

Wireless Monitoring of Heart Rate and Electromyographic Signals using a Smart T-shirt

J. Stefan Karlsson^{1#}, Urban Wiklund¹, Lena Berglin^{2*}, Nils Östlund¹, Marcus Karlsson¹,
Tomas Bäcklund¹, Kaj Lindecrantz³, Leif Sandsjö⁴

¹*Department of Biomedical Engineering & Informatics,
Umeå University Hospital, SE-901 85 Umeå, Sweden.*

²*School of Textiles and* ³*School of Engineering, University College of Borås, SE-501 90 Borås, Sweden.*

⁴*Occupational and Environmental Medicine, Sahlgrenska Academy at University of Gothenburg, SE-405 30 Göteborg, Sweden.*

[#]stefan.karlsson@vll.se
^{*}Lena.Berglin@hb.se

Abstract— We have developed a prototype T-shirt with integrated electrodes for wireless monitoring of heart rate and muscular activity. Monitoring of heart rate is insensitive to the actual placement of the textile sensors by recording ECG from many positions of the trunk: This approach reduces the risk of data loss due to problems in a single channel. A multi-channel heartbeat detector was developed, which is robust to disturbed or even missing ECG-signal in single channels. For recording of electromyographic signals, our current intermediary solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes. By extra padding over the electrode site, the positions of the electrode are more well-defined and local sweat production is stimulated which enhance the recording conditions. The T-shirt has a specially designed textile electrode system for flexible integration in clothing. Further improvements are needed, but our intention is that our textile T-shirt soon will be available to the research community. In addition to personal health monitoring, the system would allow long-term monitoring of trapezius muscle activity and heart rate variability, indicating psychological stress, which is of high interest in studies of musculoskeletal disorders of the neck and shoulder.

I. INTRODUCTION

Advances in novel textile materials and structures, as well as in communication technology have opened up for a new generation of health care systems. Health monitoring is an example of an area where integrative research and development in wearable technology is performed. The Georgia Tech Wearable Motherboard [1], was one of the first health applications integrated in a garment. The motherboard creates a system for the soldier that is capable of alerting and sending vital sign information to medical triage. The sensors in the motherboard are connected to a personal status monitor. Another example of a wearable computing health monitor is the Life Shirt [2], which is a multi-function ambulatory system monitoring health, disease and medical intervention in the real world.

The demand on textile products with respect to sustainability, flexibility and washability has turned the research to integration of electronic functionality in textile structures. Integration of textile-based sensors for ECG recording has been demonstrated in several projects such as

Vtam [3], WEALTHY [4], research at Ghent University [5] and the Swedish School of Textiles [6]. In the project WEALTHY [4] conductive and piezoresistive yarns in knitted garments are used as sensors and electrodes, to monitor cardiac patients.

Recent development in wearable health systems have resulted in a variety of prototypes integrated with textile sensors ([7] - [10]). Such systems, offer mobile and flexible surveillance of different user groups within health care, extreme working conditions, sports, etc.

Textile electrodes offer a flexible and soft solution that can easily be integrated in garments.. However, intermittent disturbances are common in bio-medical signals recorded with such solutions due to problems to get as good contact between the electrode and the skin as is achieved using a regular pre-gelled electrode pasted to the skin. To overcome these problems we have applied novel adaptive method for heartbeat detection in multi-channel ECG signals with high noise levels and intermittent signal loss [10]. The method was originally developed for extraction of motor unit action potentials in surface electromyograms (EMGs) [11], and later adapted for ECG applications [10]. A combination of signal processing using multi-channel methods and careful electrode design and a proper design of the whole system are ways to overcome the shortcomings. Our system consists of multiple textile electrodes and data transfer structures in a three textile layer construction.

In this study we have integrated textile sensors in a T-shirt to record electrophysiological signals, focusing on trapezius muscle (EMG) activity and autonomous control, as measured by heart rate variability assessed via ECG.

The overall aim is to facilitate long-term ambulatory monitoring of parameters of interest e.g. in studies of work-related disorders, and to make such monitoring fully self-administered. By integrating sensors in clothing, participants are not depending on someone assisting in the application of EMG or ECG electrodes. This specific aim of this study is to demonstrate simultaneously recorded EMG and ECG signals using electrodes integrated in a T-shirt.

II. METHODS

A. Experimental protocol

The goal with the measurements was to evaluate the T-shirt (Fig. 1) during computer work with different positions of the arm controlling the computer mouse. After the T-shirt was put on, the subject was seated for two minutes before the recording was started. At the beginning a reference EMG measurement was made, the subject stretched his arms for 10 seconds straight at 90 degrees, in the coronal plane, with the back of the hand turned upwards. The computer work consisted of moving the mouse pointer around on the screen for six minutes during two different positions of the arm that controls the mouse. During the first three minutes the wrist and the elbow were supported and the arm was held close to the body (ergonomic position). After a rest of 30 seconds the last three minutes was performed with unsupported wrist and elbow and with the arm held from the body (non-ergonomic position). Three healthy male subjects (age 29-49) participated.



Fig. 1 Example of a prototype T-shirt housing smart textile based ECG-electrodes. Commercially available dry electrodes were housed in a padded structure over the shoulder, i.e. over the trapezius muscle.

B. ECG and EMG recordings

Three ECG and two EMG channels were recorded at 1 kHz, using a wireless multichannel data acquisition system (Fig. 2) [12]. Baseline drift was suppressed by analogue high-pass filtering at 0.1 Hz. In addition, the EMG signals were digitally high-pass filtered at 20Hz to remove possible movement artifacts in the low-frequency region. The ECG was measured bipolarly and the textile electrodes were located on the chest.

Surface EMG signal was obtained from the right upper trapezius muscles using commercially available dry electrodes (Roessingh Research and Development, Enschede, The Netherlands), attached 20 mm apart to the T-shirt. Regular, pre-gelled Ag-AgCl electrodes (Medicotest, Ølstykke, Denmark), were placed 20 mm apart (center-to-center distance) next to the dry electrodes and used to obtain a traditional EMG to facilitate comparisons. The electrodes were attached

at a point two-thirds of the distance from the spinous process of the seventh cervical vertebra (C7) to the lateral edge of the acromion. A large textile electrode located at the back was used as a reference electrode for both the dry and the regular pair of electrodes. A test contraction was made before measurement to secure good electrode-skin contact in both conditions.

In order to normalize the muscle activity to a well-defined effort, the subject stretching both arms at 90 degrees in the coronal plane was used as a reference contraction. The myoelectric activity recorded during a reference contraction is called RVE (reference voluntary electrical activation) and is assumed, in this case, to correspond to about 10% of the maximal voluntary contraction (MVC).



Fig. 2 Left photo: 8-channel Bluetooth acquisition prototype unit. Right photo: The modular-constructed acquisition unit containing, CPU, signal conditioner (incl. A/D converters), bluetooth (for real-time transmission) and memory-card (for possible logger functionality).

C. Data processing

1) ECG - Heart beat detection

The basic idea behind our multichannel approach is to design a filter where the output signal has distinct peaks corresponding to the time instants where the ECG QRS complexes occur, and are close to zero elsewhere. In that signal, most of the data points have an amplitude value close to zero and the peaks have a significantly larger value and occur as a marked tail in the histogram, i.e., has a super-gaussian distribution. The aim with the filter is to maximize the super-gaussianity of the output signal.

In order to maximize the super-gaussianity, an adaptive multichannel filter, which combines both spatial and temporal filtering was used [10]. The time filtering is performed using individual finite impulse response filters on each input channel i according to:

$$\mathbf{z}_i = \mathbf{h}_i * \mathbf{x}_i \quad (1)$$

where \mathbf{x}_i is the input signal and $\mathbf{h}_i = [h_{i1} \ h_{i2} \ \dots \ h_{ip}]$ is the filter kernel.

With M input channels the spatial filtering is accomplished as

$$\mathbf{y} = g_1 \mathbf{z}_1 + g_2 \mathbf{z}_2 + \dots + g_M \mathbf{z}_M \quad (2)$$

Substitution of $g_i \mathbf{h}_i$ with \mathbf{w}_i the filter equation yields:

$$\mathbf{y} = \mathbf{w}_1 * \mathbf{x}_1 + \mathbf{w}_2 * \mathbf{x}_2 + \dots + \mathbf{w}_M * \mathbf{x}_M \quad (3)$$

Obviously, the output signal \mathbf{y} is a linear combination of time delayed input signals. The filter coefficients were

determined adaptively for blocks of length $N=3000$ using FastICA, with skewness as cost function. The algorithm was stabilised, by high-pass filtering the input signals, to suppress base line drift. In addition, the signals were normalised to zero mean and unit variance. For more details see Wiklund et al. [10].

2) EMG - Exposure Variation Analysis

In order to quantify the EMG activity, an Exposure Variation Analysis (EVA) was performed as proposed by Mathiassen and Winkel [13]. The EMG signals was RMS filtered using a moving average window of 0.1 s, and normalized to the corresponding RVEs. The signal was then averaged in consecutive intervals of 1/3 s and categorised according to length of uninterrupted intervals spent in specific amplitude levels. The signals were categorised in periods of 0-0.3-1-3-7-15 s and amplitude levels of 0-1-3.3-10-23.3-50-103.3-210 % RVE. This resulted in a matrix where each element represented percent of time in a “period per amplitude category” (Fig. 3). The categories were logarithmically arranged in order to increase the sensitivity for variations at low amplitude levels with short period lengths. Plotting the EVA-matrix resulted in a three-dimensional representation of EMG activity, where each column represented percent of total time spent in each level per period category (Fig. 3).

Short, unconscious interruptions in EMG activity (i.e., EMG activity less than 0.5% MVC) are referred to as “gaps”. Further, interruptions lasting for 0.2-0.6 s as short gaps and interruptions lasting longer than 0.6 s as long gaps. In the EVA matrix, gap levels are therefore represented by the shadowed elements in the lowest amplitude level (0-1% RVE) that corresponds to periods of 0.3 s or longer (Fig. 3).

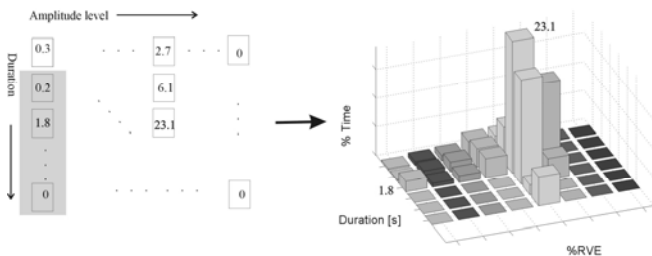


Fig. 3 Description of the Exposure Variation Analysis (EVA) matrix used in the analysis of the trapezius muscle activity pattern. Each element in the matrix represents percent of total time that the subject spent in a specified level per period category.

III. RESULTS

Fig. 4 shows a typical part of one recording, where computer work was performed. In all measurements, the EMG signals recorded with the dry electrodes were similar (except for some spikes) to the EMG signals recorded with ordinary gelled Ag-AgCl electrodes.

An example of the EVA matrices of the two different tasks can be seen in Fig. 5 from one of the subjects. The results

showed that, for this subject, the non-ergonomic working situation had higher muscle electrical activity and less variation as compared to the more ergonomic situation. The recorded EMG signals had sufficient quality for EVA analyses for all of the subjects.

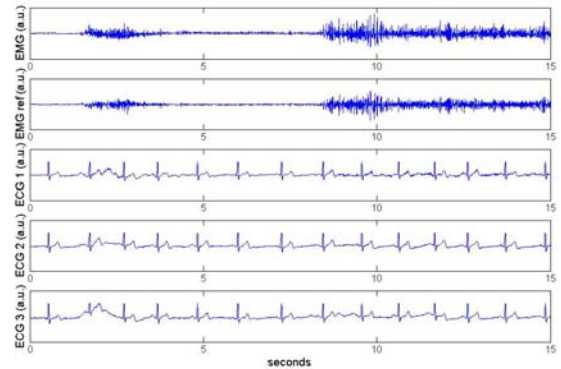


Fig. 4 Typical example of a recording. EMG muscle activity (from top: dry resp. gelled electrode) from right trapezius muscle and corresponding ECG activity during computer work.

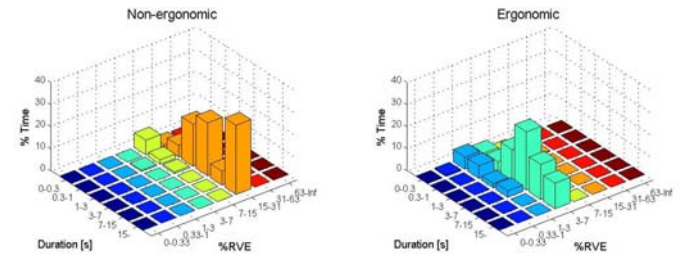


Fig. 5. EVA matrices from two different tasks, where one of the tasks was more ergonomic, see the method section for more details.

IV. DISCUSSION AND CONCLUSION

We have developed a prototype T-shirt housing textile electrodes that enables multi-channel recording of ECG (Fig. 1). Apart from the described T-shirt, the idea of a general solution incorporating both textile electrodes and data transfer has also been proved in a cardigan (Fig. 6) and a chest-band. During favourable conditions an ECG signal as depicted in Fig. 4 can be recorded, which allows for heart rate and heart rate variability analysis without adopting advanced signal processing methods. The multi-channel approach can be used during less favourable situations, e.g. when the subject is moving resulting in a bad, or even lost, signal from one or several of the ECG electrodes (Fig. 7).

The use of smart textile sensors integrated in clothing allow ECG and EMG recordings to be fully self-administered, i.e. independent of someone assisting to apply electrodes, which opens up a vast field of research and health monitoring possibilities.



Fig. 6 Prototype for ECG monitoring in home health care situations. ECG signals are registered using textile electrodes integrated in the left and right wristlet.

A. Methodological considerations

In textile electrode design there are three main problems to consider. The motion artefacts in textile structures add noise to the bio-signal. Textile electrodes are preferably used dry without conducting gel, which leads to a relative high impedance and that also affects the signal quality. Disturbances can also be generated by loss of signals from individual electrodes. Motion artefacts from the textile structures are decreased by using a stable textile structure, a woven structure for example gives less motion artefacts than a knitted [14]. Padded structures reduce high impedances since pressure on the electrode together with a sticky coating keep the electrodes in better contact with the skin.

At the time of writing no EMG signal has been recorded using textile electrodes. Monitoring of heart activity depend less on the exact position of the sensors, thus, the smart textile approach is better suited to ECG than EMG recordings. Our solution is to use a padded structure above the trapezius muscle housing commercially available dry electrodes [15]. Apart from the extra pressure on the EMG-electrodes provided by the padded structure resulting in an increased contact between electrode and skin, the padding also contributes to a better-defined recording position over the trapezius muscle.

B. ECG detection

Normally, ECG is recorded for arrhythmia analyses based on the heart rate and also for analysis of the morphology of the complexes. An ECG signal for detection of heart rate can be recorded from many positions of the trunk, which allows multiple channel recordings without demands on the actual location of each electrode. However, the latter is crucial for

determination of cardiac conduction disturbances and morphological changes after myocardial infarction.

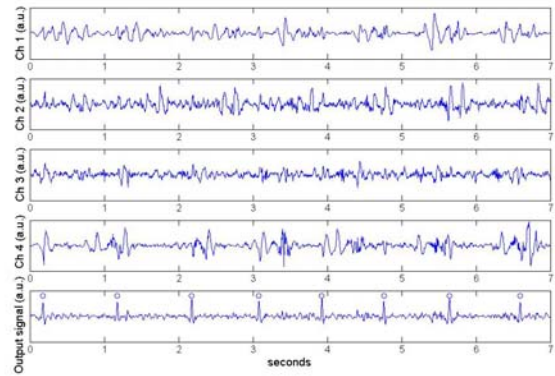


Fig. 7 Example of a noisy ECG recording and the result using the spatio-temporal filter. The bottom panel show the adaptive filtered ECG signal.

We have developed an advanced signal processing technique that allows us to monitor both heart rate and heart rate variability from multi-channel recordings where the signal in some channels may be disturbed or even missing (Fig. 7). This multi-channel approach addresses the above-mentioned difficulties with frequent disturbances that are inherent in smart textiles.

The T-shirt is more comfortable than today's traditional Holter systems, which makes it suitable for long term monitoring of heart rate, e.g. cardiac patients at the clinic or in the patients home. The system may also be used for real time monitoring of arrhythmias due to the robust heartbeat detection in ECG measurements.

C. EMG analysis

A possible limitation of our study concerns the reference contraction. Naturally, the choice of sub-maximal reference contraction will influence the position of the 3D EVA pattern along the amplitude axis, as the EMG data are normalised to the myoelectric activity (RVE) recorded during the chosen contraction. The aim of this study is to demonstrate the value of the signal recorded by means of dry electrodes housed in the prototype T-shirt rather than providing data to be considered in the evaluation of computer related tasks.

A possible extension of the EVA method is principal component analysis, PCA, can be used in order to classify the EMG activity pattern of the subjects at a group level. PCA involves a mathematical procedure that transforms a set of correlated response variables into a smaller set of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible and each succeeding component accounts for as much of the remaining variability as possible. For more information see Fjellman-Wiklund et al. [16].

D. Possibilities

The remarkable progress in mobile and ubiquitous computing as well as development of wearable products for clinical applications will break the limits inherent in current monitoring schemes. Wearable wireless devices that can

intermittently or continuously process and monitor relevant physiological signals will provide new diagnostic and therapeutic avenues for patient care. In addition, real-time feedback to the patient can be used, either as a warning of impending medical emergency or state of concern, or as a monitoring aid during e.g. exercise. Taken together, these new possibilities represent a revolution in health care monitoring which has a vast potential to significantly decrease the number and length of hospitalisations.

E. Conclusion

Although further improvements are needed, our current experiences indicate that a smart textile T-shirt allowing long term recordings of heart and shoulder activity may be available to the research community in the near future. This would extend current possibilities in e.g. simultaneous long term monitoring of trapezius muscle activity and heart rate and heart rate variability, which is highly interesting in studies of e.g. musculoskeletal disorders in the neck and shoulder.

ACKNOWLEDGMENT

This work was supported by the European Union Regional Development Fund and the Swedish Research Council (2003-4833, 621-2007-3959, and K2004-27KX-15053-01A). Authors acknowledge the technical assistance by Urban Edström at the Department of Biomedical Engineering & Informatics, Umeå University Hospital, Sweden.

REFERENCES

- [1] S. Park, K. Mackenzie, and S. Jayaraman, "The wearable motherboard: A Framework for Personalized Mobile Information Processing (PMIP)," in *Proc. of 39th Design Automation Conference, DAC, 2002*, New Orleans, Louisiana, USA.
- [2] P. Grossman, "The Lifeshirt: A multi-function ambulatory system that monitors health, disease, and medical intervention in the real world," in *Proc. of New generation of Wearable Systems for ehealth, International Workshop, 2003*, Tuscany, Italy.
- [3] J.-L. Weber, D. Blanc, B. Comer, C. Corroy, N. Noury, R. Baghai, S. Vaysse, and A. Blinowska, "Telemonitoring of vital Parameters with newly designed biomedical clothing VTAM," in *Proc. of New generation of Wearable Systems for ehealth, International Workshop, 2003*, Tuscany, Italy.
- [4] R. Paradiso, G. Loriga, M. Pacelli, and R. Orselli, "Wearable system for vital signs monitoring," in *Proc. of New generation of Wearable Systems for ehealth, International Workshop, 2003*, Tuscany, Italy.
- [5] C. Hertleer, M. Grabowska, L. van Langenhove, B. Hermans, R. Puers, A. Kalmar, H. van Egmond, and D. Matthys, "The use of electroconductive textile material for the development of a smart suit," in *Proc. World Textile Conference – 4th Autex Conference, 2004*, Roubaix, France.
- [6] L. Berglin, M. Ekström, and M. Lindén, "Monitoring health and activity by Smartwear," in *Proc. of 13th Nordic Baltic Conf on Biomed Eng and Med Phys, 2005*, Umeå, Sweden.
- [7] M. Pacelli, G. Loriga, N. Taccini, and R. Paradiso, "Sensing Fabrics for Monitoring Physiological and Biomechanical Variables: E-textile solutions," in *Proc. of the 3rd IEEE-EMBS. International Summer School and Symposium on Medical Devices and Biosensors, 2006*, MIT, Boston, USA.
- [8] M. Di Rienzo, F. Rizzo, G. Parati, G. Brambilla, M. Ferratini, P. Castiglioni, "MagIC System: a New Textile-Based Wearable Device for biological Signal Monitoring. Applicability in Daily Life and Clinical Setting," in *Proc. of the 2005 IEEE Engineering in Medicine and Biology 27th Annual Conference, 2005*, Shanghai, China.
- [9] L. Sandsjö, L. Berglin, U. Wiklund, K. Lindecrantz, and JS. Karlsson, "Self-administered long-term ambulatory monitoring of electrophysiological signals based on smart textiles," in *Proc. IEA, 2006*, Maastricht, Netherlands.
- [10] U. Wiklund, M. Karlsson, N. Östlund, L. Berglin, K. Lindecrantz, S. Karlsson, and L. Sandsjö, "Adaptive spatio-temporal filtering of disturbed ECGs: a multi-channel approach to heartbeat detection in smart clothing," *Med. Biol. Eng. Comput.*, vol. 45, pp. 515–523, 2007.
- [11] N. Östlund, J. Yu, and JS Karlsson, "Adaptive spatio-temporal filtering of multichannel surface EMG signals," *Med. Biol. Eng. Comput.*, vol. 44, pp. 209-215, 2006.
- [12] JS. Karlsson, T. Bäcklund, and U. Edström U, "A New Wireless Multi-Channel Data System for Acquisition and Analysis of Physiological Signals," in *Proc. of the 17th International Symposium on Biotelemetry, 2003*, Brisbane, Australia.
- [13] SE. Mathiassen and J. Winkel, "Quantifying variation in physical load using exposure-vs-time data," *Ergonomics*, vol. 34, pp. 1455-1468, 1991.
- [14] E. Samuelsson, "Electrical Signal Transmission in Textile Structures," Master Thesis, The Swedish School of Textiles, University College of Borås, Sweden, 2005.
- [15] HJ. Hermens and MMR. Hutten, "Muscle activation in chronic pain: its treatment using a new approach of myofeedback," *Int J o Ind Ergonomics*, vol. 30, pp. 325-326, 2002.
- [16] A. Fjellman-Wiklund, H. Grip, JS. Karlsson, and G. Sundelin, "EMG Trapezius Muscle Activity Pattern in String Players: Part I – Is there variability in the playing technique?," *Int. J. Industrial Ergonomics*, vol. 33, pp. 347-356, 2004.