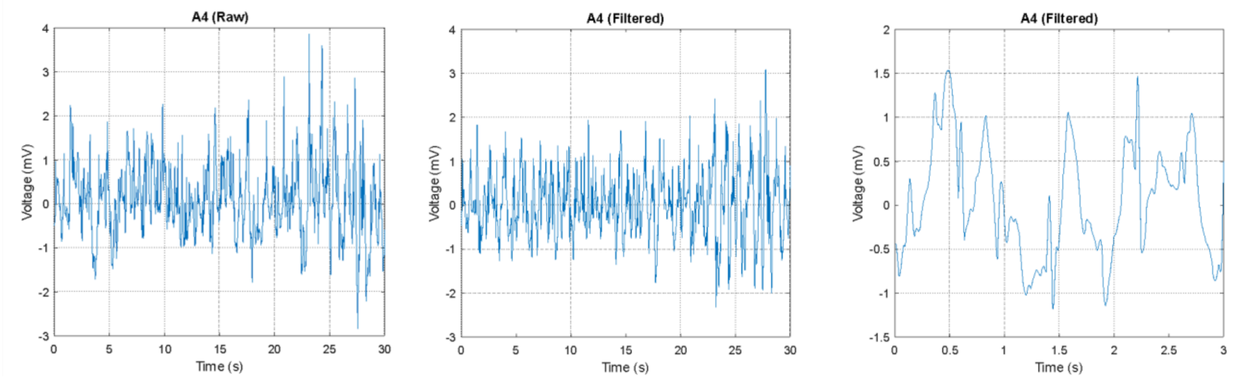


Figure 10: ECG data from test A3: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

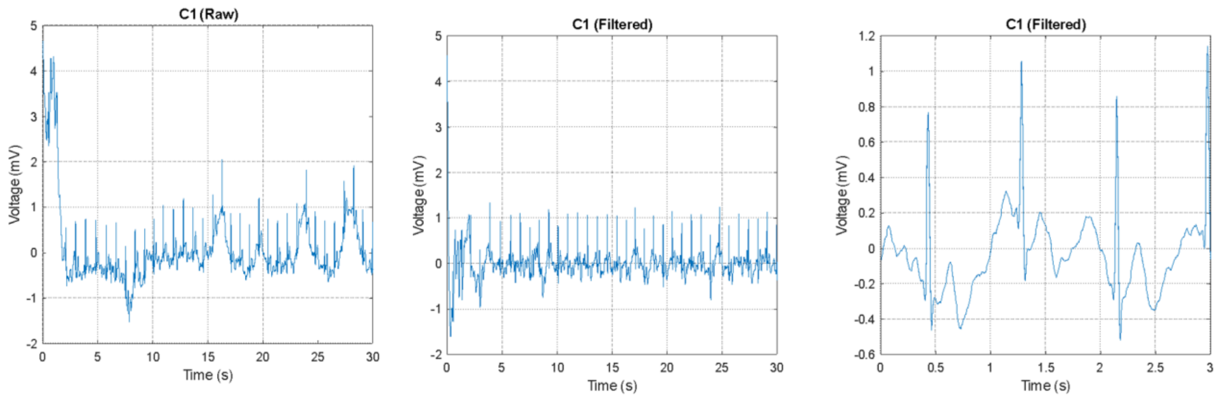


(a) (b) (c)

Figure 11: ECG data from test A4: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

3.2 Prototype with embroidered textrode

Figures 12-15 present the ECG waveforms (raw and filtered) collected by the prototype with embroidered textrode at test conditions - C1 (standing still, no water), C2 (standing active, no water), C3 (standing still, with water) and C4 (standing active, with water) respectively. The results from test C1 and C3 show characteristics R -peak of ECG both is raw and filtered data (see figures 12 and 15). In active conditions, test C2 does not recognise any ECG characteristic peak at all (see figure 13), however, test C4 shows some noisy and inconclusive results in FFT raw and FFT filtered data, which shows some degree of improvement in IMF filtered data (see figure 15).



(a) (b) (c)

Figure 12: ECG data from test C1: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

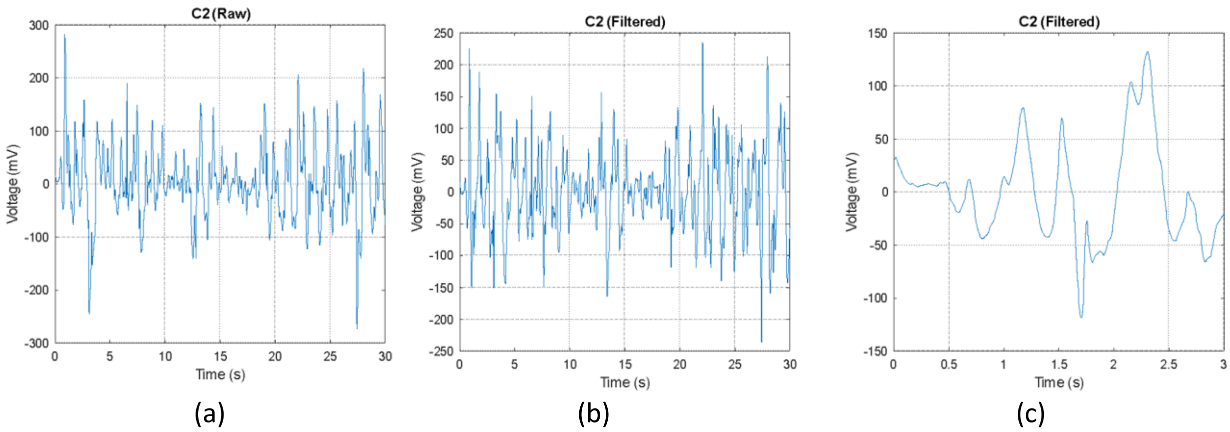


Figure 13: ECG data from test C2: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

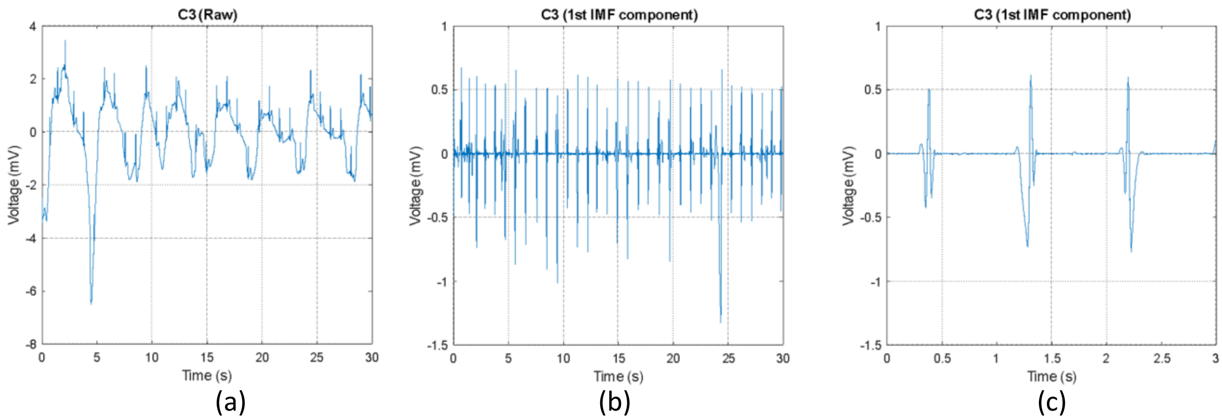


Figure 14: ECG data from test C3: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

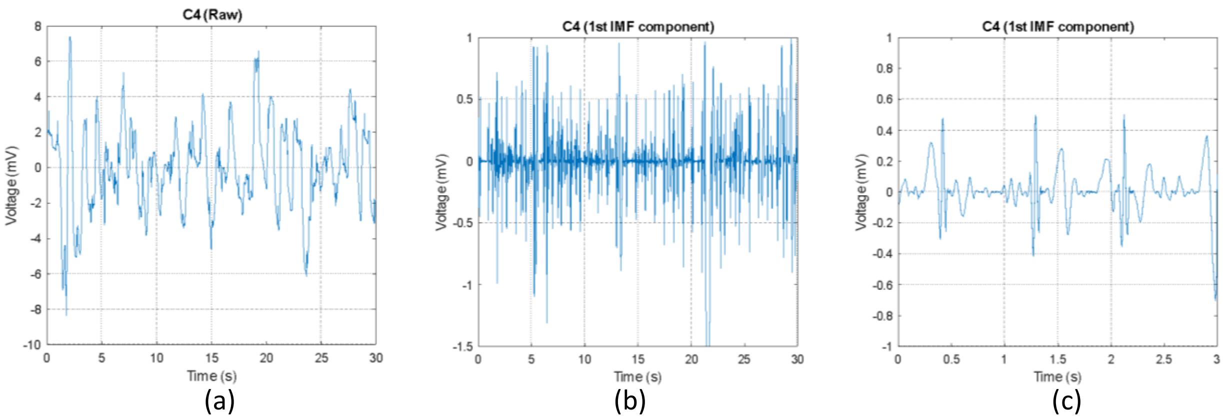


Figure 15: ECG data from test C4: (a) Raw - 30s, (b) Filtered - 30s, (c) Filtered zoomed - 3s

4. Discussion

Both prototypes can detect useful ECG data at non-active condition, from which the characteristic P,G,R,S, T peaks or in some cases P, R, and T peaks are identifiable after filtering the raw ECG data for baseline correction and filtering high frequency signals. R peaks are particularly helpful to measure the heart rate (HR) and heart rate variability (HRV), which are important biomarkers for detecting the onset of many heart diseases. Both prototypes gather ECG waveforms with distinguishable R peaks when the wearer is standing still. However, the native waveforms have signatures of baseline shifts. The data filtering tool can eliminate the baseline shifts as shown in filtered graphs.

At active condition, both prototypes collected noisy data. However, the prototype with embroidered electrode performed slightly better in active condition, especially after water application as it is evident from the figures 14c and 15c. It is important to understand why the noise is generated when the wearer is active. During the debugging process, we have found a few reasons for having very noisy signals.

- The dry skin of the wearer can be responsible for the increase of the skin-to-electrode impedance. Additionally, the humidity of the environment can also impact the skin-to-electrode impedance. Humid environment helps to develop a thin conductive sweat layer on human skin that reduces the skin impedance.
- In the current experiment set up we have used alligator metal clips to connect male snap button connected with the electrode sensors with the data acquisition system. While the wearer is active the snap buttons can move slightly and create static voltage. Therefore, the noise can be generated even if the skin-to-electrode impedance is considerably high due to the issues related with connectors. Replacement of alligator clip with female snap button should help to develop more robust connection.

The application of water improves the EC waveforms by stabilising the baseline shifts when the wearer is standing still, it cannot help capturing meaning full ECG waveforms when the wearer is active in case of the experimented prototypes, which indicate scope of further improvement of the design and materials selection.

5. Conclusion

The aim of this paper was to develop an ECG garment according the identified design criteria. The issue of user comfort was addressed through material selection and repeated fit checking using fit mannequin following standard FDD process. At the same time, efficacy of four different textile-based dry electrode configurations was tested through wearer trial with live human participant. It was found that the ECG electrodes configured from commercial conductive knitted single jersey fabric and conductive embroidery with puffy foam cushion could capture ECG signals in non-active condition and showed some promises in active condition. However, it is evident that the design of the prototype needs further improvement to capture effective ECG signal in active conditions. This is being addressed in our ongoing work. Once an effective design is established, issues of user comfort will be further explored in next step.

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Conflicts of Interest

The authors declare no conflict of interest.

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