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Data Mining Methods for Health Monitoring in Systems Based on Wearable Sensors

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***Abstract*—The ITEA2 project CareWare approach efficiently perform sensor data processing and data fusion in order to visualize the holistic view of user's health status personalized, intuitively and trustworthy way and give feedback for user about individualized intensity and time of exercising control. The ranks of Hankel matrix and second order coherence matrices for describing complexity of ECG and relationship between parameters of ECG also is informative method for evaluation of the physiological state.**

***Keywords*—wearable sensors, physiological state, complex systems.**

I. Introduction

With the increase of healthcare services in non-clinical environments using vital signs provided by wearable sensors the need to process and analyze the physiological measurements is growing significantly. This demand is dealing ITEA2 project CareWare – Electronic Wearable Sport and Health Solutions. The aim of this project is to develop and leverage novel unobtrusive cyber physical systems for monitoring and advancing personal health and wellbeing. Lithuanian partners (Lithuanian Sport University, Kaunas University of Technology, Audimas and Optitecha) are involved in Health promotion use case and will develop functional state monitoring system, based on use of new generation sensors integrated for best wearing comfort and best signal quality during the motion (dynamic mode). Integrated solution of different sensors, smart interfaces, modelling and data analysis techniques should warrant that the created system will be comfortable and effective for assessment individuality and dynamics of functional state during daily-life activities and for exercise dosage control.

The heart rate (HR) is widely used to control workloads, but HR do not reflect many important physiological processes to be monitoring in order ensure safety and effectiveness of physical activity. The CareWare system will be able to efficiently perform sensor data processing and data fusion in order to visualize the holistic view of user's health status personalized, intuitively and trustworthy way and give feedback for user about individualized intensity and time of exercising control. The complexity of a signal, in a particular case of electrocardiogram (ECG) signal may reflect the function state and healthiness.

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II. The Architecture of the Developing System

The architecture of the developing in project system of functional state and physical activity (PA) monitoring is illustrated in Figure 1. The system architecture consists of the ECG registering T-shirts, the smart phone real time platform and off-line data analysis software. The ECG and physical activity registering T-shirts with integrated textile smart ECG sensors, ECG registration device and accelerometers send data to smartphone by Bluetooth connection. The real time platform will be realized on smart mobile phone with data storage in cloud services. The system physiological evaluations decisions will be developed on the basis of monitoring software Kaunas-Load produced in SME Kardiosignalas in collaboration with Lithuanian University of Health Sciences.

This system will provides PA and ECG signal primary analysis and algorithm for individualized feedback of exercising intensity and duration, also, it will give instructions for user. The developed software will perform in real time data pre-processing (noise reduction, artifact suppression), recognition and measurement of ECG RR, JT, QRS and ST parameters. Off-line data analysis software and data base would be realized on server, and will allows detail analysis or ECG signal, data storage and correction of limits of feedback indices for specialists.

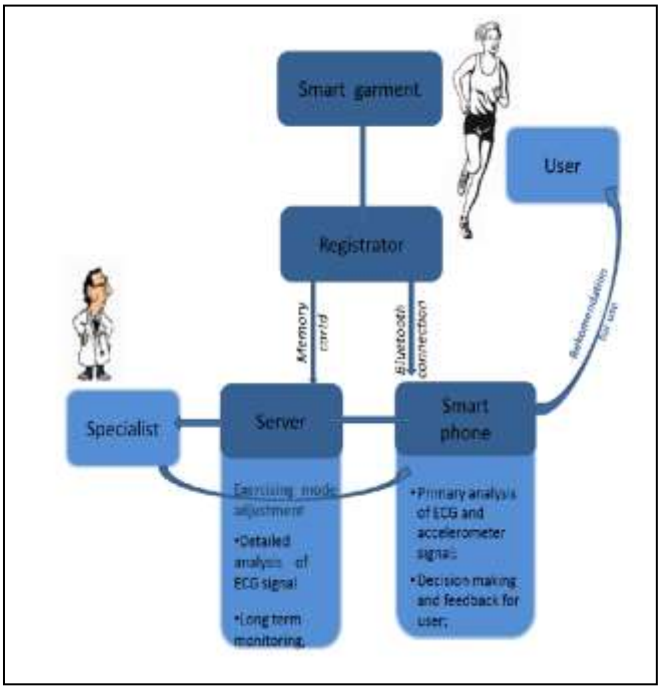

Figure 1. The system architecture

III. Methods for Monitoring of Functional State Using the Theory of Complex Systems

Developed new methods to measure connection between elements of complex system with possibility to analyze short data sets of recorded processes opposite to existing methods – when calculation of fractal dimensions require long intervals of data. The complexity of a signal, in a particular case of ECG signal may reflect the physiological function and status of healthiness of the heart. For the purpose to characterize the nonlinear complexity of signals the power spectrum, fractal dimensions, wavelet transformation, phase portrait, correlation dimension, the largest Lyapunov exponent, time-dependent divergence exponent, mass exponent spectrum and complexity measure can be used [1]. These methods verify the fact that ECG dynamics are dominated by an underlying multi-dimensional non-linear chaotic system, whose complexity measure is about 0.7 (in scale from 0 to 1).

A. Hankel Matrices

Usually in system identification problem Hankel matrices are formed when there is a sequence of output data and realization of an underlying state-space given or hidden Markov model is desired. But in this paper the ranks of the Hankel matrix will be used as features for the system identification purposes. The primary concepts for Hankel matrices analysis in finding exact, periodic and chaotic solutions of ordinary differential equations were presented in [2]. If the dynamical system *S* is described by time series which has ε − H rank, then the components K_r can be the functions $Q_r(x)e^{\lambda_r x}, r = 1,2,\ldots,m$, what means that complexity of a dynamical system *S* is outlined this way:

$$\mathrm{cmpl}\, S = \left(Q_1(x)e^{\lambda_1 x}, Q_2(x)e^{\lambda_2 x}, \ldots, Q_m(x)e^{\lambda_m x}\right). \qquad (1)$$

The accuracy of the expression depends on the chosen level of ε. Analysis of a time series using Hankel matrices is an alternative method for Fourier analysis which is widely developed. But in the proposed method the expression for dynamical systems are finite functions and in most cases it needs less parameters to describe the evaluation of dynamical systems than Fourier methods. For fast classification of dynamical systems by its complexity measure different methods can be used. Describing cardiac signals with Hankel matrices could be useful for diagnostic purposes because averaged ranks separate the healthy and sick persons' groups and also averaged complexity measure *m* shows functional level and it varies among persons investigated.

Physical activity has a positive impact on people's well-being, and it may also decrease the occurrence of chronic diseases. Functional state investigation using wearable smart sensors can provide feedback to the user about his/her lifestyle regarding physical activity and sports, and thus, promote a more active lifestyle, [7]. So far, activity or functional state recognition has mostly been studied in supervised laboratory settings. How well the daily activities and sports performed by the subjects in unsupervised settings can be recognized compared to supervised settings? The activities and functional state of person can be recognized using different techniques, for instance, a hybrid classifier combining a tree structure containing a priori knowledge and artificial neural networks, and also by using three reference classifiers. For this classification problem complexity measure also can be used and it is one of goals of project described.

B. Second Order Coherence Matrices

The internal links of dynamical system *S*. i.e. relations between two synchronous data sequences can be described by mathematical expression. Experience shows that for the description of instantaneous features of two data sequences the algebraic matrix analysis is convenient. The discriminant of matrix *A* or quadratic difference of eigenvalues is outlined by this formula:

$$\mathrm{dsk}\, A = \left|\lambda_1 - \lambda_2\right|^2 \qquad (2)$$

and it shows the informative degree of matrix [3]. The smaller value of dsk *A* implies simplicity of dynamical system described by matrix *A*. When two data sequences describing a dynamical system are calculated from initial data then it is possible to relate one matrix sequence $(A_1, A_2, A_3, \ldots)$ to these sequences when $A_n = \begin{pmatrix} y_n & y_{n+1} - z_{n+1} \\ y_{n-1} - z_{n-1} & z_n \end{pmatrix}$. Then the features of matrix sequence sufficiently reflect the interdependence of two data sequences. It shows the variation of discriminates sequence $(\mathrm{dsk}A_1, \mathrm{dsk}A_2, \ldots)$.

IV. Sensors and quality of ECG signals

This project also is focused on developing and finding novel smart textiles based on conducting polymer. The 3-D structure of this material means it is sensitive to pressures exerted from all three dimensions, making it attractive for use in wearable sensors for sport and medical applications. Future applications for this material may also lie in the area of wearable electronic components, whereby the material can be fabricated to produce resistors, capacitors, etc., [8].

Another property of smart sensor is physiological signal, received from this sensor, quality, especially during long time monitoring. In beginning of project CareWare different kind of sensors and its possibilities to transfer clear signal were investigated. The different materials and few specific shapes of ECG sensors were objects of investigation in laboratory conditions. Results of this research and examples of ECG signals are presented in Fig. 2. It must be noticed, that final material and for smart T-Shirt prototype is not selected yet, because sensors must be tested on real conditions in the end of project.

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Electrode and Time of clear signal	View	Electrode and Time of clear signal	View	Electrode and Time of clear signal	View
Sani silver with conductive Mg (point) 28%		Sani silver with conductive printing paste (plus) 55%		Sani silver with Silicon edging 24%	
Sani silver 20%		Argent Mesh with conductive Mg (point) 8%		Argent Mesh with conductive printing paste (plus) 30%	
Argent Mesh with Silicon edging 12 %		Argent Mesh 28%		TM shieldihg fabric with conductive printing paste (plus) 16%	
Strech conducti VE fabric with conductive Mg (point) 10%		Carbon felt 24%		Carbon silikon 8 %	

Figure 2. Sensors testing results

The examples of noisy and qualitative ECG, receveid from few different sensors are presented in Figure 3. There first signal a) is from carbon silicon sensor, second b) from Sani Silver with conducted Mg (point) and signal c) is after noise reduction (low and high frequencies filters).

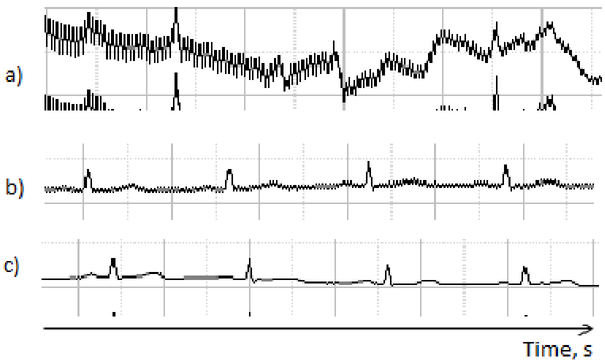

Figure 3. Examples of ECG signals

V. Results

Functional-state assessment of the cardiovascular system is used for diagnostic purposes, in both general and sports medicine, [4]. The functional state of the body can be derived from the dynamical changes in functional parameters during various testing maneuvers and exercise workloads, [5]. Separate indices show only a particular functionality issue; therefore, research was initiated on the correlation between integral indicators of the body's functional performance and health indices and physical working-capacity changes. Muscles with different functions are involved in physiological testing. The body-function compatibility, [6] and coherence between central and peripheral mechanisms of functional systems plays a significant role.

One of most popular functional state evaluation method is parameter estimation during increasing fatigue conditions exercise stress. Endurance and speed high level athletes and non-professional sportsmen's were asked perform modified veloergometry test, where load was increasing 50W every six minutes until participant was not able continue perform cycling, (Figure 4.) 12 leads of electrocardiogram (ECG) and arterial blood pressure (ABP) were monitored in order to estimate differences between different groups of investigating persons.

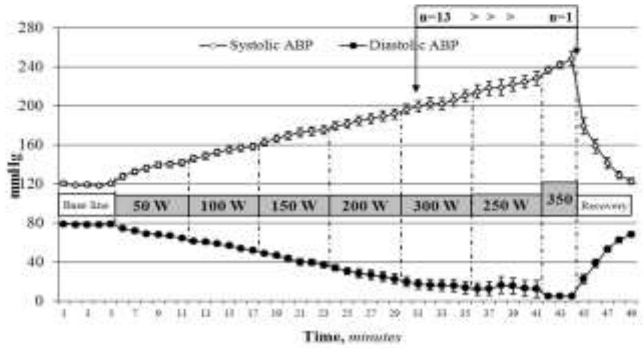

Figure 4. ABP changes during increasing fatigue stress test

Here n is number of persons participated in experiment (decreased to 1 in biggest load) and lines shows averaged systolic and diastolic ABP values.

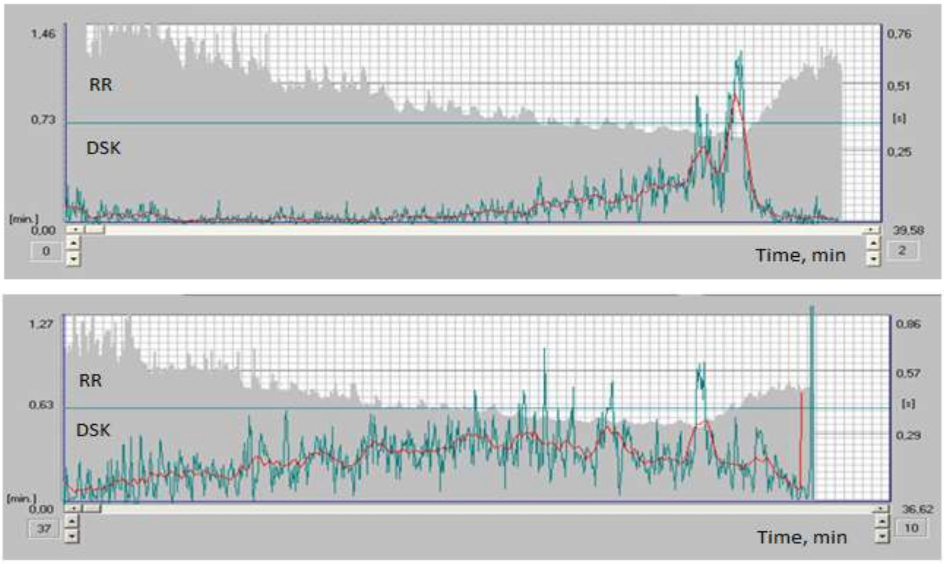

Figure 5. Dynamics of RR and RR-R aplitude concatination during increasing fatigue conditions exercise stress

In figure 5 a) shows results for elite endurance athlete, b) for non-professional sportsmen. Here gray polygon are RR values, blue – RR and R amplitude concatenation (discriminant by formula (2)), red - RR-R averaged discriminant values.

There is no significant differences observed in dynamics of heuristic indices of ECG, but dynamics of concatenation between discriminants is different according functional state of subject. Dynamics of RR-R amplitude concatenation of non-professional sportsmen is highly fluctuating (a lot of changes) during all exercise stress test (Figure 5. b)). Different dynamics of the same parameter *dsk* was observed on elite endurance athlete with high functional state - RR-R amplitude concatenation start fluctuate only just before refusing to continue the load (Figure 5. a)). High fluctuation of RR-R amplitude concatenation is quite common if internal physiological load is hard.

VI. Discussion and Conclusions

The clinically relevant information is often masked in the signal by noise and interference, and the signal features may not be readily comprehensible by visual or auditory systems of a human observer. Processing of biomedical signals is not only directed toward filtering for removal of noise and power-line interference, spectral analysis to understand the frequency characteristics of signals and modelling for feature representation and parametrization. Recent trends are oriented to quantitative or objective analysis of physiological systems and phenomena via the signal analysis [1].

The ranks of Hankel matrix and second order coherence matrices for describing complexity of ECG and relationship between parameters of ECG is informative method for evaluation of the physiological state for different persons. It must be noticed, that matrices A_n can be formed in different ways, and it depend on goal of investigations. The increasing amount of studies in this area and application of complex system theory in medicine raises hope to have more detailed and motivated interpretation of intra concatenation and complexity itself. This is one of the tasks in international project CareWare.

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