An undershirt for monitoring of multi-lead ECG and respiration wave signals

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***Abstract*—This paper presents the design and testing of a novel undershirt embedding dry bio-potential electrodes for biosignals acquisition. This undershirt is aimed to be used for monitoring vital signs of a human subject, such as multi-lead ECG and respiration wave signals. The obtained results demonstrate that the developed undershirt can satisfy the needs for bio-potential transfer to the data acquisition system in case of wearable applications.**

***Index Terms*—undershirt, bio-potential electrodes, characterization, wearable applications.**

I. INTRODUCTION

In the latest years the application of the Internet of Things (IoT) [1] paradigm to tele-medicine and healthcare systems brought the uprising of Wearable Health Devices (WHD) and Internet of Medical Things (IoMT) [2]. These systems consist of a large number of sensors capable of acquiring several vital parameters from a subject, in a non intrusive way. Usually, the acquisition of vital signs is performed using electrodes which are integrated in a piece of clothing, such as a band, a shirt or an undershirt [3]. In [4], a review of solutions based on t-shirts used for monitoring physiological signs has been proposed. The authors highlighted the main challenges for their design: (i) the material of the wearable cloth must be soft and flexible, in order to guarantee good vestibility, (ii) the cloth must be able to be worn indistinctly by women and men, and (iii) the material used for sensing must preserve its metrological performances after several washing cycles and after repeated usage. In literature, several studies tackled the problem of which material to use in order to design an electrode that complies with the above mentioned requirements, and guarantees the integrity of the acquired physiological signals. In [5] the authors characterized several electrodes (e.g., wet electrodes, ink-jet printed electrode, textile electrode and spiked electrode), in order to find the most suitable one to be utilized in prolonged acquisition. The best performances are reached by disposable wet electrodes, but they're not suitable for prolonged acquisition due to the degradation of the performances when the gel gets dry. Textile electrodes are the second best, but the absence of any kind of substance between the fabric and the skin makes them very susceptible to movement artifact, needing a more tight fastening.

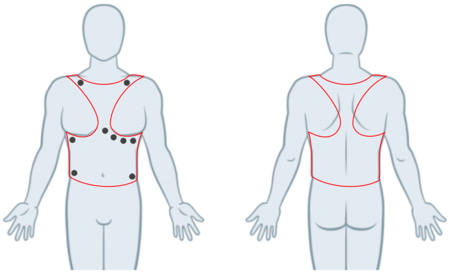

Fig. 1: The idea of an undershirt for ECG and respiration wave signals monitoring within the ATTICUS R&D project.

In [6], a direct comparison between dry and wet electrode is presented. In particular the authors performed several experiment in order to examine the effect of power lines harmonics on the electrode impedance and the change in contact impedance due to usury and the effect of movement. Similarly, the best performance are reached by wet electrodes but, the authors highlighted an interesting property of dry electrodes: over time, for long acquisition, sweating dampens the critical problems of dry electrodes, such as higher impedance (when compared to wet ones) and movement susceptibility, making them an appealing solution for WHD. In [7], the authors tested the degradation of several materials utilized in the manufacturing of dry electrode when facing repeated washing. By measuring the contact impedance after several washing cycles, the authors stated that textile polymer is a very promising material for realizing comfortable and durable electrodes and the effect of degradation are notable only after 50 washing cycles.

This paper presents an undershirt (see Fig. 1) garment as a design solution for the monitoring of multi-lead ECG and respiration wave signals. In particular, the proposed solution has been developed with the aim of: (i) guaranteeing a good level of comfort, (ii) providing a good adherence of the electrodes to the body, and (iii) allowing to be worn by both men and women.

This is part of the Ambient-intelligent Tele-monitoring and Telemetry for Incepting & Catering over hUman Sustainability (ATTICUS) project, with the aim of developing an intelligent hardware/software system, able to constantly monitor an individual and report anomalies concerning both his/her state of health, detected through the automatic measurement and analysis of vital parameters. In particular, a first prototype of the garment has been designed, using electrodes made of Carbon Black (CB), and characterized in terms of impedance, by comparing it with one of the most used type of wet electrodes (F9089/100 by Fiab).

The remainder of the paper is structured as follows. In Section II, the proposed undershirt is presented. The experimental setup is reported in Section III. The obtained experimental results are described in Section IV. Finally, in Section V several conclusion are drawn and the future work plan.

II. THE PROPOSED UNDERSHIRT

Preliminary research efforts were undertaken to choose the best prototype in terms of (i) textile surface (for the integration of the electrodes) and (ii) adaptability of the clothing in order to be worn indistinctly by women and men. The three categories of clothing initially analyzed were: the t-shirt, the thoracic band and the *bustier*. The best trade-off was met with the *bustier* prototype [8]. This latter—inspired by the idea of a traditional sports bodice—was then adapted to the ATTICUS requirements. Therefore, it was tailored to be worn by both men and women while retaining the same versatility and acquisition consistency. Indeed, the adapted prototype is composed of a thin line of fabric that crosses the centre of the chest area. The textile surface of this prototype was considered enough from the ATTICUS' medical equip in order to host the electrodes for the acquisition of the ECG and respiration signals. According to the specific requirements of the ATTICUS project, the pathological conditions to be monitored can be identified with the following configuration of signals: the *pre*-cordial leads V1, V3 and V5 combined together with the 4 limb leads RA, LA, RL, LL (Right and Left Arm, Right and Left Leg). The prototype is shown in Fig. 2. This can be considered as a reduced typical ECG 12-lead electrode placement. Furthermore, two electrodes for the acquisition of the bio-impedance respiratory signal were added: the first next to V5 and the second—by symmetry—on the other side.

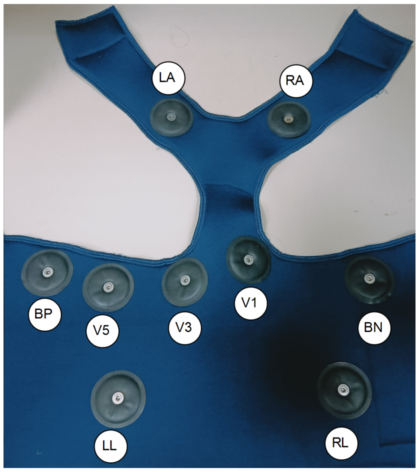

Fig. 2: The implemented undershirt with reported labels of the ECG and the bio-impedance electrodes.

According to a recent state-of-art work [9] on the best e-textile structure in terms of conductivity, the CB can be used to construct optimal configurations of wearables. In addition, if compared to other conductive fillers such as graphene-based fibres or single-walled carbon nanotubes (SWCNTs), the CB shows better stretchability [10]. Based on these considerations, the ATTICUS wearable is equipped with CB textile electrodes.

The main requirement that the *bustier* should satisfy is first of all a certain comfort for the subject wearing it. At the same time, however, it has to guarantee not only a perfect adherence to the body, but also a stability of the contacts between body and electrodes, and that such contact remains uninterrupted also during the movements of the subject, especially considering that the use of glues or natural silicone or substances—that could favour the holding of the electrodes on the skin—is not considered in the project. In the light of the above indications, first of all, the fabric to be used had to be elastic, soft and light but capable of maintaining a certain tenacity and compactness. In addition, given the intended use, the fabric also has to meet the requirements of durability, resistance to washing, daily use and continuous manipulation. Initially, the idea was to use a heavy jersey fabric of various weights, but this solution was immediately discarded due to the lack of suitability to be subjected to the application of both electrodes and Velcro - elements for adjusting the fit. After several research efforts, the attention was focused on a particular Polyester-Elastane fabric, similar to the Neoprene fabric used for diving suits, technically called SCUBA. This fabric was found to be immediately responsive to all the requirements of the project. In practice, the Scuba is porous and very flexible but not deformable. Its composition is 94% Polyester - 6% Elastane and it has elasticity in both warp and weft. Its main properties are: elasticity, resistance to scratches and accidental cuts, to crushing and wrinkling, and, within certain limits, it is insulating and resistant to water and heat. These characteristics, combined with its affordable cost and ease of processing into a pack, have determined the preference of this fabric over others.

For what concerns the wearability of the bodice, the research initially started from the characteristics of the fabric. First of all, the garment has to be used both by a man and a woman, so it was necessary to study a universal model that would suit both. To ensure adaptability to all average body shapes, the bodice is equipped with five points of adjustment in which, through Velcro, it is possible to manage the exact fit for most wearers. The adjustments are present on both sides, on both points of the shoulder and on the back.

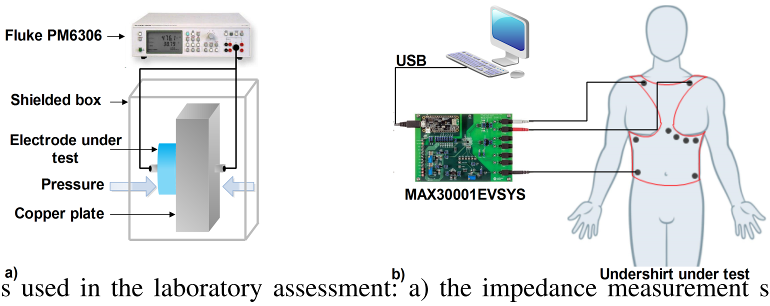

Fig. 3: Experimental setups used in the laboratory assessment: a) the impedance measurement setup for the characterization of the electrodes, b) the setup used for the signal acquisition.

The CB electrodes have been integrated into the insulant textile through a heat-sealing technique. These textile electrodes are coupled with medical buttons, in order to allow the usage of typical medical cable for the acquisition of the signals. This choice of project has the final goal to make the wearable washable. Indeed, in this way, the entire system—including both the electronic box and the wiring harness—is completely detachable and independent from the wearable. This is due to the obvious need to be able to wash and maintain the body without compromising the integrity of the electronic elements.

III. LABORATORY EXPERIMENTAL SETUPS

Preliminary performance analyses of the developed undershirt have been performed in a laboratory environment with the aims of: (i) assessing the impedance values of the the CB electrode by applying several pressure levels against the impedance values exhibited by the standard disposable electrode F9089/100 by Fiab, (ii) validating the correct acquisition of the 6-leads ECG and respiration wave signals from the developed undershirt, and (iii) comparing in terms of Power Spectral Density (PSD) the $50\,\mathrm{Hz}$ disturbance effects on the signals acquired by the undershirt against the signals acquired with standard disposable electrodes F9089/100 by Fiab. For performing the above analyses, two experimental setups have been adopted (see Fig. 3).

The first one consists of the impedance meter Fluke PM6306 [11], which is connected to the electrode under test with a terminal and to a copper plate with the other terminal, as depicted in Fig. 3a. In the case of the disposable electrode F9089/100 by Fiab, it has been attached to the copper plate with its adhesive, while the CB electrode, used in the developed undershirt, is attached to the copper plate trough a vise. The vise is used to assess the impedance variability against mechanical pressure applied on the electrode and the plate. The Fluke PM6306 has been configured for measuring the magnitude and the phase of the impedance at several frequencies ranging from $50\,\mathrm{Hz}$ to $1\,\mathrm{MHz}$. The mechanical equipment has been placed in a shielded box for reducing the effects on the acquired measurements of electromagnetic disturbances available in the environment.

As depicted in Fig. 3b, the other setup consists of the MAX30001EVSYS evaluation kit [12], which is connected to the CB electrodes embedded into the undershirt according to the ECG lead to be monitored or the bio-impedance terminals, and transmits the acquired samples to a PC via USB. In particular, the MAX30001EVSYS has been configured as follows. For the ECG signal acquisition, the Programmable-Gain instrumentation Amplifier (PGA) gain is $20\,\mathrm{V/V}$, and the sample rate of the 18-bit sigma-delta ADC is $512\,\mathrm{Samples/s}$. Two digital filters are configured: (i) the first one is a 1st-order Infinite Impulse Response (IIR) Butterworth high-pass filter with a cut-off frequency of $0.4\,\mathrm{Hz}$, and (ii) the second one is a Finite Impulse Response (FIR) low-pass filter of 12 taps with a cut-off frequency of $40\,\mathrm{Hz}$.

For the ECG acquisition, the MAX30001EVSYS evaluation kit requires the connection of three input terminals. For monitoring the Einthoven's triangle leads, the reference input terminal is connected to the RL electrode and the positive (P) and negative (N) input terminals are connected as follows (see Fig. 2: (i) for lead I, to LA and RA electrodes, respectively, (ii) for lead II, to LL and RA electrodes, respectively, and (iii) for lead III to RA and LL electrodes, respectively. On the other hand for the precordial leads V1, V3, and V5, the reference input terminal is connected to RL, the N terminal to LL and the P terminal to V1, V3, and V5 electrodes, respectively, (see Fig. 2).

Regarding the respiration wave acquisition, the bio-impedance channel of the MAX30001EVSYS has been configured to provide a current with a magnitude of $32\,\mu\mathrm{A}$ at a frequency of $80\,\mathrm{kHz}$. Before demodulating the voltage measured at the bio-impedance inputs, an analog high-pass filter having cut-off frequency of $1\,\mathrm{kHz}$ is used. After the demodulation stage, the voltage signal is amplified with a PGA having a gain of $20\,\mathrm{V/V}$. The amplified signal is converted with a 20-bit sigma-delta ADC at the sample rate of $64\,\mathrm{Samples/s}$.

Respiratory rate is an early, extremely good indicator of physiological conditions such as hypoxia (low levels of oxygen in the cells), hypercapnia (high levels of carbon dioxide in the bloodstream), metabolic and respiratory acidosis. For the respiration wave acquisition, the MAX30001EVSYS requires the connection of two output terminals, for driving the current into the body, and two input terminals, for acquiring the voltage signal. In particular, the adopted configuration consists of connecting the positive output to the positive input terminal to the BP electrode, while the negative terminals are connected to the BN electrode (see Fig. 2).

IV. RESULTS AND DISCUSSION

In this section, the results obtained with the test setups described in the previous sections are reported and discussed. In particular, the discussion is divided into three subsections. The first one deals with the results obtained with the impedance meter setup and compares the impedance measurements obtained with CB electrode and the disposable electrode. The second one contains the results obtained from 1 minute of acquisition of the ECG leads related to a healthy 27 years old male subject. The last section contains the results obtained from the acquisition of the respiration wave signal obtained in 2 minutes of quiet breathing of the same subject.

A. Characterization of CB electrodes

In Fig. 4, the magnitude and phase of the impedance measurements provided by Fluke PM6306 by considering as electrode under test the F9089/100 by Fiab and the CB electrode embedded on the undershirt are depicted. The analysis is carried out for frequencies ranging from 50 Hz to 1 MHz, and for each frequency, 30 phase and magnitude measurements are acquired for estimating the average and the standard deviation. In particular, it is possible to observe that the impedance of the Fiab electrode (called "patch") has a magnitude of around 50 Ω, while the phase, in the considered frequency range, varies from −10° to 0°. Thus, at low frequencies, the electrode can be modeled as the series of a capacitor and a resistor with a capacitance value of around 340 µF at 50 Hz, while at higher frequencies, the impedance behavior tends to a pure resistor, being, for example at 100 kHz, the capacitance reduced at the value of around 10 µF. In conclusion, for frequencies up to 100 kHz, the impedance components consist of the series of a resistor of 50 Ω and a capacitor that reduces with frequency.

On the other hand, the impedance exhibited by the CB electrode can be modeled as a pure resistor for frequencies up to 500 kHz. For the CB electrode, the impedance has been measured against frequency by considering three pressure levels applied on the electrode with respect to the copper plate. This analysis has been performed from a qualitative point of view, thus, the pressure levels have not been measured. For the three pressure levels, identified in Fig. 4 as "Carbon black: low pressure", "Carbon black: middle pressure", and "Carbon black: high pressure", it is noted that the magnitude of the impedance decreases with pressure for all the considered frequency range. In particular, a reduction of about 2 Ω, compared to the low pressure case is obtained when a middle pressure is applied, while this constant reduction is about 4.5 Ω for the high pressure case. At the frequency of 50 Hz, the magnitude of the impedance is 23.8 Ω ±0.3 Ω, 21.4 Ω ±0.3 Ω, and 18.9 Ω ±0.3 Ω, with a coverage factor of 3, for the low pressure, middle pressure and high pressure levels, respectively. The above analysis demonstrated as, at low frequency, the behavior of the CB electrode can be modeled as a resistor having resistance depending on the applied pressure, against the model consisting of a resistor in series with a capacitor that should be adopted for the disposable electrode. Due to the dependency of the resistance of the CB electrode with the pressure, it will be more sensitive to motion artifact than the disposable one.

B. Multi-lead ECG signal acquisition

Fig. 5 and Fig. 6 report four seconds of acquisition of the ECG leads in case of using the disposable electrodes and the proposed undershirt, respectively. In both cases, it is noted that the ECG acquisition related to the Einthoven's triangle leads are noisier than the precordial ones. Furthermore, the ECG signals acquired in case of precordial leads with the undershirt exhibit less noise components respect to the ECG signals acquired with the disposable electrodes, especially for V1 and V3. The Power Spectral Density (PSD) values at the harmonic frequencies of 50 Hz, 100 Hz, and 200 Hz have been assessed with the aim of quantifying the effect of electrical network disturbances on the acquired signals. In particular, before evaluating the PSD, each acquired ECG signal has been normalized with respect to the maximum amplitude of its R peaks. In Table I, the obtained PSD values for each ECG lead are reported in case of disposable electrodes and monitoring with the proposed undershirt. For leads I and II, the ECG signals acquired with the disposable electrodes have PSDs of the harmonic components lower than the PSDs of the signals acquired with the undershirt. On the other hand, for leads III, V1, V3, and V5, the signals acquired with the undershirt exhibit PSDs lower than the disposable electrodes ones. However, in all the cases, the harmonic components can be easily attenuated by using digital notch filters.

C. Respiration wave acquisition

The bio-impedance signals acquired with the MAX30001EVSYS in case of disposable electrodes and by using the proposed undershirt for a monitoring time of two minutes are depicted in Fig. 7 and Fig. 8, respectively. In case of disposable electrodes, the average of the bio-impedance measurements is 496.1 Ω and the

TABLE I: Power spectral density of the harmonic components at 50 Hz, 100 Hz, and 200 Hz for the normalized ECG signals in case of patch electrodes and undershirt with CB electrodes.

Lead	**Disposable electrodes**			**Undershirt**		
	PSD [dB/Hz]			**PSD** [dB/Hz]		
	50 Hz	100 Hz	200 Hz	50 Hz	100 Hz	200 Hz
I	−16	−62	−76	−7	−54	−69
II	−3	−53	−66	−2	−49	−63
III	1	−46	−58	−11	−59	−71
V1	−15	−61	−79	−31	−74	−90
V3	−11	−57	−71	−29	−70	−81
V5	−22	−64	−75	−37	−75	−92

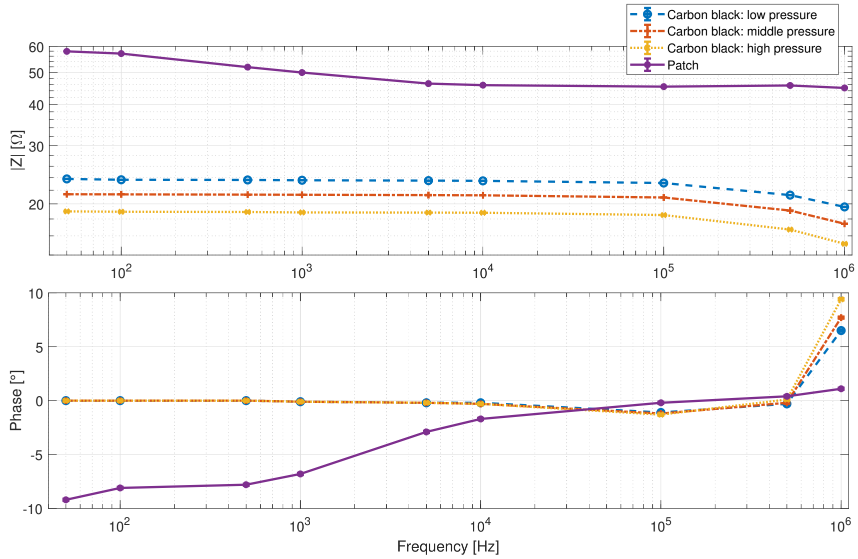

Fig. 4: Magnitude and phase of the impedance measurements for patch electrodes and CB electrodes at different pressure levels in the frequency range of $50\,\mathrm{Hz}$ to $1\,\mathrm{MHz}$.

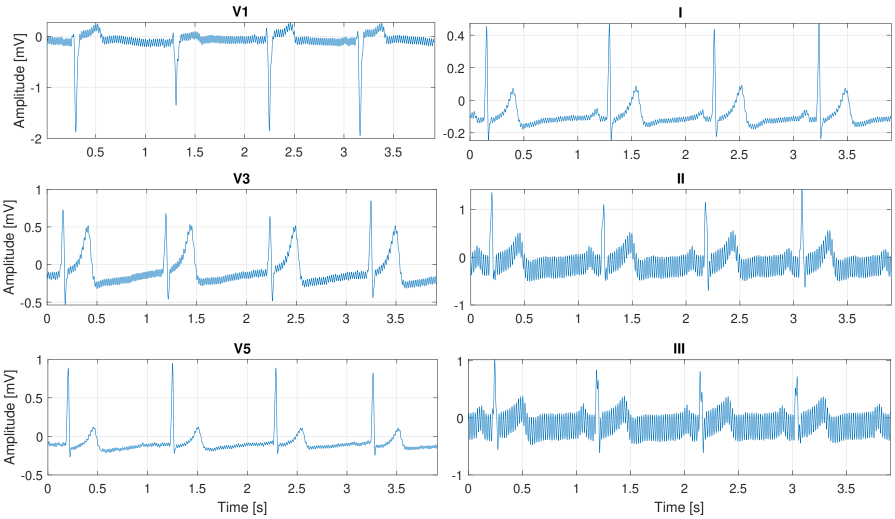

Fig. 5: ECG signals related to V1, V3, V5, I, II, and III leads acquired with disposable electrodes by means of MAX30001 evaluation board at $512\,\mathrm{Sa/s}$.

maximum variation of the bio-impedance measurements due to the subject breathing is $10.4\,\Omega$. For the proposed undershirt, the average of the bio-impedance measurements in case of CB electrodes is $147.2\,\Omega$ and the maximum variation of the bio-impedance measurements is $9.1\,\Omega$. Even if the average value of the impedance is reduced in case of CB electrodes respect to the disposable ones, the variation due to the subject breathing does not change significantly. Thus, in this preliminary analysis, it seems that the information content of the respiration wave into the bio-impedance measurements does not present significant changes if CB electrodes are used instead of the standard disposable electrodes.

V. CONCLUSION AND FUTURE WORK

In this paper, a preliminary characterization of an undershirt embedding Carbon Black bio-potential electrodes for ECG and respiration wave signals acquisition was presented. The obtained results have been assessed against commercially available patches and it was demonstrated that the adopted solution could fulfill the ATTICUS project requirements in terms of wearability and bio-potential signal integrity.

Further work is directed to test the developed undershirt in real conditions by wearing it by a subject for many hours

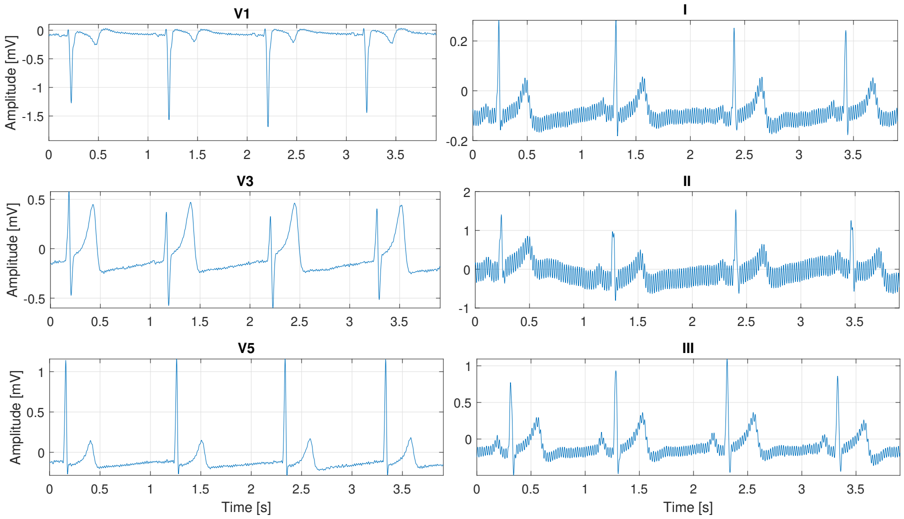

Fig. 6: ECG signals related to V1, V3, V5, I, II, and III leads acquired with CB electrodes embedded on the undershirt by means of MAX30001 evaluation board at $512\,\mathrm{Sa/s}$.

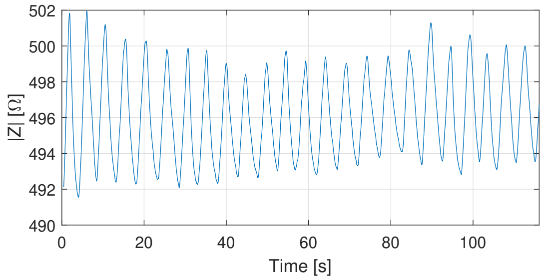

Fig. 7: Bio-impedance signal acquired with disposable electrodes by means of MAX30001 evaluation board at $64\,\mathrm{Sa/s}$.

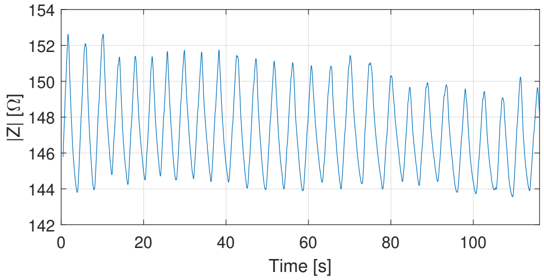

Fig. 8: Bio-impedance signal acquired with CB electrodes by means of MAX30001 evaluation board at $64\,\mathrm{Sa/s}$.

in order to assess the effect of skin humidity and body temperature variations. Furthermore, the test reported in this work will be performed on more subject, in order to valuate the repeatability of the results.

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REFERENCES

[1] E. Balestrieri, L. De Vito, F. Picariello, S. Rapuano, and I. Tudosa, “Research challenges in measurement for Internet of Things systems,” *ACTA IMEKO*, vol. 7, pp. 82–94, Dec. 2018.

[2] N. D. Wanjari and S. C. Patil, “Wearable devices,” in *2016 IEEE International Conference on Advances in Electronics, Communication and Computer Technology (ICAECCT)*, pp. 287–290, 2016.

[3] T. Wu, J.-M. Redouté, and M. Yuce, “A wearable, low-power, real-time ECG monitor for smart t-shirt and IoT healthcare applications,” in *Advances in Body Area Networks I* (G. Fortino and Z. Wang, eds.), pp. 165–173, Springer, 2019.

[4] A. S. Muhammad Sayem, S. Hon Teay, H. Shahariar, P. Luise Fink, and A. Albarbar, “Review on Smart Electro-Clothing Systems (SeCSs),” *Sensors*, vol. 20, no. 3, 2020.

[5] L. Xie, G. Yang, L. Xu, F. Seoane, Q. Chen, and L. Zheng, “Characterization of dry biopotential electrodes,” *Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, vol. 2013, pp. 1478–1481, 07 2013.

[6] A. Searle and L. Kirkup, “A direct comparison of wet, dry and insulating bioelectric recording electrodes,” *Physiological measurement*, vol. 21, pp. 271–83, 06 2000.

[7] E. Kaappa, A. Joutsen, A. Cömert, and J. Vanhala, “The electrical impedance measurements of dry electrode materials for the ecg measuring after repeated washing,” *Research Journal of Textile and Apparel*, vol. 21, pp. 59–71, 03 2017.

[8] G. Laudato and et.al, “ATTICUS: Ambient-intelligent Tele-monitoring and Telemetry for Incepting and Catering over hUman Sustainability,” *Frontiers in Human Dynamics - Digital Impacts (Frontiers)*, 2021.

[9] A. Neves, D. Rodrigues, A. De Sanctis, E. Alonso, M. Pereira, V. Amaral, L. Melo, S. Russo, I. de Schrijver, H. Alves, and others, “Towards conductive textiles: coating polymeric fibres with graphene,” *Scientific reports*, vol. 7, no. 1, pp. 1–10, 2017.

[10] S. Seyedin, J. Razal, P. Innis, and G. Wallace, “A facile approach to spinning multifunctional conductive elastomer fibres with nanocarbon fillers,” *Smart Materials and Structures*, vol. 25, no. 3, p. 035015, 2016.

[11] Fluke, “Fluke PM6306,” 1998. Available at http://www.testequipmenthq.com/datasheets/FLUKE-PM6306-Datasheet.pdf.

[12] Maxim integrated, "MAX30001EVSYS evaluation kit," 2018. Available at https://www.maximintegrated.com/en/products/analog/data-converters/analog-front-end-ics/MAX30001EVSYS.html.