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Design of the Heart Rate Measurement Module in a Telemonitoring Device for First Responders Deployed in Extreme Environments

Tanja Boljanić[1], Matija Štrbac[1], Jovana Malešević[1], Vladimir Kojić[1], Nikola Topalović[2], Goran Bijelić[3], and Miloš Kostić[1]

[1]Tecnalia Serbia Ltd, 11000 Belgrade, Serbia
[2]Faculty of medicine, University of Belgrade, 11000 Belgrade, Serbia
[3]Tecnalia, Basque Research and Technology Alliance (BRTA), 20009 Donostia-San Sebastian, Spain

ABSTRACT

This paper presents results of the H2020 SIXTHSENSE project, aiming to develop new methods for unobtrusive monitoring of first responders based on multimodal sensing. The goal is to determine Heart Rate (HR) signal from ECG recorded by a multi sensor smart patch in the specific conditions the first responders are facing on their deployments. In addition to the challenges commonly faced when processing ECG signals recorded by wearables in high intensity activities, the electrode placement is atypical as the ergonomic requirements of the targeted users imposed positioning the multi sensor smart patch on the user's back, and additional noise is generated by collocated active elements. The system was prototyped and examined in experiments simulating relevant conditions for the application of interest. The signals were analyzed with three established algorithms for ECG signal processing to determine the optimal method for HR detection.

Keywords: Electrocardiogram, Health monitoring, First responder technologies, H2020.

INTRODUCTION

Wearable devices for electrophysiological monitoring incorporated within smart textiles represent popular and growing market with numerous applications in healthcare and fitness (Liu et al., 2020). However, commercially available devices are simple activity trackers incorporated in armbands and smart watches (Degroote et al., 2020). Currently, there are no comprehensive systems for continuous monitoring physiological strain of first responders. The presented work is part of the SIXTHSENSE project[1], a research and innovation action with the aim to develop just that, a wearable health monitoring system with closed loop tactile biofeedback, that allows first responders in hazardous situations to sense their current health status.

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[1] https://sixthsenseproject.eu/

One of the most used direct indicators of the physical states is the Heart Rate (HR). Specifically, in combination with the gastrointestinal temperature, HR makes up the physiological strain index (PSI), a "real-time" monitoring tool of the overall state of the physiological strain. The PSI has been found a good indicator of current wellbeing status of the first responders in extreme environments (Carballo-Leyenda et al., 2018; Rodríguez-Marroyo et al., 2012) and is a key element in the SIXTHSENSE decision support system. The HR is a relatively robust measurement, as here the ECG signal analysis is reduced to the R peaks detection, which is possible even in presence large artefacts (Paradiso et al., 2005). However, there are many potential sources of noise, such es electromyogram, baseline drift caused by sudden movement or breathing, motion artifacts due to unstable electrode-skin contact, T waves with high-frequency characteristics similar to QRS complex, etc. (Dohare et al., 2014). Additionally, in a vast majority of wearable applications the standard 12-lead approach for ECG recording is unfeasible, and finding the optimal locations for electrodes accounting for anatomic variability, ease of use and minimization of movement artefacts, is a highly research topic (Cai et al., 2017). Placement in the chest region is prevalent, as it facilitates the signal recording and is often convenient from the usability perspective (Prats-Boluda et al., 2016). However, sometimes measuring ECG on the back is an application requirement, and despite the non-standard location, its feasibility was demonstrated in a study for detection of optimal recording position covering the entire trunk (Cho and Lee, 2015). Among the four top rated locations, two were found in both sides of the latissimus dorsi muscle. Additionally, from the clothing engineering perspective, these locations coincide with the least dynamic zone on the trunk.

To address issues related to varying types of noise and electrode placement schemes, there are many different algorithms for HR detection, with specific advantages. In this paper three were considered. The most popular and often used as the referent one is Pan-Tompkins algorithm (Pan and Tompkins, 1985), based on digital analysis of slope, amplitude and width of signals. The second is the a-QRS method based on adaptive thresholds fluctuating in respect to both noise and signal using the averaging and adaptive approach (Hooman, 2022). The last one is the wavelet analysis method prosed by (Mahmoodabadi et al., 2005).

This paper presents the custom electrode for measuring ECG that is integrated into Multi Electrode Array (MEA) basis, intended to be positioned on the back due to overall system requirements. Results are obtained in an experiment where three subjects performed functional tasks the first responders are facing on their deployments. Additionally, the subjects were exposed to electrotactile stimulation (ETS) to examine its effect on the ECG signal.

METHOD

Setup

The ECG recording electrodes used in the test were a part of the sensing multi electrode array developed for the SIXTHSENSE project. The center-to-center distance between the two active electrodes was 158 mm, and the

Figure 1: Left: recording multielectrode array with approximate placement on the subject. Middle: A subject during the test with the multielectrode array secured by an elastic girdle. Right: The ETS electrode.

reference electrode was at 75 mm below the right active electrode. Their radius was 20 mm, and each was covered with hydrogel (AG735, Axelgaard, Inc.). The recording multi-electrode array was placed over the subject's lower back, with the active electrodes at the approximate level of T11/T12. To ensure stable electrode-skin contact the ECG pads were secured with a medical tape and then covered by a stretchable girdle, as shown in Figure 1. The data acquisition and was performed with the SIXTHSENSE Alpha Mobile Device (AMD - Global Electronic Solutions, RS) using an ECG amplifier module (AD8232, Analog Devices, USA). The module was also secured with a medical tape to avoid potential noise due to connection cables and amplifier movements. The data was sampled at 1 kHz and stored in the device SD card for offline processing. Polar H10 was used as a referent heart rate sensor to determine the physiological strain in function of the maximal HR, calculated as 208 – 0.7*(age) (Tanaka et al., 2001). It was positioned on the central line below the chest with its elastic belt. The AMD prototype was also used to produce electrotactile stimulation (ETS) artefacts through a multielectrode array with 8 active pads and a common reference electrode (Figure 1, right), placed centered around the midaxillary line, as presented in the setup of (Štrbac et al., 2021). Only the six smaller were used. The ETS was performed with rectangular current controlled biphasic pulses with 300 μs width, at 30 Hz. The current amplitude was set at 200% of sensory threshold for each subject, at each pad following the conclusion of (Malešević et al., 2021). Here it ranged between 5 and 7 mA. The stimulation was played throughout the test in cycles of 0.5 s stimulation at each of 6 used pads, followed by one second pause.

Three healthy volunteers (two female, one male; between 25 and 33 years old) without any known cardiological disorders participated in the study. The study was conducted at the Institute of Medical Physiology "Richard Burian", Faculty of Medicine, University of Belgrade, Belgrade, Serbia. The experimental protocol including the informed consent signed by the participants was approved by the local ethics committee.

Protocol

The test had eight phases, each lasting for one minute, designed to simulate some of the specific tasks usually performed by first responders of interest (firefighters and mountain rescuers). The first six phases were performed on the treadmill in three levels of physical strain, without and with added ETS. The first two phases were the baseline, with the subject standing still without any perturbations and with only ETS. The third and fourth phase were with subjects walking on the treadmill at the pace that allowed maintaining the HR between 40% and 60% of the maximal HR, without and with ETS, respectively. The fifth and sixth phase were done in the same way, but with a pace and inclination that kept the HR between 60% and 80% of the maximal HR. The last two phases included simulated functional tasks. In the seventh phase the subjects used a fire-swatter simulating smothering the fire on the ground, while in the eight phase the task was to lift or lower a heavy box with handles (8 kg for females and 16 kg for mails) between the floor a waste high platform. Both stages were done for 60 seconds, starting from a rested state and at a high intensity.

Data Analysis

As described in the previous sections, ECG data was collected for 60 seconds at 1 kHz sampling rate in each experimental phase. Three commonly used and publicly available methods for detection of R peaks were applied to determine which approach was best suited for the specific application: 1) the Pan-Tompkins (PT) method[2]; 2) The a-QRS method (Hooman, 2022); 3) The wavelet multiresolution transform (WT) method. The signal preprocessing was not included in the publicly available source code of the WT method, so the procedure from PT algorithm was used. Each method provided locations of detected R peaks in the recorded signals. An outlier was defined as R peak when the HR value differed by at least 20% from the previous HR value. Three measures of algorithm performance were used: 1) the total number of detected peaks; 2) the percentage of incorrectly detected R peaks, outliers 3) the longest signal interval containing only outliers

RESULTS

Figure 2 shows representative 3 s segments of measured ECG signals for each of eight phases with detected R peaks. Calculated HRs are also indicated for each signal. An example of calculated HR for a subject during the first six phases of the test is shown in Figure 3. The threshold of 110 bpm indicates the boundary between light and moderate physical activity. Finally, in Table 1 the three methods are compared in respect to the defined measures.

DISCUSSION

The aim of the presented paper was to investigate the possibility to reliably measure the Heart Rate with a multi-sensor electrode array positioned on the lower part of the back in scenarios faced by the first responders of interest, where both increased physical activity and electrotactile stimulation are present. As shown in Figure 2, these have produced notable artifacts in

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[2] https://www.mathworks.com/matlabcentral/fileexchange/45840-complete-pan-tompkins-implementation-ecg-qrs-detector

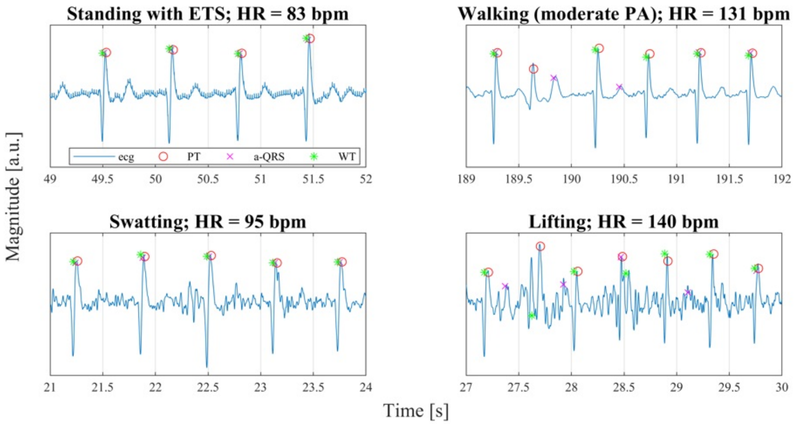

Figure 2: Examples of recorded ECG signals during different phases of the test. Phases and calculated heart rates are labeled on subplot titles. Detected R peaks are marked according to the legend.

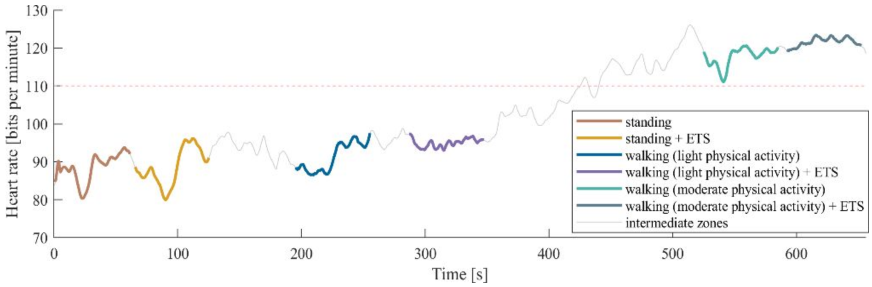

Figure 3: Estimated heart rate during the first six phases of the test with the Pan-Tompkins method. Each phase is represented with different color, while intermediate zones are grey.

the recorded signal. However, the results shown in Table 1 indicate that all three applied methods could reliably identify the R peak and thus allow HR assessment in most conditions.

In general, the results in Table 1 show that the a-QRS method is having the worst performance, especially for the Subject 3. The signals shown in Figure 2 showcase examples of this issue. It appears that there is an atypically large T peak in the recorded signals of this subject, which is more pronounced at higher exertion levels. The adaptive algorithm of this method seems to be susceptible to this type of artefact and fails to discriminate between T waves with high frequency characteristics (similar to QRS complex) from the actual QRS complex. As the first wrongly identified R peak shifts the varying threshold to a level that induces further errors. Being that the overall performance of this method was inferior to the other two methods, its use in further stages will be reevaluated.

An observation of interest for the application is that the ETS does not seem to have any significant effect on the R peak detection, as the number of outliers is comparable between the paired conditions with and without

Table 1. Total number of detected R peaks (Beat), the percentage of outliers (Out) and the longest interval containing only outliers (Null) obtained by the three methods.

		Subject 1			Subject 2			Subject 3		
		PT	a-QRS	WT	PT	a-QRS	WT	PT	a-QRS	WT
Standing	Beat [#]	109	108	109	88	88	88	118	114	113
	Out [%]	0	0,9	0	0	0	0	3,4	10	1,8
	Null [s]	0	1,53	0	0	0	0	1,51	2	2,01
Standing + ETS	Beat [#]	107	107	107	88	88	88	120	117	119
	Out [%]	0	0	0	0	0	0	3,3	0	2,5
	Null [s]	0	0	0	0	0	0	1,49	3,42	1,48
Walking 1	Beat [#]	102	102	102	91	91	91	121	111	114
	Out [%]	0	0	0	0	0	0	11,6	24,3	6,2
	Null [s]	0	0	0	0	0	0	1,49	3,89	1,48
Walking 1 +ETS	Beat [#]	98	98	98	95	95	93	118	113	114
	Out [%]	0	0	0	0	0	0	5,1	14,3	3,5
	Null [s]	0	0	0	0	0	0	1,58	3,63	1,58
Walking 2	Beat [#]	118	108	126	118	115	119	132	98	131
	Out [%]	5,9	16	11,1	0	1,7	0,8	1,5	61,2	0,8
	Null [s]	1,5	9,4	3,1	0	1,53	1,51	1,38	14,6	1,39
Walking 2 +ETS	Beat [#]	125	128	121	122	109	120	132	98	129
	Out [%]	8,8	31	5,8	0,8	12	0	5,3	57,1	1,6
	Null [s]	1,5	5,6	1,43	0,5	0,59	0	1,89	10	1,88
Swatting	Beat [#]	91	91	91	102	97	99	121	114	120
	Out [%]	0	0	0	9,8	27	13,3	1,6	6	1,7
	Null [s]	0	0	0	2,5	14,52	3,18	0,94	2,53	1,05
Lifting	Beat [#]	95	94	94	111	102	114	139	103	138
	Out [%]	2,1	1,1	0	8,1	28,4	14,9	18,7	44,1	23,2
	Null [s]	1,4	2,22	0	4,2	15,1	3	2,39	13,9	3,13

these artefacts. Even though the noise generated by the ETS system is several orders of magnitude higher than the ECG signal at the source, the recorded noise is significantly smaller. One of the possible causes of small interference could be the concentric design of the ETS electrode intentionally selected for this purpose (Jiang et al., 2014). Additionally, the used short pulses (300 μs), at 30 Hz are very susceptible to the standard preprocessing applied in R peak detection methods (Pan and Tompkins, 1985). Finally, the intensity of physical activity seems to be the main cause of erroneous detection of R peaks in all three methods. This is in line with earlier observations where activities entailing high level of body movement were identified as major contributors to inaccurate HR estimation (Pola and Vanhala, 2007). The unstable skin electrode contact was cited as the most probable cause of wrongly identified artefacts, which is in line with our observations. The relatively good results even in the high intensity activities can probably be attributed to the use of adhesive hydrogel and a tight-fitting elastic girdle. The highest levels of error were noted in the tasks of high intensity walking, swatting, and lifting. However, even in cases where over 50% of the detected R peaks were outlier, the longest period without correctly detected R peaks was not higher than

15s. This means that HR could be correctly assessed and updated at a rate of at least 4 times per minute, which is acceptable in all practical applications.

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