Health Monitoring using Textile Sensors and Electrodes

An Overview and Integration of Technologies

H. Carvalho, A.P.Catarino, A. Rocha
School of Engineering
University of Minho
Guimarães, Portugal
helder@det.uminho.pt

O.Postolache
Instituto de Telecomunicações/ISCTE
IUL
Lisbon, Portugal
opostolache@lx.it.pt

***Abstract*—This paper gives an overview of technologies and results of integration and test of textile integrated sensors and electrodes for monitoring of biosignals (electrocardiographic - ECG and electromyographic - EMG), breathing and moisture. Using a seamless jacquard knitting machine, it is possible to integrate these sensors and electrodes directly into the fabrics, which can then be used in clothing for monitoring of elderly people, in sports or in hazardous occupations. The total integration of the sensing elements and connections into the garment presents great advantages in physical as well as psychological comfort of the user. It has been shown that the measurements are of adequate quality for most of the applications. In some cases, as is the case of ECG and EMG, signals acquired are similar to those obtained using conventional electrodes.**

Keywords*—*e-textile; biosignal monitoring; ECG; EMG;

I. INTRODUCTION

The use of textile-integrated sensors and systems has produced great interest in the last years. Textiles are excellent interfaces for bio-signal sensing. They are flexible, stretchable and conform to the body. As they are used daily and at all times, they are an interesting solution for ubiquitous, continuous health monitoring [1,2]. The significant progress in the development of conductive yarns able to be integrated into textiles by conventional textile production processes has created new possibilities for the development of continuous health monitoring applications.

Breathing rate and movement monitoring have been proposed and tested using extension sensors based on knitted textiles made with textile conductive yarns, described in [3-6, 12, 13], as well as using specially made rubber coatings doped with carbon fibers, and conductive polymers, as described in[7-10]. Electrodes for physiological signal sensing, such as ECG, EMG or skin impedance have been developed and demonstrated in other work [11-19]. Moisture sensing using textiles has been proposed in [20]. In this work, a review of the above mentioned technologies is given, in the perspective of application in a new context. The described sensing techniques are evaluated for use in the development of a shirt integrating ECG/EMG measurement, moisture detection and breathing movement detection for use in applications such as monitoring of individuals in risk environments (firefighters, workers in specific industries, etc.), sports, health monitoring for the elderly, continuous electronic health records, or other. An overview of the techniques and previous work is followed by the proposal of a new product integrating several of the techniques described.

II. ECG/EMG MEASUREMENT

A. *Textile electrodes*

The standard electrodes, generally made of Ag/AgCl present at a macroscopic scale a homogeneous surface and their electrical properties do not suffer from dimension modifications promoted by stress, since these electrodes are made of one or more layers of uniform deposited material. The same is not true if one intends to replace these electrode with textile based ones. One of the key characteristics of weft knitted fabrics is their elasticity, very appreciated by the end user, which results in body fit and very comfortable pieces of garment. This kind of fabric may me especially adequate to embed sensors and in this case electrodes due to the capability of closely follow the human body and thus proportionate and optimal contact between skin and electrode, thus avoiding the use of conductive adhesive gel. Another advantage would be the possibility of the piece of garment being reusable by means of a standard maintenance process like washing and drying at home.

If it is intended to replace such standard electrodes by textile based ones, one must find a textile structure capable of similar behavior. Thus, in a first stage a study was conducted using several conductive raw materials, in the form of continuous filaments or staple yarns with the purpose of constructing weft knitted structures and study their electrical behavior, namely the impedance dependence from mechanical characteristics such as elongation. The raw materials used were stainless steel multifilament yarns (Bekinox), staple yarns made with a blend of 80% polyester and 20% stainless steel fibers (Bekintex), and silver coated multifilaments with and without a core of bare elastane (Elitex). Basic weft structures were produced, such as jersey, simple pique, locknit

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among others, since the structure could also influence the impedance behaviour during stretch. A MERZ model MBS seamless jacquard knitting machine with a single needles system, located in the cylinder, was used. The disk is equipped with transferring jacks, knives and springs which allow a very flexible the control of the yarn entry in the knitting zone. Being a jacquard machine, it is possible to obtain complex structures with localized variations, and produced embedded electrodes. From this preliminary study, we were able to observe that, depending on the raw material used and the structure, different impedance behaviors could be obtained. And thus, other applications could be found for these textiles based conductive structures. The tests were made under standard laboratory conditions (25ºC, 65% humidity), and stretching the fabrics from rest up to 100% of its initial dimension, in length and width.

For the particular purpose of proposing a textile electrode, the study showed that the best candidate was using the silver coated yarn, with or without bare elastane and with minor differences between the different structures that were analyzed. In fact, the impedance remained constant regardless the stress applied to the knitted structure and how much stretched it was. 100% stainless steel also presented very good electrical characteristics, however, the resulting fabric cannot be used due to be too abrasive and unpleasant when in contact with skin and it was not able to recover its rest dimensions since the yarn and resulting structure do not possess mechanic memory. Thus, one could use the advantages that weft fabrics can provide without compromising the quality of the signal obtained in the case of the textile electrodes suffer some kind of stretching.

After choosing the raw material, a t-shirt was produced with the tested structures and tested with subjects. It was found that the contact with skin was not the ideal one, so it was designed a particularly voluminous structure at the area used as electrode. The electrode area protrudes from the rest of the fabric, improving contact between the skin and the electrode.

Fig. 1. Textile electrode embeded - knitted directly - into a shirt fabric (A) and electrical path to the electrode also embeded in the knitted fabric (B).

Compression of the shirt was also included into the t-shirt’s structure to improve skin-electrode contact further and to stabilize the electrode’s position.

The electrode areas are knitted with a textured multifilament polyamide yarn with a thin silver coating (less than 10 nm) called Elitex. They present very low values of electrical resistance (in the order 30 Ω/m). Using the same knitting technology allows the integration of electrical connections in the textile substrate. Electrical insulation, if necessary, is achieved by coating with specific silicone compounds (Elastosil® from Wacker). Elastosil silicone has been found to have a high adhesion capability, high electric isolation and stretch when compared with similar materials.

Figure 1 shows an example of a knitted electrode and an electrical connection. In a first phase, the electrical connections have not been joined to the electrodes to enable the study of signal quality before and after using the textile conductor as a path for signal transmission. Standard snap fasteners have been applied to allow the direct connection to the electrode or connection between the electrode and the textile conductors. In a final product, the ECG connections would be routed to a single line, located for instance on the back of the shirt and from there to a single place to connect to the specific acquisition circuit.

The same technology and material was also used to implement surface EMG measurement and electrical paths, as shown in Figures 2 and 3. In this case, several muscles needed to be monitored and the data transmitted through textile conductive lines. The resulting piece of garment – legging was involved several pairs or electrodes fulfilling the requirements of SENIAM orientations that were produced in different locations.

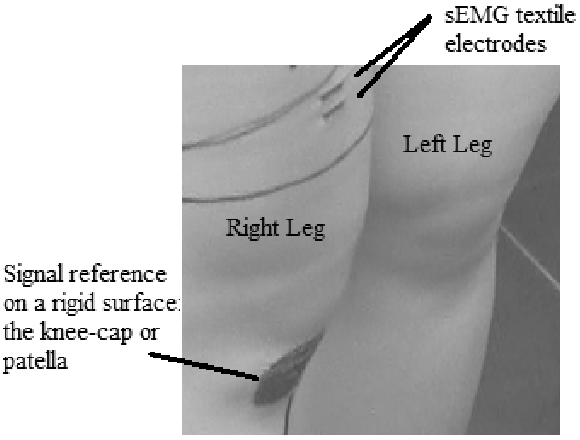

Fig. 2. Surface EMG electrodes knitted directly into fabric, in this case to measure muscle activity in a main prupolsor muscle.

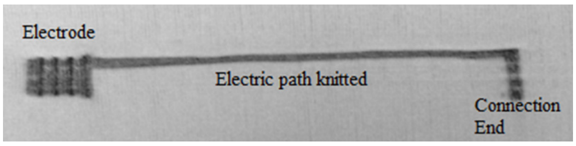

Fig. 3. Detail of knitted sEMG electrode and electrical connection. It was found that a path made of six courses (rows) of conductive yarn are enough to obtain a minimum impedance, thus reducing production costs.

B. Signal conditioning and acquisition hardware

To acquire, process and transmit the signals obtained with these textile electrodes, a solution was devised. It should be small and comprehend several features necessary to this kind of signals.

The TI ADS 1198 medical analog front-end was used to implement a signal conditioning circuit for ECG and EMG signals. Figure 4 shows a block diagram of the implemented circuit.

A differential pre-amplifier was designed to connect to one of the channels of the ADS1198 providing additional gain and AC coupling. Figure 5 shows the PCB of the final implemented circuit on its first version.

The circuit connects via SPI to a National Instruments I2C/SPI interface board. Software developed in Labview displays and processes the acquired signals. The SPI interface allows for an efficient connection to other, portable equipment, such as a wireless transmission node. Bluetooth or Zigbee can then be used to communicate and transfer the information into a remote station, thus resulting in a portable ECG monitoring system.

C. Measurement examples

The following figures illustrate the resulting signals when the textile electrodes were used in human subjects.

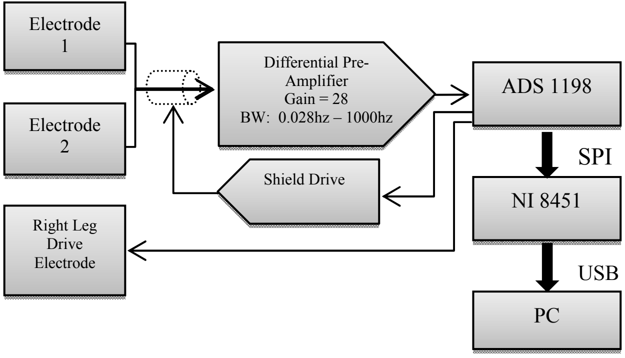

Fig. 4. Block diagram of ECG/EMG signal conditioning circuit based on TI ADS 1198

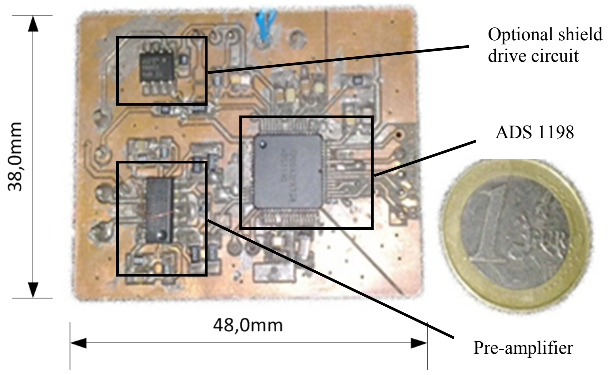

Fig. 5. PCB dimensions and components.

Figure 6 compares the signals obtained between standard Ag/AgCl electrodes (A) and textile electrodes made with the special structure and silver coated filaments (B). Synchronous measurements were performed with the purpose of reproducing the same conditions and typical measures were calculated, such as RMS. The morphological analysis shown that both present similar envelopes in terms of shape, however the textile electrodes showed a slightly smaller value in amplitude. Nevertheless, the signals are clearly similar which suggests the possibility of using the textile electrodes as valid alternatives.

In Figure 7, an ECG waveform sample taken with textile electrodes from a female subject at rest is shown. Asynchronous measurements were made with several subjects from both gender and using standard electrodes as well as textile electrodes. The signals obtained, when compared from a morphological point of view present clear similarities, even more evident than for sEMG.

III. BREATHING MOVEMENT MEASUREMENT

A. Textile extension sensors

Textile extension sensors are one of the most studied subjects in e-textiles. They can be used for measuring breathing rate of a person, or the angle formed by human joints. The study previously made and described in section II.A showed that there are strong textile candidates for this purpose, namely the structures made with blends such as Bekintex, even for single face fabrics, such as jersey and its variations.

In fact, the study showed that there is a relationship between elongation and impedance, which can be used to quantify extension.

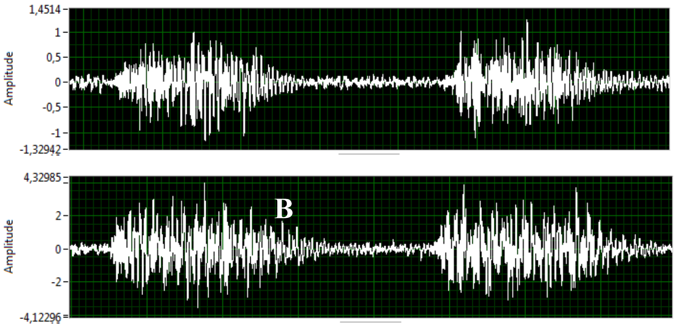

Fig. 6. sEMG signals obtained with conventional Ag/AgCl electrodes (upper) and with textile electrode (lower)

Fig. 7. ECG signals obtained with textile electrode

While the advantages seem to be quite obvious, there are however some difficulties that need to be overcome. Reliability, mechanical stress, life cycle are important issues when a sensor is to be integrated in a fabric. Proposed solutions involve essentially conductive rubbers and textile structures involving conductive yarns.

In a preliminary approach, a simple weft-knitted double face rib fabric using Bekintex yarn (20% stainless steel 80% polyester staple yarn from Bekaert, Belgium) sewn into an accessory as shown in Figure 8, showed a reasonable, although not optimal behavior as a breathing movement sensor (Figure 9).

Other work studied different conductive materials and structures to improve the strain sensor performance. Fabrics coated with conductive polymers such as PPy or a mixture material of carbon and rubber have piezoresistive properties and they can be used as strain sensors. These sensors can be easily integrated into wearable, instrumented garments [21]. A smart flexible sensor based on a thermoplastic elastomer (Evoprene)/carbon black nanoparticle composite was developed to adapt to textile structures and was shown to be able to measure their strain deformations [4].

B. Production and test of textile extension sensors

In this work, textile-based extension sensors based on a single face weft-knitted structure, with conductive yarn and bare elastane as raw materials, were developed and optimized. Samples with different sizes were submitted to mechanical and electric characterization, which showed different behaviour regarding the textile structure used. Three basic textile structures were selected: Jersey, simple pique and locknit, using conductive fibers – Bekintex - and bare elastane from CREORA.

Fig. 8. Breathing movement measurement accessory based on electrically conductive knitted fabric.

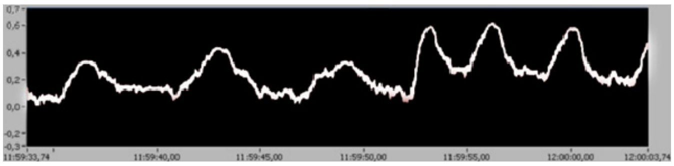

Fig. 9. Respiration wave measured by textile sensor.

The parameters under study were the loop length, the sensor's dimension and the structure. The test workbench was based on a tensile testing machine and a resistance meter (Figure 10). Cyclic tests were performed in order to obtain the resistance change with strain, stopping at maximum extension and not stopping at maximum extension. The conductive fabrics were stretched between 5% to 100% in 5% and 10% steps, and at a constant speed of 60mm/m. An example of an extension sensor is shown in Figure 11.

It was found that by stretching in the course direction a repeatable resistance change waveform was obtained, in which strain was inversely proportional to resistance in all the experiments. Submitting the wale direction to cyclic stress resulted in non-reproducible waveforms. The structures showed a typical waveform shape slightly depending of the structure used to produce the fabric and with a linear behavior.

Lower strains resulted in a non-linearity when the fabric returns to rest and is again submitted to traction. It was then found that a pre-stretch of between 30-50% was necessary to obtain better results, with a repeatable shape.

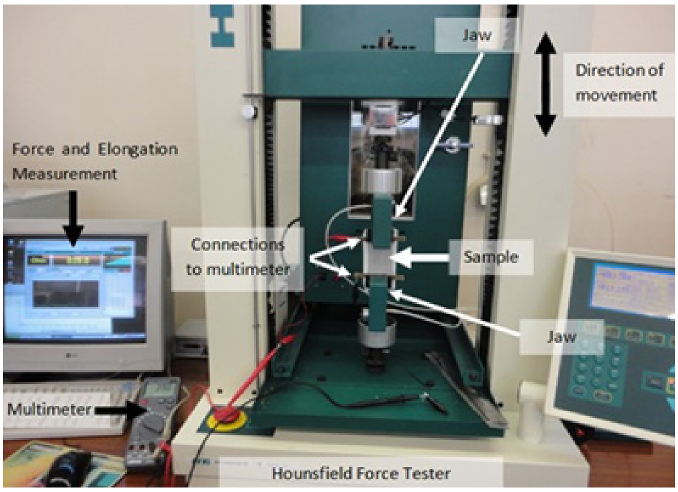

Fig. 10. Test setup for textile extension sensors

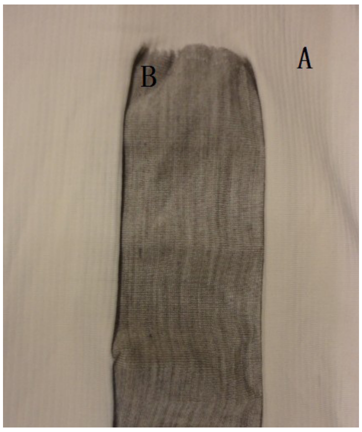

Fig. 11. Textile extension sensor integrated into fabric. A: Polyamide yarn. B: Bekintex conductive yarn.

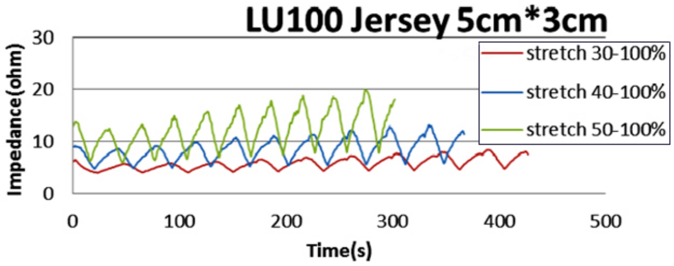

Fig. 12. Resistance variation with extension for three different pre-stretching

However it augments the possibility of material fatigue, thus resulting in a waveform that increases in amplitude with time. The pre-stretch of the sensor also has an influence on the higher was the resistance amplitude. From the tests made, single jersey appeared to be the structure resulting in sensors with best performance. Figure 12 shows the results of the 5x3 cm jersey structure, using loop length (LU) 100, stretched in the course direction. The differences in length for the three plotted waveforms are due to the fact that a higher pre-stretch takes less time to achieve the maximum length of 100%. Further studies are being conducted in order to improve the characteristics of this textile extension sensor.

IV. MOISTURE SENSING

A. *Textile moisture sensor*

The measurement or sheer detection of excessive moisture is a very important feature for some applications. One of them is the prevention of pressure ulcers in individuals with reduced mobility. The physical parameters most influencing the development of pressure ulcers are pressure, friction and moisture at the skin interface. Another one is the prevention of skin burning in hot environments, such as those to which firemen and some kinds of workers are exposed to. The combination of high temperature and excessive moisture/wet clothes is the factor promoting severe skin burning.

Measurement or detection of moisture can be achieved by measuring the resistance between conductive areas of a textile or by measuring the resistance of the conductive areas themselves. Conventional textile materials are normally electrical insulators, unless moisture with conductive properties is absorbed, which is the case of sweat, for instance.

Based on this principle, moisture sensors have been developed in previous work to measure the approximate content and distribution of moisture in an area of a cushion or mattress[20]. The measurement is based on two layers of striped fabric which has been woven alternating cotton yarn with electrical conductive yarns and wires.

The two layers are turned 90 degrees one in respect to the other, thus forming a matrix. It is possible to measure the distribution of moisture by measuring the resistance between stripes on a single measurement layer, or between stripes of the upper and lower sensing layers.

Fig. 13. Fabrics with conductive stripes and intermediate absorbing layers

The remaining fabric layers are cotton knitted fabrics, assuring both a comfortable interface to the user's skin as well as good liquid absorption.

B. *Signal conditioning and acquisition hardware*

The multiplexing scheme shown in Figure 14 connects one of the conductive stripes of the fabric on the lower sensing layer with another one of the upper sensing layer in the signal conditioning circuit shown in Figure 15.

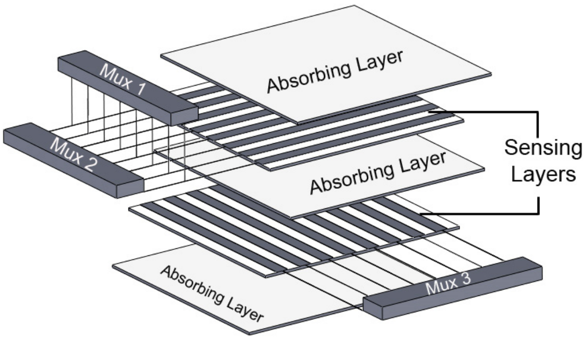

Fig. 14. Multiplexing of the sensor matrix

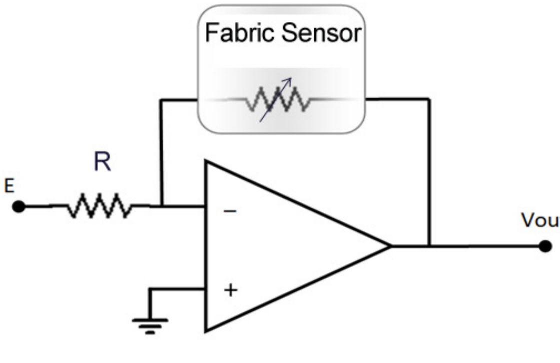

Fig. 15. Signal conditioning for a fabric moisture sensor, where E represents a reference voltage.

It is possible to adjust the sensitivity of the moisture measurement by adjusting the resistance R.

Tests have shown that the sensor is able to give a good indication of moisture amount and distribution, although the output signal is influenced by mechanical pressure variations that the fabric might be subject to. Humidity sensors made with a specific combination of hydrophilic and conductive materials embedded in a weft knitted t-shirt are now under development and test.

V. MAINTENANCE AND REUSABILITY

One of the most important advantages about using textile based sensors is the possibility of reusing them, once they are already part of the fabric. This implies maintenance operations, which should be as simple as possible. For the applications presented and in particular the textile electrodes, normal cleaning operations were performed and the t-shirt prototype was used for several times without decaying the signal quality. The use of coatings to embed sensors in fabrics or to improve the extension textile based sensors may require special caution with abrasive mechanical maintenance procedures.

Nevertheless, due to the advances in the fiber technology area, special care can be required in order to maintain the correct performance of this new generation of textile fibers and yarns. With that purpose, new labeling was adopted which contemplate different procedures in which the textile based sensors and their garments can be positioned.

VI. CONCLUSIONS

This paper presents an overview of several textile based sensors and their applications. Depending on the electrical characteristics observed when characterizing the conducting structures, different applications can be proposed: Electrodes, electrical paths, humidity sensors and extension sensors, among other examples. Based on the results obtained one can conclude that textile based sensors are a promising alternative to standard sensors in many situations. The fact of being embedded in garments, thus becoming part of the daily life of a user, presents the additional advantage of being comfortable and reusable.

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