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Textile Electrodes for Heart Rate Measurement: A Comparative study for Firefighters' Monitoring

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Abstract. This work compares the performance of wet gel electrodes and textile-based electrodes for monitoring the firefighters' heart rate during on-duty missions. Both types of electrodes are connected to a customized wearable node that acquires the bio-signals and computes the heart rate. Both types of electrodes were evaluated by two subjects and in three different scenarios: sitting, standing and moving the arms, and walking. The tests have demonstrated that in static scenarios the results obtained for both type of electrodes are comparable. However, in dynamic scenarios, the performance of textile electrodes worsens, especially when the wearer is moving the arms. Although the results obtained from textile electrodes during walking are not as good as the wet get electrodes, its information is still useful for monitoring the firefighters' heart rate.

Introduction

Urban fires are considered extremely dangerous for the firefighters' safety as the surrounding environment is harsh, highly dynamic and represents immediate life-threatening to the firefighter (e.g., high temperatures, exposure to toxic gases, skin burns, and danger of collapse) [1, 2]. Therefore, to improve the firefighters' safety during on-duty missions, the Personal Protective Equipment (PPE) should be equipped with sensors to monitor physiological and environmental parameters (e.g. external temperature, CO, CO2, heart rate, and breathing rate). Among these parameters, monitoring the heart rate is crucial as the firefighters are under a huge physical stress during on-duty missions. With the advent of the wearable devices, new solutions are being researched for monitoring physiological and environmental parameters. E-textile solutions are attractive for these systems as they are flexible, comfortable, stretchable, and provide ubiquitous and continuous monitoring [3, 4].

In order to meet the firefighters' needs during urban fires, the PROTACTICAL Cyber-Physical System (CPS) was proposed. This project was financed by the Portuguese QREN program (I&IDT-Project in Co-promotion No. 23267) and aims to improve the firefighters' performance, resilience, and safety [5]. The goals of this project are five-fold, namely: providing thermal isolation; monitoring physiological and environmental parameters, provide real-time communication between the firefighter and the incident commander; and monitoring the firefighter's position. This paper focuses on physiological parameters' monitoring, more specifically, it assesses the viability of monitoring the heart rate using textile electrodes embedded in a t-shirt.

In the last years, the scientific community has been working on different aspects of textile electrodes for heart rate monitoring. In [6–8] the authors studied impact of electrodes size, position, materials and structures on the electrode performance. In [3] the authors studied the impact that motion artifacts due moving the arms have on the electrodes performance and they observed that some peaks can be missed. In [9] the authors monitor forty patients that suffer from heart diseases while they are lying on a bed. In [10] the authors applied textile electrodes to monitor the infant's heart rate while they are sleeping. Authors also studied the impact that small movements (turning side) has on the heart rate performance. Although these works are impressive, most of them do not use a golden standard like the conventional wet get electrodes to validate the performance of the textile electrodes [11]. Additionally, most of the systems are evaluated without or with very limited movements, by just one person and the acquisition device is too big to be wearable.

Therefore, to overcome these limitations, in this work the performance of textiles electrodes is compared with conventional wet get electrodes in three distinct conditions (sitting on a chair, standing and moving the arms, and walking) and by two persons. The heart rate is measured based on a customized wearable node (node-PROTACTICAL 1) that is integrated into a Wireless Body Sensor Network (WBSN)-PROTACTICAL.

The remainder of the paper is organized as follows. In the next section, the materials and methods are presented, namely the description of the PROTACTICAL CPS and the node-PROTACTICAL 1 architectures and the design of textile electrodes embedded on a t-shirt. Then, the results obtained from the planned experiences are presented and discussed. Finally, the main conclusions of the work performed are presented as well as some future lines to expand the current work.

Materials and Methods

PROTACTICAL Cyber-Physical System. The PROTACTICAL CPS is a smart PPE that was designed to enhance firefighters' occupational health, safety, situational awareness, and comfort. This system is capable of tracking and locating firefighters [5], monitoring environmental and physiological parameters, and detecting, in real-time, life-threatening scenarios. To do that, this system collects data globally (through the WBSN-PROTACTICAL), processes the information centrally (through the Base Station PROTACTICAL), and distributes the results locally. The bidirectional communication between the firefighters and the incident commander or Base station PROTACTICAL is done through the Ad Hoc-PROTACTICAL network. Fig. 1 shows the architecture of the PROTACTICAL CPS as well as the interactions between the different elements of the system.

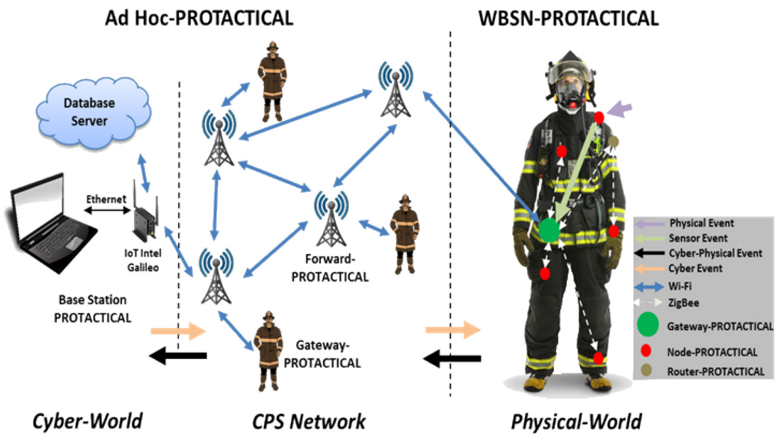


Fig. 1. PROTACTICAL Cyber-Physical System's architecture overview.

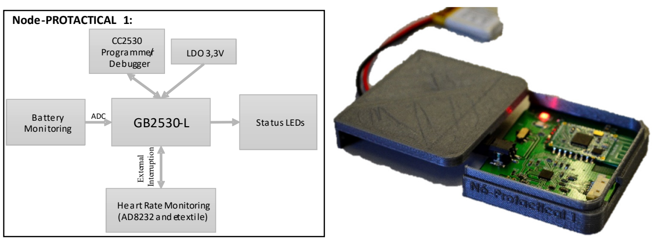
The WBSN-PROTACTICAL is designed to interact with the physical-world through the sensing and actuating capabilities of the nodes-PROTACTICAL that compose the network of the smart PPE. The gateway-PROTACTICAL is the node responsible for coordinating and managing the WBSN. The complete list of nodes that compose the WBSN-PROTACTICAL as well as the corresponding monitored parameters is shown in Table 1.

Table 1. Nodes and Monitored Parameters within the WBSN-PROTACTICAL.

Node	Garment	Monitored Parameters
1	Shirt	Heart Rate
2	Shirt	Sweat Detection and Inner Temperature (back)
3	Shirt	Breathing Rate
4	Coat	Heat Flux across the coat, Inner Temperature (front), and Inactivity/Fall Detection
5	Coat	CO, CO_2, Environmental Temperature, and Relativity Humidity
6	Boot	Inactivity and Relative Position
7	Coat	Inactivity, Panic Event, and User Feedback
Gateway	Coat	Absolute Position (GPS), Indoor Location, Environmental Temperature

The Ad Hoc-PROTACTICAL is the network of the CPS and is responsible for the bidirectional communication between the firefighters and the incident commander. To make the network scalable to cover the whole building, an ad-hoc routing protocol was implemented. The network is expandable through the use of Forward-PROTACTICAL devices that are deployed as the firefighters enter a building. The Base Station PROTACTICAL is responsible for storing and displaying the information received from the several WBSNs-PROTACTICAL, managing the network, and triggering distress messages towards the firefighters if a life-threatening scenario is detected.

Node-PROTACTICAL 1. In order to have a good acceptance among users, wearable devices have strict requirements in terms of weight, volume, and energy consumption [6, 7]. Therefore, all nodes-PROTACTICAL are designed to be unobtrusive, energy-efficient, autonomous, and to provide reliable measurements even under harsh. As depicted in Table 1, the goal of node-PROTACTICAL 1 is to measure the firefighter's heart rate. When compared to the acquisition of the full ECG signal, the heart rate requires considerable less computational resources and it is capable of providing insightful information about the users' health condition [6, 8, and 9]. Additionally, heart rate acquisition only requires a two-electrode configuration, this configuration reduces the number, size, and complexity of the connections paths, and allows the device to be placed near the heart, making the system more robust and less vulnerable to common-mode interference. Like the other nodes that compose the WBSN-PROTACTICAL, the node-PROTACTICAL 1 is composed of three main blocks: sensing, energy, and processing/transmitting. Fig. 2 shows the block diagram and the final prototype of the node-PROTACTICAL 1 used in this work.



(a) (b)

Fig. 2. Node-PROTACTICAL 1: a) diagram block representation and b) photo of the final prototype.

The processing/transceiver block is based on the low-power system-on-chip (SoC) CC2531 from Texas Instruments. This SoC includes a ZigBee-compliant transceiver and a MCS-51 compliant microcontroller that are responsible for the communication with the network coordinator and the acquisition and data processing from the sensing devices, respectively. The energy block consists of a small battery and a low dropout (LDO) circuitry. The LDO circuit is designed to provide a stable voltage to the other components of the node. A Transmission Power Control (TPC) mechanism, like the one described in [16], is implemented on the node to extend the battery lifetime. Besides extending the battery lifetime, TPC mechanisms are an essential tool to reduce the external interferences and the specific-observation-rate in wireless communications [17]. Finally, the sensing block of the node-PROTACTICAL 1 is devoted to measuring the wearer's heart rate. To do that, the AD8232 single-lead heart rate monitor front end from Analog Devices is used [18]. This heart rate front end was selected as it is capable of measuring small biopotential signals even under noisy conditions [3, 13]. Fig. 3 shows the schematic of the signal conditioning implemented for the heart rate monitoring. In the first stage, an Instrumentation Amplifier (IA) with a gain of 100 V/V is used to amplify the biopotential signal. Then, a two-pole high pass filter with a cutoff frequency of 7 Hz is used to remove the motion artifacts and the drift caused by varying electrode-skin polarization and the contact noise. Additionally, a two-pole low-pass filter with a Sallen-key configuration and a cutoff frequency of 25 Hz is used to attenuate the line noise and other interferences. At this stage, an additional gain of 11 V/V is applied to the filtered signal.

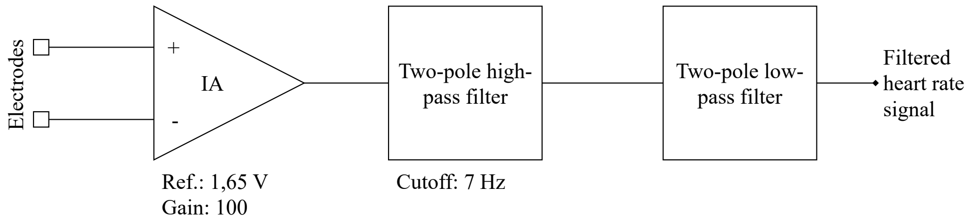


Fig. 3. Schematic of the heart rate conditioning signal.

The heart rate is calculated based on a weighted average of the RR intervals over a one minute window (Fig. 4). I.e., based on the ultralow-power internal analog comparator of the CC2531 SoC, the R peak is detected anytime the voltage of the filtered biopotential signal is above a predefined value (3V in this work). When this event occurs, an Interrupt Service Routine (ISR), corresponding to an external interrupt, is triggered and a SoC internal timer counts the elapsed time between two consecutive R peaks. The elapsed time is then converted to beats per minute.

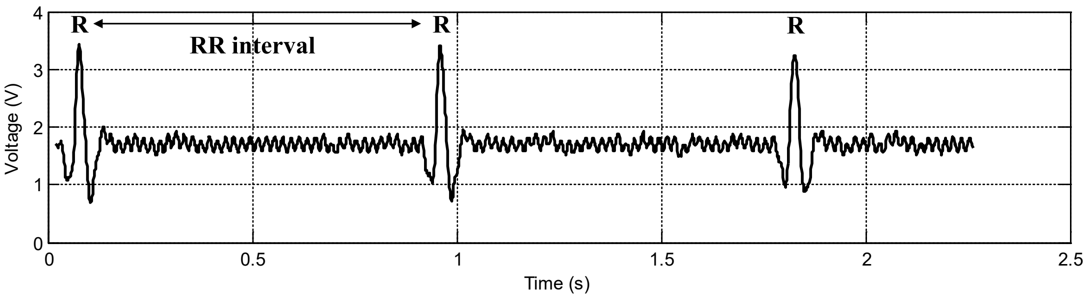


Fig. 4. An amplified and filtered biopotential signal with the R peaks and RR interval highlighted.

In addition, the AD8232 also offers a built-in feature that allows the detection of the loss of connection of an electrode. When this event occurs, one of the outputs, called Leads Off Detecting (LOD), goes to a high state. This is a useful feature to improve the system reliability and robustness.

Textile Electrodes. The firefighter's heart rate is measured based on a t-shirt with the electrodes knitted into the fabric. The t-shirt is produced in a MERZ model MBS seamless jacquard knitting machine and is designed to have a tight fit with the wearer's body. This design choice aims to improve and stabilize the contact between the electrodes and the skin, as well as, to improve the comfort. The t-shirt´s compression effect is achieved by using a combination of polyamide and bare elastane. A silver coated textured polyamide elastic yarn from Elitex, with low electrical resistance (in the order of tens of Ω/m), is knitted into the fabric to make the textile electrodes [15]. The contact between the skin and the textile electrodes is improved by producing the electrodes based on a patented technique that creates a voluminous structure on the electrode area, which makes the electrode area stand out from the rest of the fabric [6]. As identified in previous studies [3, 13], the best position for the electrodes is below the pectoral muscles. In this position, the electrodes are closer to the ribs and, thus, the electromyography interference can be avoided. To connect the electrodes to the node-PROTACTICAL 1, conductive leads are knitted on the base fabric with the same yarn of the electrodes but without the voluminous structure. Fig. 5 shows the t-shirt used to measure the heart rate with the textile electrodes, the conductive leads, and the node-PROTACTICAL 1.

Fig. 5. Final prototype of the t-shirt for the heart rate measurement.

Results and Discussion

Two healthy subjects were used to assess the performance of both electrodes, subject A (male, 29 years, 66 kg, and 1.68 m) and subject B (male, 32 years, 88 kg, and 1.71 m). For each subject, activity, and electrode, 20 individual tests were performed with a duration of one minute. Both electrodes are tested while user is performing different activities (sitting, standing and moving the arms, and walking). The electrodes are compared based on the averages of the heart rate and the number of beats. The number of beats is the sum of each R peak detected.

Fig. 6 shows the heart rate signals of both electrodes after filtration and amplification. As can be seen in the figure, the heart rate signal with the wet gel electrodes has less noise (Fig. 6a and c). Nevertheless, the R peak is easily identified in all figures. Another observation from those figures is that moving the arms significantly increases the noise on the heart rate signal for the textile electrodes. Additionally, in Fig. 6d we can also observe that the last R peak is slightly attenuated due to the movement of the arms, in some situations, this phenomenon can be more severe and may cause some peaks misdetection.

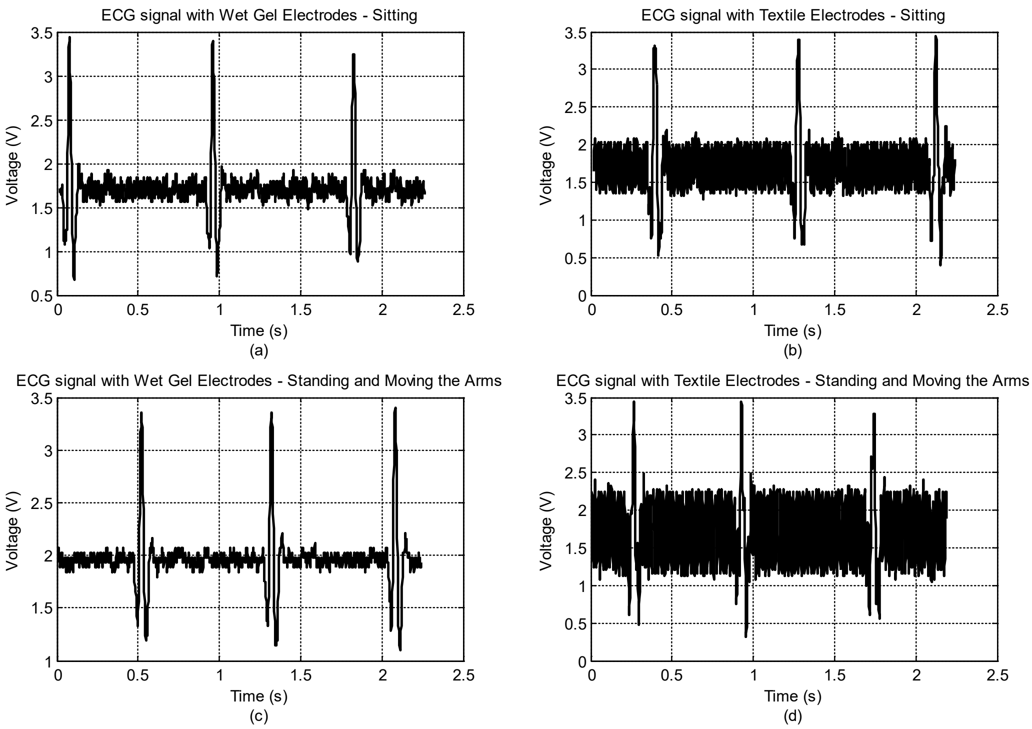


Fig. 6. Heart rate signal acquired for the different configuration tests. The first line of figures represents the results obtained when the user is sitting with a) wet get and b) textile electrodes. The second line represent the results obtained when the user is standing and moving the arms with a) wet gel and b) textile electrodes.

The results for the different electrodes, test scenarios, and subjects are summarized in Table 2. As can be observed, the results of the textile electrodes are consistently lower than the wet gel electrodes in all evaluated scenarios. When the user is sitting, the performance difference can be neglected (around 3 beats/minute). However, when the user starts moving (the standing and walking scenarios), the performance of textile electrodes significantly worsen independently of the experiment and user. E.g., when user A is standing and moving the arms, the heart rate reported when using the wet get and textile electrodes can be as different as 23 beats/minute (Table 2). This performance difference can be explained by the number of beats detected. In the same scenario (user standing and moving arms), the average number of beats detected was only 16 and 18 for the subject A and B, respectively. Although during the walking test the number of beats detected was higher (46 and 47 for subject A and B, respectively), the performance of textile electrodes was still significantly lower than the wet gel electrodes (76 and 80 for subject A and B, respectively). Nevertheless, average heart rate reported with textile electrodes is comparable with the average heart rate reported with wet get electrodes for the walking test. The bad results obtained for the standing and moving the arms experiment can be explained by the loss of connection and/or the electromyography noise added into the system due to the movement.

Table 2. Electrodes Comparison.

Subject	Test Scenario	Electrode	Heart Rate (beats/min)	StD	Number of Beats	StD
Subject A	Sitting	Wet Gel	67.58	1.32	67.27	1.29
		Textile	64.75	2.21	64.30	1.93
	Standing and Moving the Arms	Wet Gel	82.08	6.05	72.91	4.70
		Textile	68.85	16.12	16.38	9.52
	Walking	Wet Gel	82.32	3.92	76.15	5.46
		Textile	73.63	12.06	46.32	8.97
Subject B	Sitting	Wet Gel	74.31	3.30	73.49	2.71
		Textile	71.66	5.55	69.89	3.94
	Standing and Moving the Arms	Wet Gel	84.72	5.48	75.67	5.29
		Textile	73.48	14.35	17.68	10.67
	Walking	Wet Gel	83.46	2.98	79.64	5.31
		Textile	76.23	8.64	44.51	6.37

Conclusions

In this paper, a comparative study between wet gel and textile-based electrodes for heart rate monitoring was performed based on a customized wearable node. These electrodes were evaluated for static and dynamic scenarios. Although wet get electrodes have shown to be more robust in all scenarios, the textile-based electrodes have demonstrated to provide useful information when the wearer is sitting and walking. However, for high intensity movements the performance of textile-based electrodes severely worsens.

As future work, the connection between textile electrodes and the skin should be improved, as well as, the connection between the conductive leads and the node-PROTACTICAL 1. It should also be studied the viability to acquire other useful information from the heart rate signal (e.g., the heart rate variability).

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