Study of vital sign monitoring with textile sensors in swimming pool environment

[1]M.Silva, A.Catarino, H.Carvalho, A.Rocha, J.Monteiro [2]G.Montagna
[1]University of Minho, [2]Technical University of Lisbon
marcoskytos@gmail.com; whiteman@det.uminho.pt; helder@det.uminho.pt; amrocha@det.uminho.pt; joao.monteiro@dei.uminho.pt
g.montagna@gmail.com

Abstract- This paper presents the results of a series of experiments aiming at the optimisation of vital sign monitoring using textile electrodes to be used in a swimsuit. The swimsuit will integrate sensors for the measurement of several physiological and biomechanical signals; this paper will focus on ECG and respiratory movement analysis. The data obtained is mainly intended to provide tools for evaluation of high-performance swimmers, although applications can be derived for leisure sports and other situations.

A comparison between electrodes based on different materials and structures, behaviour in dry and wet environments, as well as the behavior in different extension states, will be presented.

The influence of movement on the signal quality, both by the muscular electrical signals as well as by the displacement of the electrodes, will be discussed. The final objective is the integration of the electrodes in the swimsuit by knitting them directly in the suit's fabric in a seamless knitting machine.

I. INTRODUCTION

The improvement of performance in sports is intimately related with training methodology combined with the well-being and health status of the athlete. Trainers make a constant effort to modify the movements and training rhythm of the athletes, especially in rhythmic and cyclic sports such as swimming or athletics [1][2].

In this project a swimsuit is being developed, which will integrate sensors to measure several biomechanical and biophysical parameters during the exercise. The parameters that will be monitored include the measurement of ECG (electrocardiographic activity), EMG (Electromiography, i.e. muscular activity), respiratory activity, accelerations and trajectories of the limbs and other parameters. The environment in which this measurement system is will be used poses several specific issues, such as electric isolation, data transmission, protection from water, etc. In this paper, an overview of some results obtained using textile electrodes for ECG measurement will be given. It is interesting to note that the results of this project can in general be easily transposed to other sports and applications, such as health monitoring in leisure sports, for the elderly, patients with cardiac disease, etc.

II. BACKGROUND - ECG MEASUREMENT WITH TEXTILE ELECTRODES

Several researchers have published work regarding the measurement of ECG signals using textile or textile-integrated electrodes. Reference [11] gives a comprehensive overview of this subject.

In References [3] and [10], the use of dry rubber electrodes is proposed, either as detachable electrodes made of conductive rubber[3], or as a rubber electrodes printed on the fabric and made conductive by a deposition of silver particles [10]. In other cases, the electrodes were produced of textile materials, but separately from the suit/vest in which they would later be integrated by sewing or another joining process[4][5][7]. Yet other researchers [6][9] produced fabrics in which the electrodes were knitted into the fabric itself, thus achieving a total integration with the textile. This is also the approach followed in our work.

The use of textile electrodes presents obvious advantages in terms of integration of the sensor and comfort to the user, but it has two main disadvantages: an increase of the skin-electrode impedance in most of the cases, over traditional electrodes, and an increase of motion artifacts in the signals, since the electrodes are not effectively kept in place [11].

To produce textile electrodes, many possibilities exist. The first of them is to print the electrode on the textile material, using conductive inks or deposit conductive particles. This is the approach followed in [10].

The other possibility is to weave or knit the electrode using conductive yarns [4][5][6][8]. Once again several possibilities exist here. The most immediate would be to use metallic wires, which would present excellent conductivity and thus lower skin-electrode impedances. However, besides being extremely uncomfortable to use, they are also somewhat difficult to process industrially.

In the last years, several manufacturers have begun offering conductive yarns with properties very close to normal textile yarns, which can be easily processed in standard textile machines. Roughly, these can be divided in normal textile yarns with conductive materials deposited on their surface (e.g ELITEX®), and staple yarn spun with a blend of normal textile fibres and conductive metallic fibres (e.g.: BEKINTEX®).

In this work, we intend to study other aspects involving the production of these electrodes. On one hand, we will present different textile structures of the knitted material, with the objective of increasing the contact area between skin and textile and thus reducing the impedance. On the other hand, two new factors arise in the integration of the electrodes in

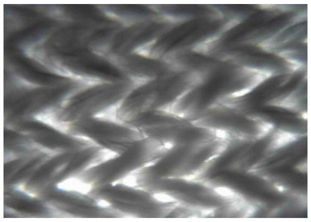

Fig. 1: Jersey fabric forming ECG electrode in relaxed state.

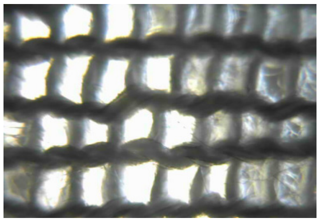

Fig. 2: Jersey fabric forming ECG electrode in stretched state.

swimsuits: The extension of the sensor when the suit is worn, and the presence of water.

III. SPECIFIC FACTORS OF ECG MEASUREMENT IN A SWIMSUIT

Swimsuits, especially racing swimsuits, are worn very tightly compressed against the skin. At first glance, this is an advantage, since the contact between the electrode and the skin is promoted. However, since the electrode is to be integrated into the fabric itself, it will also be stretched and expectably this will influence skin-electrode contact negatively. Fig.1 and 2 illustrate this fact.

Another obvious aspect is the presence of water. In a dry environment, the equivalent circuit of the connection between the heart and the amplifier can be represented as seen in fig.3. Fig.4 adapts the equivalent circuit to the situation where the electrodes are submerged in water. The presence of water predictably has two main effects on the ECG measurement:

- It reduces the skin-electrode resistance $R_{c,}$ represented in figs.3 and 4 by the electrolyte resistance and the electrode resistance R_t , because it wets the electrode resulting in a similar effect as of an electrolyte gel;
- When the swimmer is under water, the pool water can be represented by an impedance Z_w, connected in parallel at the input of the amplifier, thus reducing the resulting amplitude of the ECG signal.

IV. EXPERIMENTAL SET-UP

A. Hardware

The electrodes were connected to an INA 129 instrumentation amplifier according to the schematics represented in fig. 5. The instrumentation amplifier was followed by a second amplifying stage (inverter based on OPA 277) and a second-order Butterworth filter was used as anti-aliasing filter, with a cut-off frequency of about 3 kHz (not represented in fig.5).

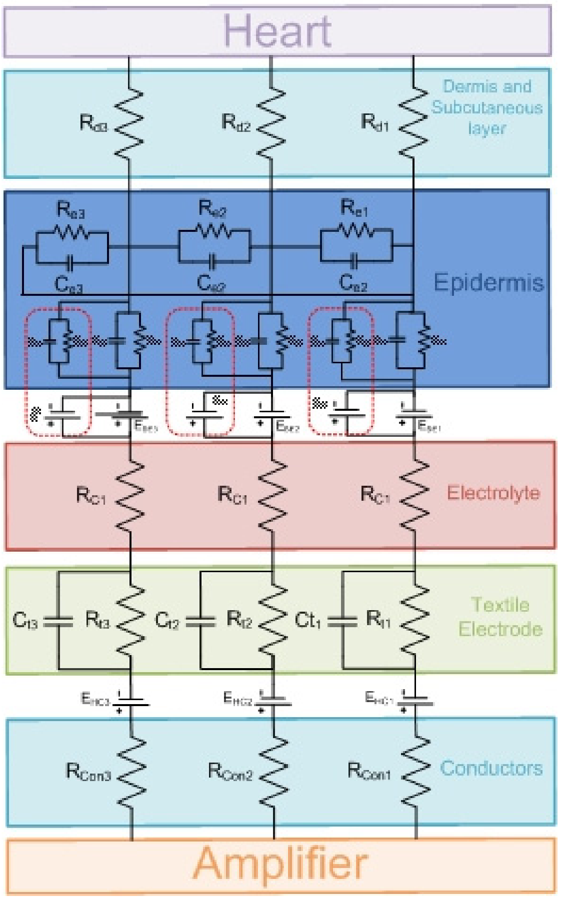

Fig. 3: Equivalent electric circuit of skin-gel-electrode system, adapted from [12] .

The signals were acquired using a National Instruments NI-USB 6259 Multifunction data acquisition board plugged to a PC. Sampling frequency was set at 10kHz, which is a rather high frequency for ECG signals, but this allows the evaluation of noise and motion/muscular signal artefacts present in the signals, normally located at higher frequencies.

B. Software

A data acquisition and processing application was developed in National Instruments Labview. Besides a function of continuous acquisition and data streaming to file, the program includes digital filtering functions that allow a quick and interactive setting of the filter rejection bands with immediate observation of the effect on the waveforms. In a first stage, we are using a spectral filtering and reconstruction algorithm, as presented in [13], that allows an exact setting and choice of multiple, rejection bands.

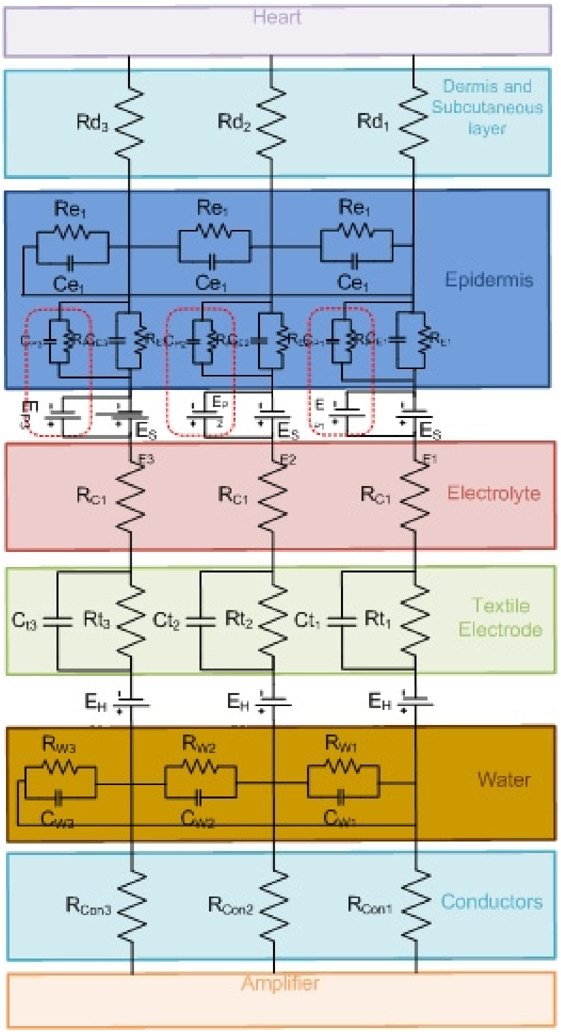

Fig. 4: Equivalent electric circuit of skin-gel-electrode system when submerged in water (adapted from [12])

After filtering, we have implemented a simple peak detection function based on the computation of the first and second derivatives and the definition of a minimum detection threshold to reduce false detections. This function is used only to detect the R-wave (the main peak of the ECG signal) with the purpose of computing heart beat rate and arrhythmia.

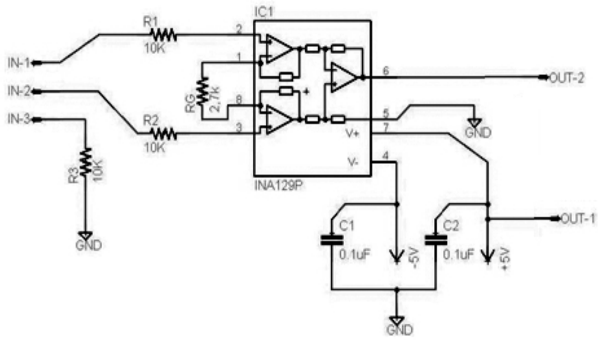

Fig. 5: Signal conditioning schematics of pre-amplifier

C. *Textile Electrodes*

In this first approach, the textile electrodes developed are based on a single face knitted fabric, a jersey structure – A structure - , and a structure similar to rib – B structure.

The raw material used in both structures was Bekintex (400 dTex) and bare elastane (78 dTex), knitted on a circular knitting machine, The textile electrodes were produced under repeatable conditions, where the yarn input tension and the covering factor, expressed here as loop length, were accurately controlled. Due to new developments regarding yarns with improved electrical conductive characteristics, this research will in near future be extended to other raw materials.

The second structure – B, was produced with the purpose of improving skin-electrode contact, especially when stretched, given their more complex surface texture.

The first evaluation was to compare the performance of the electrodes produced with commercially available textile electrodes. For this purpose, the electrodes were cut in 2x2cm squares and compared with equally sized electrodes cut from fabrics based on silver-coated yarns, available from Textronics – C structure, used in this case as a reference. The electrodes were placed on the subject's body using adhesive tape and on the same places. This initial evaluation showed that there were no significant differences between the signals obtained from the fabric made in the laboratory A, B and the one used as reference, C, apart from a slightly higher noise level in structures A and B electrodes that can easily be removed by filtering.

D. *Experimental plan*

The experiment was planned as a short preliminary study of several variables that will play a role when the ECG measurement is performed during swimming. Its purpose was to provide an overview of the relative influence of the intervening parameters on the process, in order to give the necessary insight for planning of more detailed studies. It also helped to tune the amplifier and the processing software, namely in the choice of the filters' rejection bands.

The factors under analysis were the following:

- Knitted structures: Structures A and B;
- Moisture influence: Electrode dry, wet and under water;
- Stretching effect : Electrode in relaxed and stretched condition;
- Effect of muscular contraction in ECG signal;
- Signal pickup with movement of the arms.

The results herein presented were all obtained in a laboratorial environment. The electrodes were always placed at the same positions on the subject's body. The wet and submerged states were achieved by submerging the subject in water (submerged state) and after leaving the water (wet state).

The relaxed electrodes were placed on the subject's body with adhesive tape, whilst to produce the stretched state, the same electrodes were sewn onto a tight-fitting knitted fabric tube that was worn by the subject. This is a simulation of how the textile electrodes will be in the swimsuit, with the exception that in the latter the electrode will be embeded in the fabric.

Measurements were made with the subject in three different situations:

- Relaxed and breathing normally;
- Lying still and contracting the pectoral and abdominal muscles;
- Moving the arms intensely.

V. RESULTS AND DISCUSSION

In the next sections an overview of the results obtained will be presented.

A. *Dry, relaxed electrode type A structure*

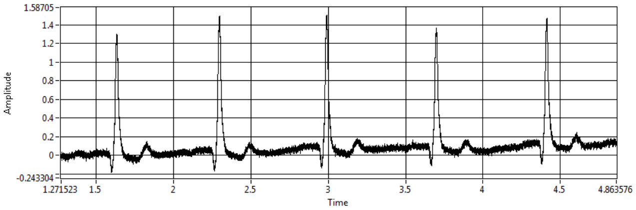

Fig. 6: ECG signal picked up with a dry, relaxed electrode and subject relaxed

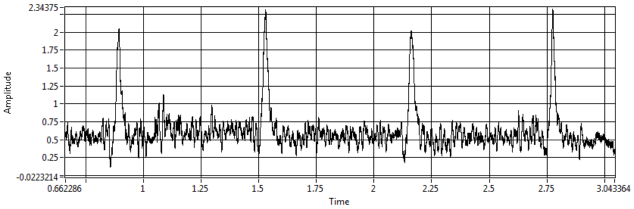

Fig. 7: ECG signal picked up with a dry, relaxed electrode and subject contracting pectoral and abdominal muscles

This was the first result obtained, showing a clear ECG signals with the QRST waves well-defined. As expected, upon muscle contraction the signal becomes noisy, with the muscular activity masking off the Q and ST-waves. Although not yet attempted, the recovery of these components is expected to be quite difficult, but heart beat rate is still perfectly well depicted.

B. *Wet, relaxed electrode type A structure*

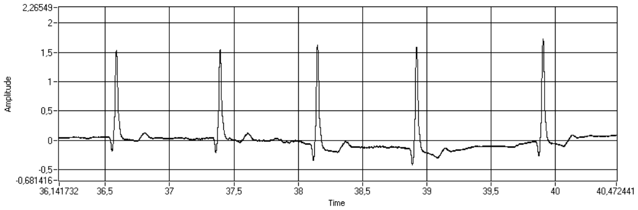

Fig. 9: ECG signal picked up with a wet, relaxed electrode and subject relaxed

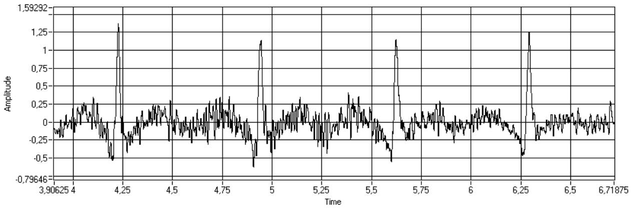

Fig. 10: ECG signal picked up with a wet, relaxed electrode and subject contracting pectoral and abdominal muscles

The wetting of the electrodes produces an even better signal, as expected and previously discussed. The amplitude is higher and the signal is less noisy. Muscular activity produces the same effect as described previously.

C. *Submerged, relaxed electrode type A structure*

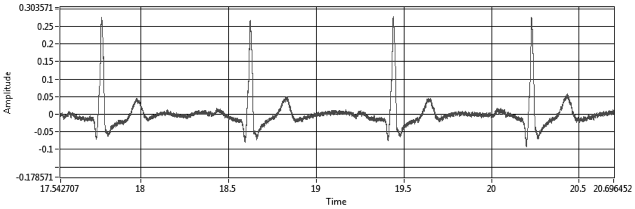

Fig. 11: ECG signal picked up with a submerged, relaxed electrode and subject relaxed

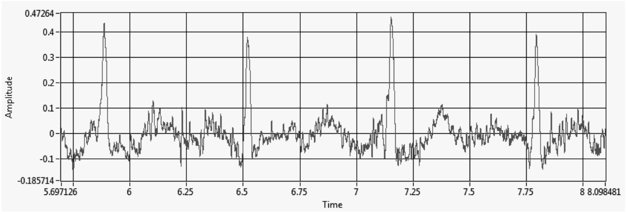

Fig. 12: ECG signal picked up with a submerged, relaxed electrode and subject contracting pectoral and abdominal muscles.

The submersion of the electrodes produces a significant reduction in signal amplitude, as previously predicted. Nevertheless, the signal is clean when the subject is relaxed.

D. *Dry, stretched electrode type A*

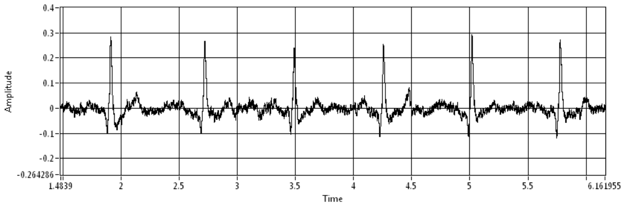

Fig. 13: ECG signal picked up with a dry, stretched electrode and subject relaxed

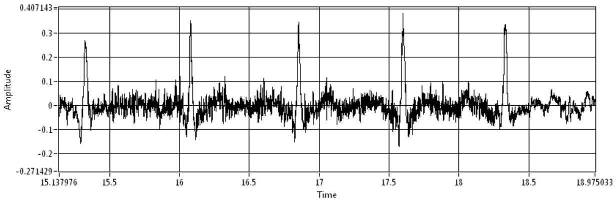

Fig. 14: ECG signal picked up with a dry, stretched electrode and subject contracting muscles.

Upon stretching of the electrodes, the signal amplitude is reduced and the signal becomes noisier. This can be explained by the increase of both the skin-electrode and electrode inner resistance, since the amount of elastane is quite significant and now has reduced the contacts inside the fabric.

E. Wet, stretched electrode type A

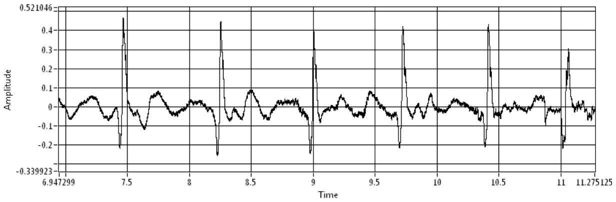

Fig. 15: ECG signal picked up with a wet, stretched electrode and subject relaxed

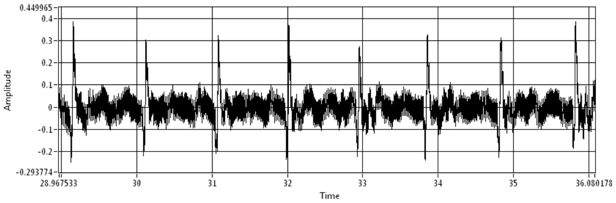

Fig. 16: ECG signal picked up with a wet, stretched electrode and subject contracting muscles

Again, wetting the electrodes produces an improvement of the signal.

F. Submerged, stretched electrode type A

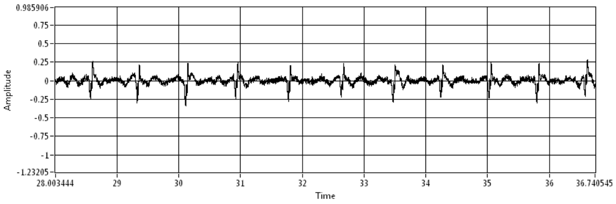

Fig. 17: ECG signal picked up with a submerged, stretched electrode and subject relaxed.

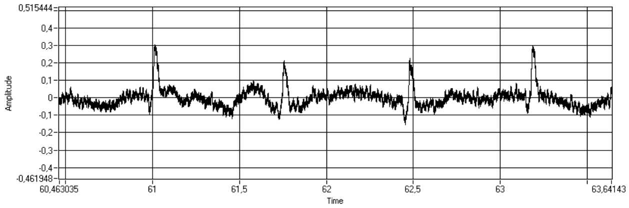

Fig. 18: ECG signal picked up with a submerged, stretched electrode and subject contracting muscles.

As can be observed, signal amplitude has been significantly reduced by submerging the stretched electrode.

G. Stretched electrode type B

Fig. 20: ECG signal picked up with a wet, stretched electrode type B, subject relaxed

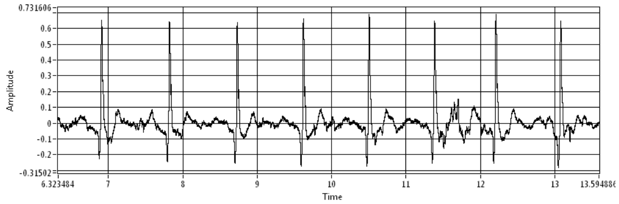

Fig. 20: ECG signal picked up with a wet, stretched electrode type B, subject relaxed

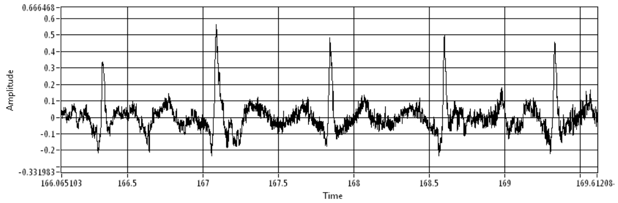

Fig. 21: ECG signal picked up with a submerged, stretched electrode type B, subject relaxed

The use of a different structure produces a very interesting result. In fact, the signals produced present higher amplitude (compare signal of fig.17 to signal of fig.20). This result shows that it is worthwhile to design and test new structures, since it may improve the contact between skin and electrode, particularly when compression is involved.

H. Arm movement and signal processing

Finally, fig.22 presents a signal in which the effect of intense arm movement can be observed.

To detect heart beat rate, the analysis of the signals obtained have led to configure the filters to eliminate the bands between 0 and 3 Hz and all above 150 Hz.

As can be seen, after this operation the detection of the R-wave is quite straightforward, but the remaining waves have been masked off. Future tests will show if the extraction of these values is possible on the unfiltered signal, after the detection of the exact locations of the R-wave.

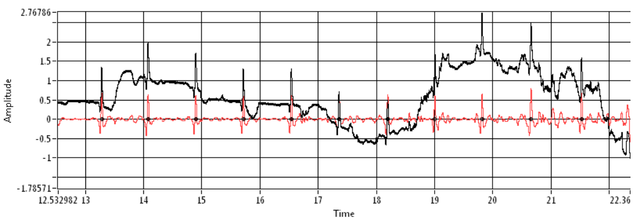

Fig.26.ECG signal picked up with arm movement, before and after filtering. Black dots identify the location of the R-Wave, detected automatically

VI. CONCLUSIONS

This paper presented the first results of a series of experiments aiming at vital sign monitoring using textile electrodes that are intended to be used in a swimsuit. Monitoring in water constitute a challenge because it will reduce the signal. At the same time, since it is intended to fully embed the textile sensor in the swimsuit, the former will suffer some stress due to stretching and this will also affect the signal. To study the phenomena, two different textile structures were produced and compared with a commercially available structure, used here as a reference. After confirming the similarity of the obtained waveforms for reference and the produced fabrics, several experiments were carried out, taking into account some of the parameters that may influence the ECG waveform, which involve humidity presence, electrode stretching and subjects activity.

The experimentation performed has confirmed many expectations of the project group, and it provided a great amount of data to prepare the signal processing algorithms. It has been shown that in all situations it is possible to clearly display the R-wave of the ECG. An automatic detection of the R-wave seems to be feasible, providing not only the important measure of heart beat rate, but also providing the exact location of the R-wave and allowing the computation of values in its vicinity, with the purpose of quantifying and logging the whole QRST complex.

Regarding the textile electrodes, it has been shown that a systematic design and testing of modified structures of the knitted material is meaningful. Special attention should be given to the optimisation of the electrode in its stretched state, since a significant deterioration of the signals has been observed in this situation.

Considering the specificity of pool environment, it can be concluded that – although not strictly necessary – the electrical isolation of the electrodes is valuable. On the other hand, the presence of water between the electrode and the skin, and in the electrode, is favourable, having the effect of an electrolyte gel.

In future work, this study will be performed with other types of yarns. The emphasis, though, will be on the testing of new structures and the complete integration of the electrodes and their connections in the swimsuit. This will be achieved by conventional textile processes including knitting, printing and transfer printing.

VII. ACKNOWLEDGMENT

The authors wish to thank FCT, which is funding this research through project number PTDC/EEA-ELC/70803/2006.

VIII. REFERENCES

[1] Clarys, J.; Rouard, A.. “The frontcrawl downsweep: shoulder protection and/or performance inhibition. Journal of Sports Medicine and Physical Fitness, 36 (2): 121-126, 1996

[2] Gonçalves, P.; Pereira, S., Vilar, S.; Figueiredo, P.; Sousa, A.; Fernandes, R., Vilas-Boas, J.P. ,”Underwater electromyography system and his dialog with other instrumentation”. In: Book of abstracts of the 10th International Symposium and Medicine in Swimming. Rev. Port. Ciências do Desporto, 6 (Supl. 1): 21, 2006

[3] Jens Mühlsteff, Olaf Such, Dry electrodes for monitoring of vital signs in functional textiles, Proceedings of the 26th Annual International Conference of the IEEE EMBS, San Francisco, USA, 2004

[4] M. Catrysse, R. Puers, C. Hertleer, L. van Langenhove, H. van Egmond,D .Matthys, "Fabric sensors for the measurement of physiological parameters", Transducers '03, The 12th International Conference on Solid State Sensors, Actuators and Microsystem Boston, 2003

[5] M. Catrysse, R. Puers, C. Hertleer, L. van Langenhove, H. van Egmond,D .Matthys, "Towards the integration of textile sensors in a wireless monitoring suit", Sensors and Actuators A 114, 302–311, 2004

[6] C. Hertleer, M. Grabowska, L. Van Langenhove, M.Catrysse, B. Hermans, R. Puers, A. Kalmar, H. van Egmond3, D. Matthys, "The use of electroconductive textile material for the development of a smart suit", World Textile Conference - 4th AUTEX Conference Roubaix, June 22-24 2004

[7] J. Ottenbacher, S. Römer, C. Kunze, U. Großmann, W. Stork, “Integration of a Bluetooth based ECG system into clothing”, Proceedings of the Eighth International Symposium on Wearable Computers (ISWC’04), 2004

[8] R. Paradiso, G. Loriga, and N. Taccini, IEEE Trans. Biomed. Eng. 9, p.337–344, 2005

[9] J.Coosemans, B.Hermans, R.Puers, "Integrating wireless ECG monitoring in textiles", Sensors and Actuators A 130–131, 48–53, 2006

[10] Linti, H. Horter, P. Österreicher, H. Planck, "Sensory baby vest for the monitoring of infants", Proceedings of the International Workshop on Wearable and Implantable Body Sensor Networks (BSN’06), 2006

[11] Xu, P. J., Zhang, H. and Tao, X. M., “Textile-structured electrodes for electrocardiogram”, Textile Progress,40:4,183 — 213, 2008

[12] J.G.Webster, “Medical Instrumentation: Application and Design”, JohnWiley & Sons, Inc, NewYork, 1998

[13] H.Carvalho, P.Ferreira, A.M.Rocha, J.Monteiro, “Signal Feature Extraction for Sewing Analysis using Non-Linear Techniques”, Proceedings of the 2003 IEEE International Symposium on Industrial Electronics (ISIE), IEEE, ISBN 0-7803-7912-8, Rio de Janeiro, Brazil, 2003