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Wearable and Superhydrophobic Hardware for Ambulatory Biopotential Acquisition*

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Abstract— **Wearable monitoring devices are a promising trend for ambulatory and real time biosignal processing, because they improve access and coverage by means of comfortable sensors, with real-time communication via mobile networks. In this paper, we present a garment for ambulatory electrocardiogram monitoring, a smart t-shirt with a textile electrode that conducts electricity and has a coating designed to preserve the user's hygiene, allowing long-term mobile measurements. Silicon dioxide nanoparticles were applied on the surface of the textile electrodes to preserve conductivity and impart superhydrophobic properties. A model to explain these results is proposed. The best result of this study is obtained when the contact angles between the fluid and the fabric exceeded 150°, while the electrical resistivity remained below 5 Ω·*cm*, allowing an acquisition of high quality electrocardiograms in moving patients. Thus, this tool represents an interesting alternative for medium and long-term measurements, preserving the textile feeling of clothing and working under motion conditions.**

I. INTRODUCTION

According to strategic objective 1 of the World Health Organization (WHO) [1] "to ensure improved access to, quality and use of medical products and technologies", telemedicine is proposed as a tool that improves coverage and saves lives [2]. In fact, there are many successful cases worldwide [3], [4], [5]. However, acquisition techniques need to be adequately improved in moving patients. For example, one of the main reasons why cardiovascular diseases remain the biggest cause of death is that heart failures can occur suddenly during daily activities, and far from a hospital [6]. About 80% of people affected by heart failure are over 60 years old, and many of them live alone; therefore society needs to be prepared to provide solutions to the growing needs of the aging population [6], [7].

There are a number of methods for carrying out long-term measurements, such as holter devices and data transmission using mobile networks, which have evolved considerably and are part of new trends including M-Health [8] and 4G Health [9]. However, there are limitations to acquiring biosignals like electrocardiogram (ECG), such as the difficulty created by disturbances caused by motion, and the lack of comfortable and discrete, long term sensors, which can remain free of contaminants, even when used for long periods of time. Additionally, the use of disposable electrodes irritates the skin and is expensive. Reducing disturbances with software means increasing the computing cost, hence the importance of improving the hardware, specifically the sensors. In order to solve these difficulties, the idea of biosignal acquisition using tools that offer added comfort like a casual garment, with embedded textile electrodes, begins to take hold [10, 11, 12]. Taking measurements of ECG with textile electrodes means that the garment must comply with the standards of medical clothing, such as the fluid-repellent property. But, if textile electrodes were to be coated with plastic materials then it could be uncomfortable and lose the textile feel. A garment that measures and monitors the wearer's biosignals is a viable alternative if there is a compromise with factors such as the computational cost, diagnosis accuracy, comfort and hygiene. The question is how to create a hygienic measuring tool without using antibacterial coating which creates the sensation of being in contact with a plastic.

This paper presents a superhydrophobic hardware devoted to telemedicine applications based on an ambulatory system. The hardware is wearable and allows real-time ECG signal processing on moving patients. Several conditions must be met for using a sensorized garment, including that electrodes have electrical conductivity and that its surface possesses enough antibacterial protection for use in humans for long periods of time. In order to ensure proper digital signal processing, the physicochemical and electrical sensor conductivity is analyzed.

II. MATERIALS AND METHODS

It is necessary to overcome the challenges of comfort and hygiene, ensuring the quality of the measurement with flexible electrodes, carrying signals to a small and portable processing tool. In this paper, these challenges have been faced by using an acquisition protocol based on a garment (t-shirt) with woven sensors which are connected to a Holter-type electrocardiograph that transmits real-time data using mobile networks. The electrocardiograph is connected to electrodes within the textile, which is made of electrically conductive fibers.

A. *Knitted textile electrodes*

Adhesion of the electrodes is ensured by weaving them into an elastic fabric, volume is given with flexible filler in order to gently increase the pressure on the patient's skin, because *textile filling performs textile spring function* [10]. The electrode weaving techniques influence the efficiency of the acquisition, and one of the best options is weaving in random patterns; previous work found that the best results

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were achieved with *the embroidered electrodes, which have a large contact area with the skin.* [11].

B. Fluid-repellent fabric by hydrophobic effect

Textile electrode should conduct electricity to the acquisition module, but it should not absorb water. The hydrophobic properties of the garment inhibit bacterial and fungal growth, as it does not provide the optimal conditions for development. To ensure that the textile electrodes are protected from fluids but still conduct electricity, traditional coatings such as long polymer chains cannot be used, as this would isolate the material. Instead, a smart surface must be created to protect the garment from humidity while allowing the acquisition of electrical signals. So, the whole t-shirt is protected with a special nano-coating.

It is possible to determine whether a surface is moist by measuring the contact angle formed between the liquid droplets and the surface, in this case, the water dynamic wettability will be modeled [13]. A small contact angle (<90°) indicates that the wettability is high, and the fluid will spread over the surface moistening it, while a large contact angle (> 90°) means that the wettability is low and the contact between the fluid and the surface decreases, forming compact drops. In the case of water, a low wettability surface is called hydrophobic. Superhydrophobic surfaces exhibit contact angles (θ) greater than 150°, resulting in poor contact between the liquid drop and the surface (see Fig. 1).

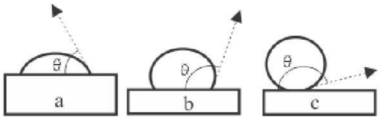

Fig. 1. Contact angle: (a) $\theta < 90°$ hydrophilic material; (b) $\theta > 90°$ hydrophobic material; (c) $\theta > 150°$ superhydrophobic material

Wettability is described establishing a relationship between molecular energy and the contact angle θ as follows:

$$\cos\theta = (\gamma_{SG} - \gamma_{SL})/\gamma_{LG} \quad (1)$$

where γ_{SG}, γ_{SL} and γ_{LG} represent the surface tension of the solid-gas, solid-liquid and liquid-gas interfaces. A drop remains suspended in the air with a spherical shape as the surface will seek to minimize its total energy by minimizing the surface area. This is also achieved with a proper atomic structure and a rough surface.

Superhydrophobic behavior of a microtextured surface was explained by Cassie–Baxter [14] relating the contact angle of a liquid in an air-solid compound interface (θ_c), the fraction of water-solid interface area (f_1) and the water-air interface (f_2) [13]:

$$\cos\theta_c = f_1\cos\theta - f_2 \quad (2)$$

$$f_1 + f_2 = 1 \quad (3)$$

$$\cos\theta_c = f_1(\cos\theta + 1) - 1 \quad (4)$$

C. Superhydrophobic particles by sol-gel method

Silicon dioxide (SiO2) becomes nanoparticles to create the tri-phase (rough solid)-liquid-air. Sol-gel processing is one of the most effective techniques for the synthesis of organic- inorganic hybrid materials. This technique is inexpensive and flexible, enabling room temperature preparation of high purity powders [15]. The process involves hydrolysis and condensation of metal alkoxide such as tetraethyl orthosilicate (TEOS) in the presence of a mineral as catalyst [16]. The reaction is carried out in two stages; first TEOS and water produce ethanol and silicon tetrahydroxide, as indicated by the following hydrolysis:

$$\underset{\text{TEOS}}{\mathrm{Si(OC2H5)_4}} + \mathrm{4H2O} \xrightarrow[\text{pH 11-12 (NH3)}]{} \mathrm{Si(OH)4} + \mathrm{4C2H5OH}$$

Polycondensation of the silicon tetrahydroxide is carried out in a second step, generating nanoparticles.

$$\mathrm{Si(OH)4} \xrightarrow[\text{pH 11-12 (NH3)}]{} \text{Nano-SiO2 (Sol)} + \mathrm{2H2O}$$

D. Proposed model for hydrophobic and electrically conducting textile sensors

A disordered nanoparticle network film causes the tri-phase (hydrophobic solid)-liquid-air, allowing the material to bend through nearby blocks of hydrophobic material. This study aims to create a superhydrophobic and electrically conductive fabric. To this end, we consider the conductive fiber as a fraction of the contact material in equations (2) and (3) to obtain an interface (hydrophobic solid)-fluid-air-(conductive fiber). In order to model the effect, we consider that some conductive fibers are so thin that they can pass between the nanoparticle matrix (Fig. 2-A). Microfibers transiting between the nanoparticles located on the electrically conductive thread are weak and bend easily. When a droplet is placed on the material, it is supported by the hydrophobic matrix which is harder than the fibers, pressing the microfibers and establishing little contact between them and the air (Fig. 2-B).

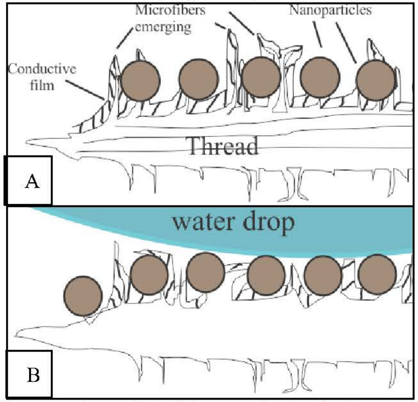

Fig. 2. Micron-scale model of the superhydrophobic conductive fabric; (A) the electrically conductive microfibers are flexible and emerge between the nanoparticles; (B) fibers bend when pressure is exerted, for example when a drop of water falls and is supported by the nanoparticles.

The electrically conductive microfibers come in contact with the patient's skin in order to sense and transport biopotentials and communicate signals to the processing module. The air from the interface is reduced by the presence of microfibers; this does not influence the ability to repel water, because when a drop falls, the microfibers bend, generating a surface similar to that produced by the solid-air compound. In this case, it is considered the contact between the fiber surface and the drop (f_3) into a new air-water-(hydrophobic solid)-(conductive fiber) interface, as follows:

$$\cos\theta_c = f_1 cos\theta_1 - f_2 cos\theta_2 - f_3 cos\theta_3 \quad (5)$$

$$\theta_2 = 180°; cos\theta_2 = -1 \quad (6)$$

$$\cos\theta_c = f_1 cos\theta_1 - f_3 cos\theta_3 - f_2 \quad (7)$$

$$f_1 + f_2 + f_3 = 1 \quad (8)$$

$$f_1 + f_3 - 1 = -f_2 \quad (9)$$

$$\cos\theta_c = f_1(\cos\theta_1 + 1) + f_3(\cos\theta_3 + 1) - 1 \quad (10)$$

The proposed model of fluid repellency also applies to other fluids such as blood, as they share similar properties. This model allows developing hygienic, conductive textiles.

III. EXPERIMENTAL SETUP

A general procedure is depicted in Fig. 3, where the electrodes were made of conductive yarn SFY750, woven in a random pattern [11], over two pieces, the first made of lycra and the second based on viscose-spandex fabric. Nano-SiO2 in liquid medium was applied, using high volume low-pressure (HVLP) spray, adjusted to FDA 21 CFR 172.48, prepared by the sol-gel technique. The fluid-repellent property is checked by observing the angle formed between the liquid/solid interface, while the acquisition quality is measured from the resistance and direct acquisition testing. The location of the nanoparticles on the fabric and microfiber was assessed with an Environmental Scanning Electron Microscope (ESEM) Philips XL30. The particle and fiber composition was identified using energy-dispersive spectroscopy (EDS) with EDAX Genesis equipment.

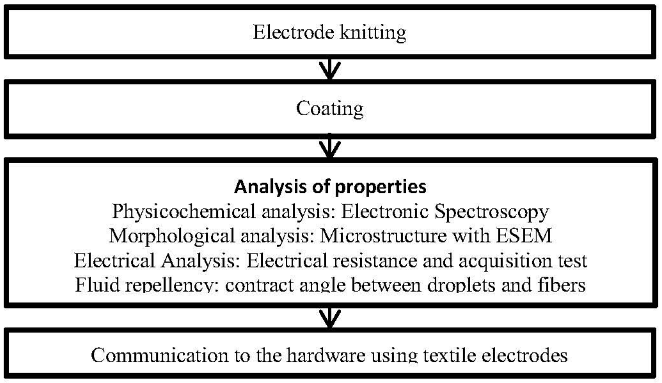

Fig. 3. Block diagram for the experimental procedure

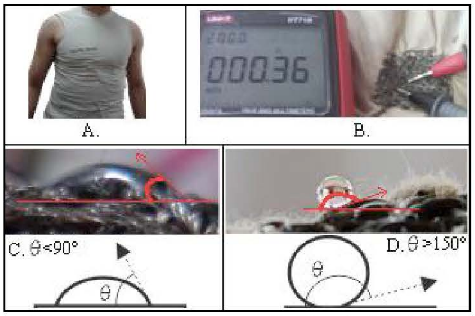

Fig. 4. Results; A. Smart garment; B. Electrical resistance of the coated electrodes; C. Contact angle without surface modification ($\theta <$ 90°); D. Contact angle with surface modification ($\theta >$ 150°).

As shown in Fig. 4-B, the electrical resistance was measured using a digital multimeter UNI-T UT71A/B, and the acquisition was made by connecting the electrodes to an Electrodoctor Holter developed by the Signal Processing and Recognition Group and CELBIT LTDA Company. The tailored algorithms are implemented in Matlab using Discrete Wavelet Transform (DWT), which has proven to be a good technique for filtering and segmentation, and for maintaining moderate computational cost.

IV. RESULTS

A. Creation of the garment

Before the surface modification, contact angle with water is low (Fig. 4-C), but after the nanoparticles were applied over the entire garment (Fig. 4-A), hydrophobicity was checked by trying to impregnate the fabric with water. As a result the garment did not get wet and drops rolled along the surface. The contact angles exceeded 150°, thereby indicating superhydrophobic on the surface that contributes to the hygiene of the patient (Fig. 4-D). It is believed that high hydrophobicity, in addition to the particulate composition, is due to the nano/microparticles, as well as their distribution (spacing of about 20 microns) and their rough shape (Fig. 5-A). The composition was determined by EDS analysis. Spectrums obtained from the conductive fibers showed peaks for iron and carbon (Fig. 5-C), while spectrums from the particles showed peaks for silicon atoms with oxygen as shown in Fig. 5-B.

B. Physical aspect analysis

We find that the coating material at certain concentrations may alter the color of the garment. Tests on alight colored garment (lycra), cornsilk (R= 255, G= 248, B= 220) changed the color to beige (R= 245, G= 245, B= 220).

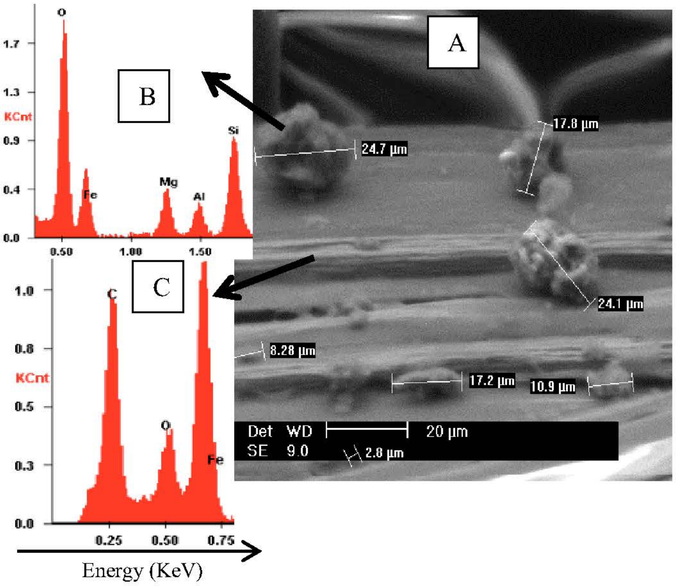

Fig. 5. Material characterization; A. Environmental Scanning Electron Microscope (ESEM) image of conductive yarns coated with nanoparticles; B. Energy-Dispersive Spectrum (EDS) for the Nanoparticles; C. EDS spectrum for the conductive yarns.

C. Electrical Analysis

The measured resistivity of the nano-coated yarns is below 0.5 $\Omega\cdot cm$, enough for effective acquisition of good ECG. Through conventional coating procedures, electrodes would have lost conductivity. The acquired ECG signal from a moving patient, using flexible electrodes (Fig. 6-A), is filtered with DWT, (Fig. 6-B). The ECG signal quality, as well as the measurement of artifacts that distort the signal (base line, power line, contracting muscles, sensor-skin contact), have been studied in previous work using correlation, DWT and diversity-based approaches [17].

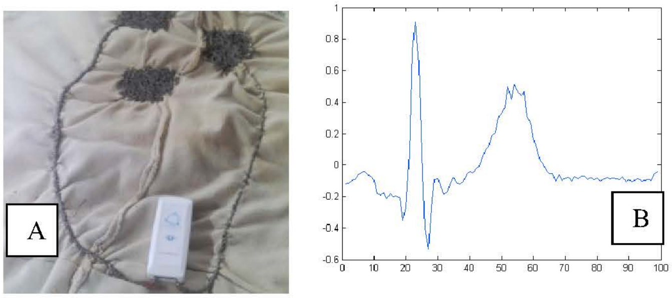

Fig. 6. A. Woven electrodes on the inner of the garment and connected to portable ECG; B. Acquired ECG using the sensorized garment.

V. CONCLUSION

A garment-based biopotential measurement system for moving patients is developed. Acquisition using this smart t-shirt in a moving patient shows the presence of good quality ECG features, such as *P* wave, *QRS* complex, and *T* wave (see Fig. 5-B). A good contact with the wearer's skin is ensured by using a flexible filling material inside the textile electrodes. The fabric and electrode hydrophobicity is tested to preserve the textile feel, and a model for electrical sensing in a superhydrophobic and conductive fiber is proposed.

It is believed that the change in color is due to diffraction effects on the semi-crystalline structure made by the particles which vary in size and distribution, causing a shift of light wavelengths and decreasing the percentage of visible transmitted light, making the garment a little darker. To achieve an optically transparent coating, particles should not exceed 200 *nm* in diameter and must transmit at least 90% of incident light in a wavelength range of 300 to 1500 *nm* [18].

The proposed architecture includes the possibility of increasing the number of measured variables, including temperature, movement and blood pressure, to establish cross-correlations between different biosignals [17]. Future work also could study the mechanisms of adhesion of nanoparticles to textile fibers, to improve durability, and of equal way other applications of smart textiles could be considered for sectors such as military and food industry.

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