Paper

WEALTHY – a wearable healthcare system: new frontier on e-textile

Rita Paradiso, Giannicola Loriga, Nicola Taccini, Angelo Gemignani, and Brunello Ghelarducci

Abstract— A comfortable health monitoring system named WEALTHY is presented. The system is based on a wearable interface implemented by integrating fabric sensors, advanced signal processing techniques and modern telecommunication systems, on a textile platform. Conducting and piezoresistive materials in form of fibre and yarn are integrated in a garment and used as sensors, connectors and electrode elements. Simultaneous recording of vital signs allows extrapolation of more complex parameters and inter-signal elaboration that contribute to produce alert messages and patient table. The purpose of this publication is to evaluate the performance of the textile platform and the possibility of the simultaneous acquisition of several biomedical signals.

Keywords— fabric sensors, fabric electrodes, physiological signs.

1. Introduction

One of the emerging new tendencies for healthcare monitoring systems is rising from areas relatively far away from the traditionally involved technologies.

During the last decade we have assisted at a revolution in telecommunication domain, while during 80's the electronic devices scale has shifted from a micro to a nano dimension. Nowadays, a new generation of monitoring devices based on the growth of the knowledge derived from the past research experience and on the use of textile multi sensing interfaces is rising.

The systems have to combine the advances of telecommunication, microelectronics and material science to guarantee a continuously remote monitoring of multiple physiological functions, as well as comfort and wearability. The spotlight is shifting from external environment control to human oriented systems, where the subject-actor is constantly virtually linked and interactive.

This tendency is changing dramatically the common life style, as well as the needs of people. Citizens are becoming more and more used in telecommunicating and in managing information, and the idea of a surrounding virtual world is no more an alien concept. New tools are being developed to be used every where, during normal life, capable to help people to increase their health status awareness, to train them to act at a preventive level by modifying their life style, to give them the feeling of a reassuring link. The interaction between physician and patient is growing in quality and the contribution is coming from both sides.

New systems designed to be minimally invasive, based on flexible and smart technologies conformable to the human body are conceived to improve the autonomy and the quality of life of patients. They are also cost-effective in providing around-the-clock assistance, in helping physicians to monitor cardiac patients during rehabilitation phase, in decreasing hospitalization time.

The system can also assist professional workers subject to considerable physical and psychological stress and/or environmental and professional health risks.

The aim of the work presented is to set up a fully integrated garment system, able to acquire simultaneously, in a "natural" environment a set of physiological parameters. The system is designed to be minimally invasive, comfortable and wearable, to this aim conductive and piezoresistive materials in form of fibre and yarn are used to realize clothes where knitted fabric sensors and electrodes are distributed and connected to an electronic portable unit, the acquired signals can then be transmitted to a remote monitoring system.

The simultaneous recording of vital signs allows parameters extrapolation and inter-signal elaboration [1, 2] that contribute to produce alert messages and personalized tables of user's health.

2. The WEALTHY system

Strain fabric sensors based on piezoresistive yarns, and fabric electrodes realized with metal based yarns, enable the realization of wearable and wireless instrumented garments capable of recording physiological signals and to be used by the patient during everyday activity. Breathing pattern, electrocardiogram, electromyogram, activity pattern or behaviour, temperature, can be listed as physiological variables to be monitored through the proposed system. A miniaturized short-range wireless system can be integrated in the sensitive garment and used to transfer the signals to the WEALTHY box/PCs, PDA and mobile phones. An "intelligent" system for the alert functions, able to create an "intelligent environment" by delivering the appropriate information for the target professional is the complementary function to be implemented. The system is targeting the monitoring of patients suffering from heart diseases during and after their rehabilitation.

3. WEALTHY functions

The WEALTHY system has been developed as the integration of several functional modules. The main functions are shown in Fig. 1, namely: sensing, pre-processing, transmission, processing and data management.

The garment interface is connected with the portable WEALTHY device where the local processing as well as the communication with the network is performed. A knitted fabric platform containing insulated conductive tracks connected with sensors and electrodes has been implemented to make the cloth. Most signals are transmitted unprocessed to the monitoring system where they can be analyzed off-line. In order to reduce the needed data capacity of the wireless link to the central monitoring system, some sensor signals are processed by the portable patient unit (PPU) to extract essential parameters. Local pre-processing of signals has to be decided in a trade-off between the gain in term of wireless link occupancy and the increase of needed local processing power.

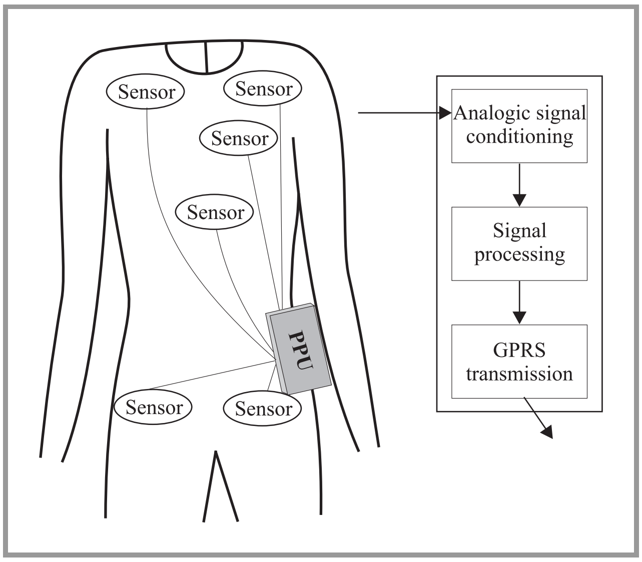

Fig. 1. Overall WEALTHY function.

The ECG leads that can be gathered are:

- precordial V2 and V5;
- einthoven D1, D2, D3.

ECG signals are sampled on the PPU at 250 Hz, a local processing is applied in order to extract parameters with a higher sampling rate, so that ECG parameters, such as heart rate (HR) value and QRS duration can be computed with a significant number of samples.

In order to decrease the amount of data transmitted by GPRS, the ECG signal is decimated to obtain a sampling rate of 100 Hz, and the operator at the monitoring centre can view and record only one ECG signal by selecting the desired one.

Respiration and movement activity come from piezoresistive sensors, sampled at 16 Hz. The signals from these sensors are transmitted without local processing.

The PPU is designed to have a simple user interface, a few LEDs and a buzzer for user warning purpose and a button to let him manually trigger an alarm. The PPU electronics is built on an "Europe" form factor board (first prototype dimension: 160 mm $\times$ 100 mm, first prototype weight: 400 g) and packaged in a metallic enclosure. It contains the necessary functions to condition physiological signals, such as filtering, digital analysis and to perform specific higher level processing like HR extraction, run the application, as well as communicate over GPRS with a monitoring centre. All the circuits, sensors and communication module are powered by a 1100 mAh/3.6 V lithium battery. The battery autonomy ranges between a few hours and eight hours, depending on the level of use of the GPRS link. It can be recharged using a dedicated front panel connector.

The WEALTHY central monitoring system is a s/w module interpreting physical sensor data received from the PPU and representing them in simple, graphical forms. It will be used by the proper staff in order to judge the automatically generated alerts and forward only the critical alerts to the doctors and the patients.

The central monitoring system performs the following tasks:

- coordinates and controls the data flow between the different actors;
- collects and stores the data transmitted by the sensors integrated in the WEALTHY garment through the portable patient unit;
- continuously monitors vital health parameters of the patients;
- generates alerts to inform doctors for critical health situations;
- gives access to the central database to doctors and other health professionals;
- presents to the qualified users the health situation of the patients using different user-friendly interfaces.

All the monitoring system modules are able to run on a single computer without the need of dedicated high-end servers.

The final aim is to recognize those parameters that define an event. Several statistical tools based on a multifunctional analysis, such as principal component analysis (PCA) or independent component analysis (ICA), may be used for this purpose. In order to offer full mobility to the patient or the user, the acquired signals are transmitted wirelessly from the PPU to the remote monitoring system. The communication is based on TCP/IP that is the standard protocol for GPRS communication. For GPRS bandwidth limitation reason, the monitoring centre shall select the ECG lead to be transmitted (one at the time). All signals are sent in quasi real-time to the remote monitoring centre.

Off-line processing, depending on the application, is carried out at the monitoring centre. A preliminary list includes:

- tachogram;
- ST deviation;
- T wave area;
- spectral analysis of RR signal.

Combining these parameters and the information obtained by the other signals (movement, respiration, HR, etc.) the system generates automatic alerts. A set of rules for the determination of the alert criteria has been implemented in the alert module. New alerts are also possible to be included by authorised personnel, as well as modification of the alert criteria [3].

The user will be able to watch the health status of all patients connected to the central monitoring system (through the WEALTHY garments). The definition of the monitoring profiles will provide an easy to use monitoring of the patients' health status in real time and with different fully customisable views.

Simultaneously, the user will be able to review the generated alerts and using past medical data will determine the true and false alerts and correspondingly contact doctors through direct phone calls and online alerts. This central control module is not necessary in order for the monitoring system to work. It is an optional module ensuring the minimal generation of false alerts to the doctors and will be necessary for large scale hospitals dealing with hundreds of patients.

The WEALTHY platform will give the possibility to monitor and assist patients through a remote medical advice service. The use of intelligent systems provides to physicians the data to timely detect and manage health risks, diagnose early illness or injury, recommend treatment that would prevent further deterioration and, finally, to make confident professional decisions based on objective information all in a reasonably short time.

4. WEALTHY interface

Strain fabric sensors based on piezoresistive fabric or yarns, and fabric electrodes made with metal based yarns, enable the realization of wearable and wireless instrumented garments capable of recording physiological signals, to be used during the routinely activity, to be worn instead of a classical garment without discomfort for the user. Respiration, electrocardiogram, electromiogram, activity sensors, temperature, may be listed among the physiological variables that can be monitored through the proposed system.

Piezoresistive fabric sensors have been realized by using lycra® fabric coated with carbon loaded rubber, as well as by weaving a commercial electroconductive yarn (PAC 250 dtx x 1, by Europa NCT, Poland). These fabrics behave as strain gauge sensors and show piezoresistive properties in response to an external mechanical stimulus. The coated lycra® fabric has been used to detect respiration signal, due to the higher efficiency shown in term of quality of the signal, compared with the other fabric sensor. The Europa yarn has been used for the activity sensors and knitted in the multifunctional fabric. The behaviour of a knitted piezorestive sensor is different when stretched towards warp or weft direction. Preliminary tests have been done to select the more efficient technique of knitting and the direction of stretching. The fabric sensor have been integrated and oriented in a way to maximize the gauge factor according with the response shown during the preliminary tests.

Electrodes have been realized with a yarn where two stainless steel wires are twisted around a viscose textile yarn (Elitè by Lineapiù s.p.a., Italy). Electrodes were knitted by using the tubular intarsia technique [4] to get a double face, using the external – non conductive – part to isolate the electrode from the external environment. The basal yarn (not sensitive) was the same yarn used as core for the conductive electrode yarn. To improve the electrical signal quality in dynamic condition a hydro-gel membrane purchased by ST&D Ltd (Belfast-UK), has been used. The use of the membrane affects also the comfort as electrodes have a rough surface and a prolonged contact with the body can give rise to skin irritations. The contact between conductive fabric and skin can be improved by increasing the adherence of the garment with the use of a higher percentage of elastic component in the yarns. Another approach is the use of conducting rubber or silicon as coating layer for the electrodes; in our future work both the approaches will be investigated.

Connections have been realized by means of the tubular intarsia technique. A supplementary layer has been woven by using of vanise technique. The final connection is a multi layered structure where the conductive surface is sandwiched between two insulated standard textile surfaces. The same conductive yarn is used for the electrodes as well as for the realization of connections, a particular of the textile prototype is shown in Fig. 2.

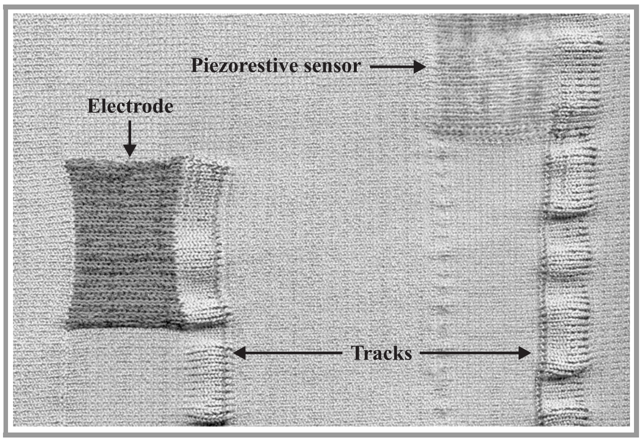

Fig. 2. Part of the WEALTHY interface.

The knitting fabric has been made with a flat-knitting machine (Vesta Vx 12 – Steiger, Switzerland). A draft position of sensors was implemented on the knitted fabric, and then by means of the use of models was possible to cut the fabric in a way to get the sensors in the desired configuration. The garment was finally sewed, which means that the final position of sensors and connections was achieved in the manufacturing phase.

The prototype model [5] is shown in Fig. 3 where the electrodes position is highlighted. In Fig. 3 the Einthoven

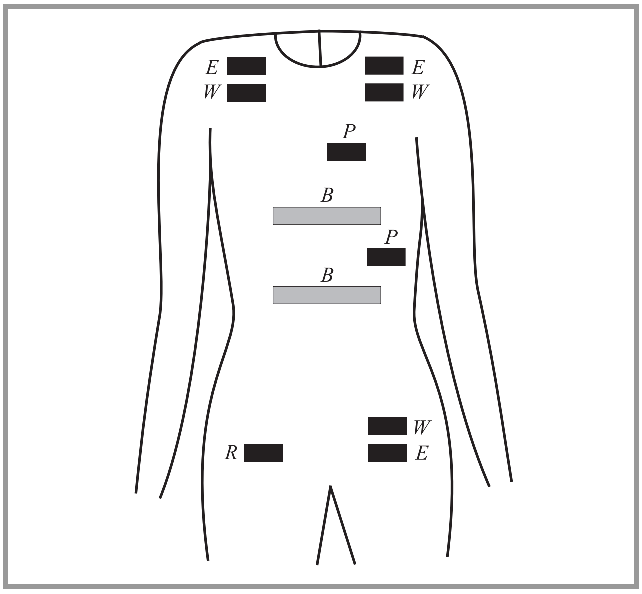

Fig. 3. Prototype model: *E* – Einthoven, *W* – Wilson, *R* – reference, *P* – precordial leads, *B* – breathing sensors.

and Wilson derivations (*E, W*), V2 and V5 as precordial leads (*P*) and the reference electrodes (*R*) are shown, while two breathing sensors (*B*) are positioned one on the thorax and the other on the abdomen. In Fig. 4 the position of the 6 movement sensors is shown.

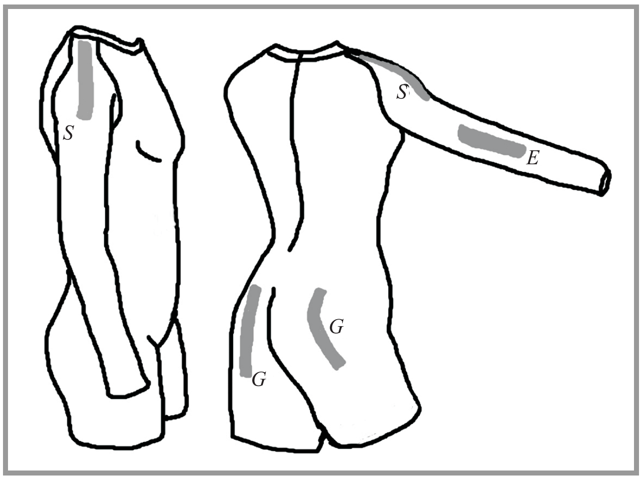

Fig. 4. Prototype model: *S* – shoulder movement, *E* – elbow movement, *G* – gluteus movement sensors.

The stainless steel threads have been selected for the realization of fabric electrodes for a series of reasons: first of all they are compatible with industrial textile processes, they are inert and stable in the presence of O_2, finally the cost of steel is very competitive compared with pure silver, or pure gold.

Naturally the fineness and flexibility of metal components have been chosen to get a final conductive yarn suitable for knitting, weaving and more in general for textile processing, which means that the metal threads used are washable, flexible and biocompatible. The same approach has been used for all the sensorial yarns and fabric developed in the project. It is also possible to work with silver coated threads that are occasionally employed for special fashion effects or for antibacterial purposes in textile world. Preliminary tests done with fabric containing polyester yarns coated with silver have shown that the use of stainless steel threads is more convenient: in fact during the experiments it has been observed that the conductivity of the silver electrode was lower than the stainless steel ones, when samples with the same dimension were compared. This is probably due to the small amount of metal components localized only in the coating layer of the threads. It is important to underline that the fabric cannot be realized only with metal yarns otherwise this region of the garment will be too rigid and not conformable, the amount of metal in the fabric is a compromise between the demand to increase the conductivity and the necessity to improve the touch sensation (the hand) of the cloth. Moreover the quality of silver adhesion was very poor, after several tests large metal coating regions looked removed; the electrodes need to be used with gel or conductive past and finally the electrodes have to be chlorinated.

Conductive and piezoresistive yarns are resistant to repeated washing in aqueous solutions, the physiological signals detected after washing have shown that the performances of the fabric sensors are not affected by the process.

5. Methods

The purpose of this publication is to evaluate the performance of textile sensors, electrodes and connections integrated in a garment (sensing part of the WEALTHY system), and to prove the possibility of the simultaneous acquisition of several biomedical signals during training session.

All the tests have been effected using the WEALTHY textile interface, adding two electrodes, not integrated but sewn, on the right leg, in order to monitor the EMG activity of the quadriceps muscle.

Piezoresistive signals have been conditioned by a voltage divider, followed by a Butterworth low pass filter (cut frequency at 10 Hz).

Signals from fabric electrodes have been conditioned by a GRASS-TELEFACTOR mod. 15LT device equipped with differential amplifiers mod. 15A54, with settable gain and band pass filter, notch filter at 50 Hz.

The ECG signals from fabric electrodes were conditioned setting gain 1000 and band pass filter with frequency range between 1 and 100 Hz. Surface EMG signals from fabric electrodes positioned on the right leg (quadriceps) were conditioned setting gain 2000 and band pass filter with frequency range between 10 and 500 Hz.

Every analogic signal has been acquired by an acquisition card (National Instruments PCI 6036) with sampling rate of 1000 Hz.

The experiments have been performed according the following experimental paradigm.

The baseline conditions were recorded when the subject was lying in supine position (R1) for a period of 10 minutes, followed by a control period of 2 minutes with the subject sitting on a cyclette (R2). This was followed by a period of progressively increasing physical exercise (cycling with increasing frequency and force) M1, M2, M3, M4, 5 minutes each. Then the period (R3), still in vertical position on the cyclette, for 2 minutes, as in R2.

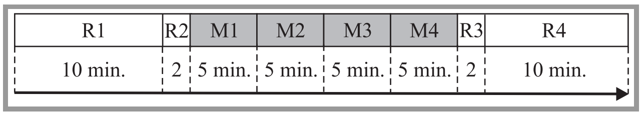

Fig. 5. Experimental design.

Finally, the subject was asked to stand up and to lie in supine position for other 10 minutes (R4) as in R1. The experimental protocol is summarized in Fig. 5.

6. Results

The ECG leads used to evaluate the performances of the WEALTHY textile interface are:

- precordial V5;
- precordial V2;
- Einthoven D2.

These signals are acquired simultaneously with the respiratory activity (abdominal and thoracic) and the activity of the right quadriceps.

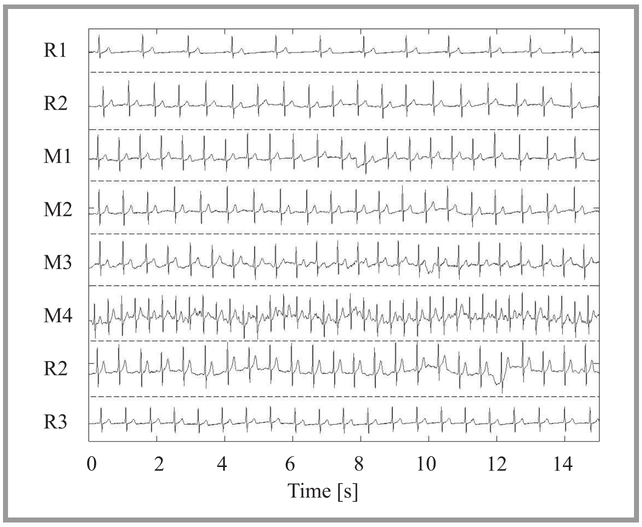

Fig. 6. V5 precordial lead signal in each experimental condition.

The results obtained in the whole sessions have been analyzed in order to demonstrate the robustness of the system.

In Fig. 6 the recordings from the V5 leads are shown, acquired according to the protocol previously described, for a period of 15 s each.

The analysis of the precordial leads shows that the quality of the signals is not affected by movement artefacts, in the frame of this trial.

In Fig. 7 it is possible to notice that the response of D2 lead is still satisfying for regular movement (M3). In fact only during M4 (very intense activity) the signal is noisy and could be very hard to get useful parameters (heart rate).

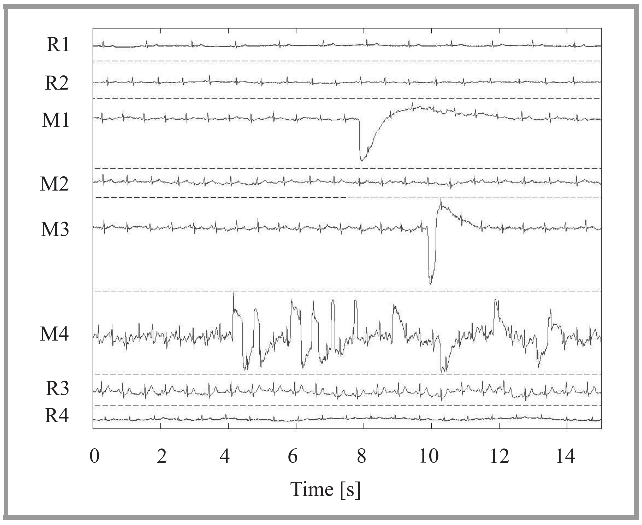

Fig. 7. D2 Einthoven lead signal in each experimental condition.

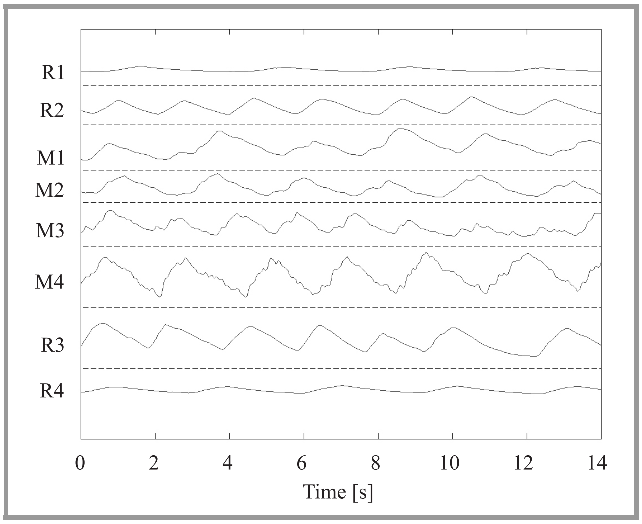

Fig. 8. Respiratory activity, reading plethysmography in thoracic position, in each experimental condition.

The signal obtained by the piezoresistive sensor placed on the thoracic position is shown in Fig. 8. It is affected by noise during the M-phase, but is still possible to obtain the respiratory rate and to have information about the plethysmography of thorax with an appropriate algorithm of analysis.

In Fig. 9 it is possible to notice the increasing of muscular activity by analyzing the results of surface EMG signal.

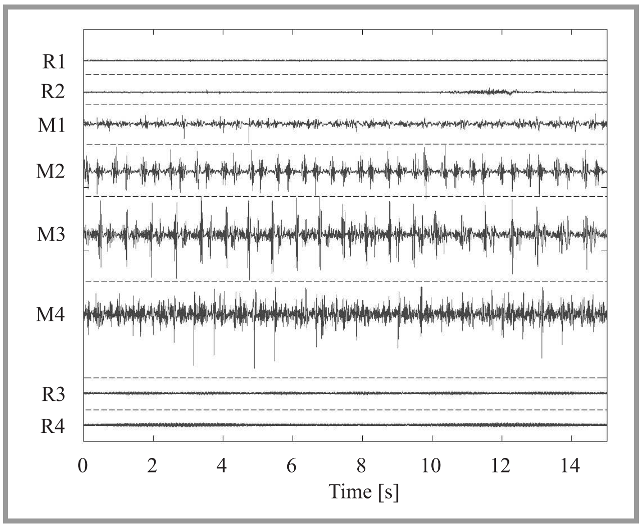

Fig. 9. Surface EMG signal from right quadriceps in each experimental condition.

The amplitude of signal and median frequency, defined as the frequency below which lies 50% of the total power of the PSD, increases with the speed of spinning movements and the effort required by the increasing resistance set on the cyclette, as shown in Table 1.

Table 1
Median frequency of PSD of the surface EMG during movements

Experimental condition	M1	M2	M3	M4
Median frequency [Hz]	17.58	24.41	25.39	28.32

7. Discussion

The achieved results show that fabric electrodes endowed in the sensing shirt allow a continuous and simultaneous monitoring of bioelectrical and biomechanical physiological signals in a behaving subject. In a previous work [6] has been shown that the signals recorded by fabric electrodes are comparable to those acquired with gold-standard electrodes commonly employed in research and clinical use. The electrical and mechanical properties of fabric electrodes have not been modified by their integration in the wearable shirt, as the characteristics of electrocardiographic (ECG), electromyographic (EMG) and respiratory (RESP*) signals are comparable to those obtained with standard electrodes in similar conditions. The response of the system during the different activity phases are clearly observable in Fig. 6, where the EGG data indicate that precordial leads exhibit a remarkable stability and are free from artefacts even during the maximal exercise intensity (M4), when also the background noise appears negligible. In the standard D2 derivation the signal is less stable and the amount of artefacts related to movement clearly increases (Fig. 7). This may be related to the lack of adherence of the garment to the upper chest when the subject had to grab the cyclette handle bar during exercise. Moreover, the strong engagement of the pectoral muscles in this type of exercise may be responsible for the higher background noise observed. The signal to noise ratio can be improved by trying to set the fabric electrode position on a rigid surface such as the clavicle and the sensing shirt will be modified accordingly in the future. The good quality of the ECG signal allows the computation of heart rate and its variability throughout the experimental cycle. As described in the literature during physical exercise there is a progressive increase of heart rate (Fig. 10), correlated to a parallel decrease of heart rate variability (Fig. 11).

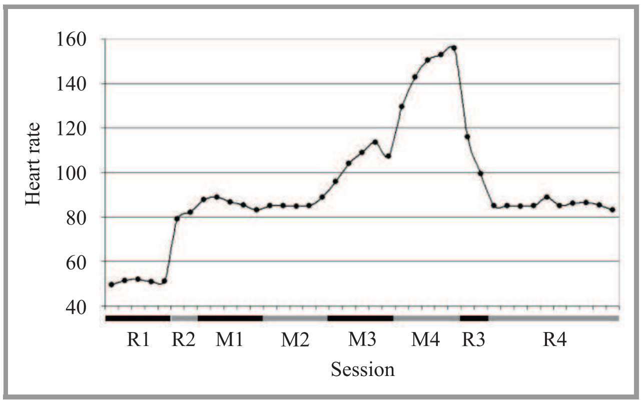

Fig. 10. Heart rate obtained analyzing V5 signal in each experimental condition.

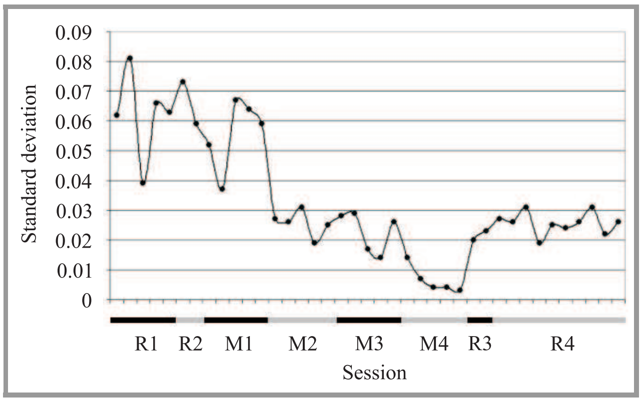

Fig. 11. Heart rate variability.

Due to the good quality of recorded signals, the ECG can be adequately employed to study non invasively and in behaving conditions more complex functional indexes related to the sympatho-vagal balance, such as low frequency and high frequency components derived by spectral analysis of RR interval variability [1], respiratory sinus arrhythmia and area under T wave of the ECG.
In Fig. 8, respiratory signals are shown detected through piezoresistive sensors. Also in this case is evident a remarkable stability and an excellent signal to noise ratio during

the experimental session. Moreover the signal time course is adequate to reproduce the thoracic excursions without detectable phase shifts. Thus the respirogram yields accurate information about respiratory rate while the variations of signal amplitude can give only a qualitative estimation of the respiratory depth.

The surface activity of selected lower limb muscles such as the quadriceps can easily be recorded by fabric electrodes similar to those used for recording ECG. The EMG shown in Fig. 9 exhibits bursts of activity synchronous with the pedalling cycle which rise by increasing the frequency and the force required by the exercise.

As shown in Fig. 12, the sensing shirt makes possible a simultaneous and multi-parametric acquisition of several physiological variables in different behavioural conditions. This possibility represents a significant advantage when it is necessary to monitor the vital asset of workers in extreme environmental conditions as well as sportsmen during high physical performance or military personnel engaged in war sites.

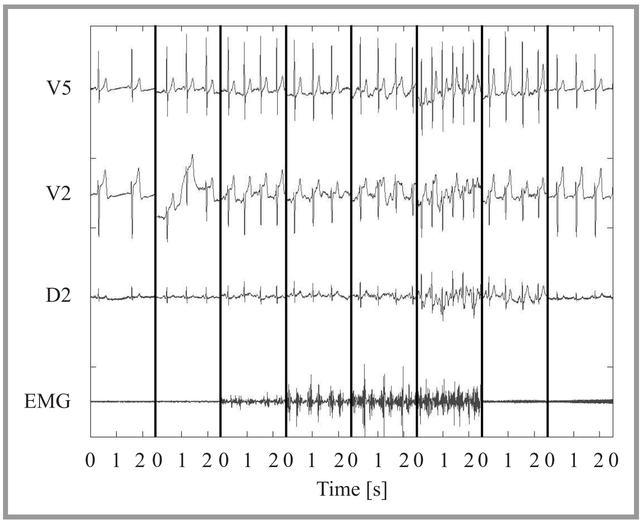

Fig. 12. Overview of changing in all electrical signal during experiment.

The most innovative feature of this system consists of the use of functionalized materials in form of fibres and yarns, which can be knitted or woven into a sensing fabric. Preliminary results [7] show that the basic sensing features on which vital sign recording is based can be implemented using integrated knitted sensors and electrodes. Previous authors works [8, 9] have shown that low frequency mechanical signals of cardiopulmonary origin (respiratory signals, ballistogram) or generated by body segments relative motion (kinaesthesia) could be recorded by textile strain gauges. Finally bioelectric potentials related to cardiac or skeletal muscle activity (ECG, EMC) have been faithfully recorded by metal based fabric electrodes. The integration of these different components with appropriate elastic electrical conductors and properly designed connectors to the wearable electronic unit, leads to a comfortable wearable cloth which has no counterpart in any existing monitoring system. These new integrated knitted systems enable applications extending even beyond the clinical area and open new possible applications in sport, ergonomics and monitoring operators exposed to harsh or risky conditions (fire fighters, soldiers, etc.). The possibility of simultaneously recording different physiological signals provides an integrated view of normal and abnormal pattern of activity which could be otherwise impossible to be detected by recording each signal in different time. Finally it must be outlined that the possibility of recording physiological variables in a more "natural" environment may help to identify the influence of the psycho-emotional state of the subject in the performance of a physical activity. This is not easily detectable when recording is done within a protected (medical) environment. A further innovation is the in-context data interpretation. While a simple telemonitoring system would just transmit or record real-time physiological signs, the WEALTHY system will be able to process physiological parameters in context, so that appropriate feedback can be given to the patient.

8. Conclusions

The innovative approach of this work is based on the use of standard textile industrial processes to realize the sensing elements. Transduction functions are implemented in the same knitted system, where movements and vital signs are converted into readable signals, which can be acquired and tele-transmitted. In our fabric sensors, electrodes and bus structure are all integrated in textile material, making possible to perform normal daily activity while the clinical status is monitored by a specialist, with a comfortable wearable cloth which has no counterpart in any existing monitoring system [10, 11]. WEALTHY system benefits from the performance of the textile sensing interface to guarantee a continuously remote monitoring of user vital signs, the signals are acquired and elaborated on body and a set of signals and parameters are teletransmitted and managed by a remote control system. The philosophy of this approach is focused on the realization of a friendly, human oriented textile based system, where the choose of sensing material is a compromise between comfort for the users and signal quality for the specialists.

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Rita Paradiso graduated in physics from the University of Genoa and received her Ph.D. in bioengineering in 1991. Molecular electronics, biosensors, biomaterials for biomedical applications have been her main research topics. In particular she worked on bio-functionalized surfaces and their characterization. She worked in London during the Ph.D. at the Physics Department of Queen Mary College. In 1993 she got a Post Doctor CE fellowship, in the frame of Human Capital and Mobility project at the Molecular Chemical Laboratory – CNE Saclay, France. In 1994 she was Post Doctor fellow from the Genoa University, at the Department of Material Engineering of the University of Trento. During 1998, she worked at the "IRST – Instituto Trentino di Cultura" on a project related to bio-activation of MEMS, FIBIA. From 1998–1999 she was Research Manager of Technobiochip s.r.l. – Marciana (LI) – Italy, working on two BRITE-EURAM II projects: BE97-4511 (PRO.MO.FILM) and BE97-5141 (BIO.M.I.ST.) and on a National Project PNR, Tema 10: Biosensors for the Environmental Control. She has over 20 scientific publications and conference presentation since 1989. She joined Smartex in 2000 as R&D Manager, and from Sept. 2001 is the coordinator of WEALTHY (IST-2001-37778), from January 2004, is working in MYHEART an Integrated Project (IST-2002-507816).

e-mail: rita@smartex.it
Milior s.p.a.
via Pistoiese 755/D
59100 Prato (PO), Italy

Giannicola Loriga graduated in electronic engineering in 2002, with a specialization in bioengineering with a dissertation on development and implementation of wearable systems for vital signals monitoring. In 2003 he got a fellowship for the WEALTHY project at the Interdepartmental Research Centre "E. Piaggio" of the University of Pisa. His research activity has been focused on the study of sensors for monitoring respiratory activity. He developed and patented a portable system for bioelectrical impedance measures. He joined Smartex in Apr., 2004, where he cares about software and hardware development and signal analysis.

e-mail: loriga@smartex.it
Smartex s.r.l.
via Giuntini 13 int. L
56023 Navacchio (PI), Italy

Nicola Taccini graduated in electronic engineering in 2002, with a specialization in bioengineering with a dissertation on development and implementation of systems for cinematic body variables detection. He joined Smartex in July, 2002, where he cares about software and hardware development and signal analysis.

e-mail: taccini@smartex.it
Smartex s.r.l.
via Giuntini 13 int. L
56023 Navacchio (PI), Italy

Angelo Gemignani graduated in medicine at the University of Pisa in 1991. He received the Ph.D. in basic neuroscience in 2000. He was a resident in psychiatry from 1991 to 1996 and since 2002, researcher at Department of Physiology and Biochemistry, Faculty of Medicine at University of Pisa, Italy. Since 1988 he has been involved in different scientific domains from sleep disorders to cognitive and emotional modulation of brain and autonomic activity. He spent three years (1995–1998) as a research fellow at the Laboratory of Neurobiophysics, "Unitè de Recherche en RMN Bioclinique – INSERM U438", Grenoble, where he worked on the post-processing of fMRI signal during actual movement and motor imagery. His main methodologies of research are neuropsychological tests, wake and sleep EEG, autonomic variables and fMRI. He has a good experience in the postprocessing of autonomic signal as well as of EEG and fMRI signal. His current research interests include cognitive neuroscience, experimental psychology and neurophysiology. Use of behavioural (EEG, EOG and EMG) and autonomic (ECG, respiration and skin resistance) parameters and functional magnetic resonance imaging (fMRI) in combination with cognitive modulation (i.e., hypnosis) to study brain functions and brain response to motor and cognitive/emotional activation in healthy subjects.

e-mail: gemignani@dfb.unipi.it
Università di Pisa
Dipartimento di Fisiologia e Biochimica
Via S.Zeno 31
56127, Pisa, Italy

Brunello Ghelarducci was born in 1942 and has obtained his medical degree at the University of Pisa in 1967. He specialized in neurology in 1970. In 1971 he begun his career in the Institute of Physiology in Pisa, directed by Prof. G. Moruzzi. Since 1986 he is full Professor of human physiology in the Medical Faculty of Pisa. His research activity has always been performed in the field of vestibulo-spinal sensorimotor integration and of cerebellar motor coordination. In 1973–1974 he has worked with Prof. Masao Ito in Tokyo University on cerebellar plasticity in the control of the vestibulo-oculomotor reflex. He has continued this line of research in Pisa studying the development and the characteristics of cerebellar control on the vestibulo-oculomotor reflex in the rabbit and in newborn humans. Since 1983, in collaboration with Prof. K. M. Spyer of the University College of London, he has begun a series of investigations on the role of the cerebellum in the control of autonomic reflex activity in the rabbit, in particular of the autonomic and behavioral responses to alerting stimuli. These investigations, funded by the Ministry of Scientific Research, by the National Research Council and by the European Training Programme have revealed the importance of the posterior cerebellar vermis in the control of the development of visceral responses to aversive stimulations in the newborn and in the coordination of complex autonomic and behavioral responses to the same stimuli in the adult. More recently he has been engaged in a research program aimed to study the autonomic and electroencephalographic responses evoked in humans by an aversive stimulation. In these studies a fear-like state has been induced by means of hypnosis. Professor Ghelarducci has published several papers in international journals and belongs to several scientific organizations such as IBRO, the Physiological Society of London, the European Neuroscience Association and the Japanese Physiological Society.

e-mail: ghelarducci@dfb.unipi.it
Università di Pisa
Dipartimento di Fisiologia e Biochimica
Via S.Zeno 31
56127, Pisa, Italy