Complex Systems Approach in Monitoring Functional State during Exercising

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Introduction. With the increase of healthcare services in non-clinical environments using vital signs provided by wearable sensors the need to process and analyse 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. In this paper the information about Lithuanian partners (LSU, KTU, Audimas and Optitecha) project input – system of functional state and physical activity (PA) monitoring will be introduced.

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 PA. The CareWare system is 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.

The architecture of the developed system of functional state and PA monitoring is illustrated in Fig. 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 PA registering T-shirts with integrated textile ECG sensors, ECG registrator and accelerometers send data to smartphone by Bluetooth connection. The real time platform is realized on smart mobile phone and provides PA and ECG signal primary analysis and algorithm for individualized feedback of exercising intensity and duration; also it gives instructions for user. The developed software performs in real time data pre-processing (noise reduction, artefact 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 allow detail analysis or ECG signal, data storage and correction of limits of feedback indices for specialists.

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 analyse 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. The result of registered ECG of 10 adult males during incremental exercise test was analysed.

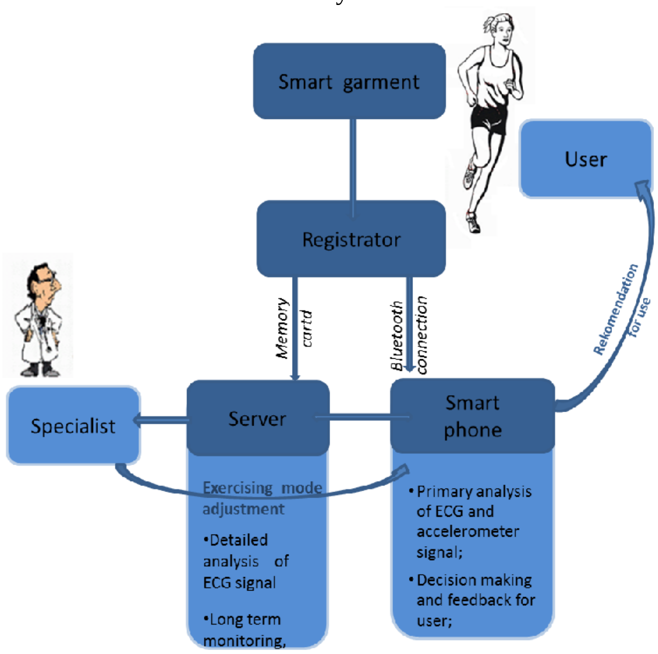

Fig. 1.The system architecture

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).

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 $\varepsilon - H$ 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:

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

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.

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:

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

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 $(\text{dsk } A_1, \text{dsk } A_2, \ldots)$. Example of matrix analysis presented in Fig. 2.

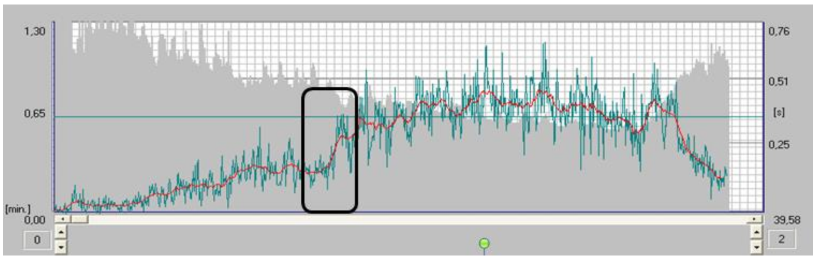

Fig. 2. Example of matrix analysis, i.e. discriminat dynamics between ECG parameters during incremental exercise test and recovery. In gray (background) is shown dynamics of RR intervals of ECG. The sudden change of discriminant values indicate the essential changes in body.

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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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 is informative method for evaluation of the physiological state and more detailed interpretation of intra concatenation and complexity itself.