The Analysis of ECG Complexity during a Bicycle Ergometry Test

Agne Slapsinskaite[1], Alfonsas Vainoras[2],[1-2]*Lithuanian University of Health Science*,
Liepa Bikulciene[3],[3]*Kaunas University of Technology*

Abstract **–The paper presents the application of special algebraic algorithm. The objective of research isto evaluate the fluctuations of ECG functional parameters of young physically active men at two different ergometry tasks – constant power cycling and incremental power cycling. We have evaluated the fluctuations of functional parameters and the experimental data has shown that the changes in physiological conditions canbe very rapid, asynchronous atdifferent levels of the organism.**

Keywords **– Algebraic algorithm, constant power, ECG functional parameters, incremental power.**

I. Introduction

Physiological output signals such as heart rate, blood pressure and others have fluctuating dynamics. We can observe the human body as a complex system, in which the organism adapts to an ever-changing environment. With the help of integrated responses from three primary holistic systems, execution **P** (skeletal and muscle system), supply **S** (cardiovascular system) and regulatory **R** (neurohumoral system), the organism is able to react to different stimuli respectively [3] (Fig. 1). This integral model [17] allows one to evaluate the body integrity and reflects the main functional interactions while considering the body general functional state and its adaptability.

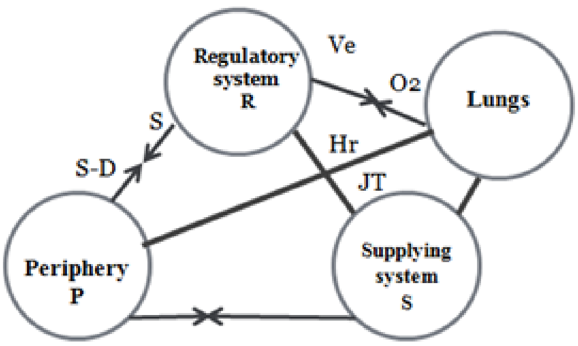

Fig. 1. The integral holistic system model.

The cardiovascular system, one of the holistic systems in the human body, reveals peculiarities in physiological functions when subjected to constant or gradually increasing load tests [18]. At the onset of exercise, the cardiovascular system adapts to variations of loads with a series of integrated responses to meet the metabolic demands of the exercising muscles. Interconnections and fluctuations in cardiovascular system output can provide valuable information not only to evaluate adaptation processes, but also to improve the understanding of recovery processes. Certainly, the period of recovery is influenced by the intensity of exercise. For instance, there is difference between recovery after moderate to high intensity exercise and low to moderate intensity exercise. Thus, recovery processes and the best recovery method search still attract interest. That is the reason why a number of recovery methods have been systemically investigated in recent studies [2]. Until now little information is available concerning the interconnections between holistic systems during such endurance and incremental exercises. A better understanding of recovery processes can be achieved by observing, analysing interconnections after exhausting tasks.

For better understanding of working capacity or exertion dynamics during the tasks different scales were invented. Rating of perceived exertion (*RPE*) measures one's individual (subjective) judgment of the personal working capacity. The Borg 6–20 *RPE* Scale [4] is designed to estimate sensations of exertion in relation to physiological markers that rise commensurately with increments in exercise intensity. It is widely cited that the duration of the task can be determined not only objectively (e.g., heart rate) but also subjectively (e.g., Borg's Scale) or even by coupling the actual and perceived exertion of the subjects during the exercise test while comparing the ratio of heart rate and rating of perceived exertion. Our society has learned to trust objective data; however, in the case of exertion, controversial works can be found, e.g. *RPE* predicts the maximal work capacity with less error compared to heart rate [5]. The lack of consensus on the use of only objective, subjective or objective and subjective method still exists. Research is still conducted in studies regarding organism fatigue, and recovery processes (after physical loads) due to the peculiarity seen in the responses.

Constant power volitional exhaustion exercise testing makes subjects continue working until they become metabolically exhausted. Incremental power shows provoked reactions at different load. While having a volitionally exhausted subject or reactions towards provocative load, it is interesting to observe recovery of different ECG functional parameters that reflect processes at different levels of organism, metabolism and heart regulation. The objective of this research was to evaluate the fluctuations of ECG functional parameters of young physically active men at two different ergometry tasks – constant power cycling and incremental power cycling. For this task an algebraic algorithm was applied based on the concept of the rank of a sequence [6], [9]. The concept of the rank of a sequence has been successfully used to express solutions of nonlinear differential equations in forms comprising ratios of finite sums of standard functions [10],[11],[15], for time series forecasting [13], logistic-matrix representation [12] and research of chaos [14],[16].

II. Material and Methods

Participants

Study groups were divided according to the physical feature into*Group1* (endurance cohort) that performed constant power cycling task and *Group2* (sprint cohort) that performed incremental power cycling.

Group1 included 9 healthy *Spanish* males (average age – 23±3). All experimental procedures were approved by the local research ethics committee and carried out according to the ethical guidelines laid down in the Declaration of Helsinki.

Group2 involved10 healthy participants (20.1±2.23). Only males with experience in sprint (practicing more than 2 years) were chosen, as the cardiovascular system reactions to physical load differ with gender. This was done in order to obtain a relatively homogenous group for getting more comparable data. When arriving at the laboratory, participants were asked to dress in shorts and wear trainers.

All of the participants were familiarized with Borg‘s *RPE*6-20 scale and testing procedure prior the test.

Cycling Task and RPE Procedure

Group1 performed constant power cycling task (Sport Excalibur 925900), which was started with individually hard corresponding *RPE* = 15 (Borg‘s *RPE* 6-20 scale) constant power. Test was divided into 4 parts: 1) rest – 1 minute interval before the test; 2) constant power cycling (70 rpm) at an individual intensity until reaching value of 15 in *RPE*; 3) cycling and reporting the *RPE* (every 15 sec.) until reaching the volitional exhaustion; 4) 5 minutes of recovery after the volitional exhaustion.From the onset of exercise the participants had to self-monitor received exertion and report it for the first time when they felt that exertion reached *RPE* = 15. After the first report, participants continued reporting the score of perceived exertion every 15 seconds. To ensure accurate perception of *RPE* and maximal focus on the task, the participants were asked to “report” every 15 seconds. The chosen intensity had to be kept until volitional exhaustion was reached without loss of determined pacing. When pacing was lost for longer than 30 seconds, the end of the task was recorded. The total time differed from participant to participant.

Group2 underwent the test protocol, which consisted of three main parts – rest, load and recovery. In this study, the rest part took 1 minute while participants were just sitting on the bike without pedalling. After the rest it proceeded to physical work that included computer-based bicycle ergometry test based on a provocative incremental increase in the load. Bicycle ergometry test began with 50 W and in every minute the load was increased by 50 W. The test was continued till 250 W that made 5 minutes of pedalling at 60 cycles per minute. Although the maximum load was not reached, the test should end earlier if the distressing cardiovascular symptoms appeared. Finally, the last part of the protocol was recovery that took five minutes. The total time of the protocol was eleven minutes.

ECG Monitoring

A computerized ECG analysis system “Kaunas-load” developed by the Institute of Cardiology of Kaunas Medical University was applied for 12-lead ECG recording and analysis.“Kaunas-load” helps to reveal and evaluate the synergistic aspects of essential systems of the human body and extends the possibilities of functional diagnostics [1],[8],[19]. The arterial blood pressure was measured utilizing Korotkov’s method in the area of upper left arm and the following functional parameters were gathered: heart rate, *RR* interval, *JT* interval, *QRS* interval (at rest), cycle ergometer test and recovery (after volitionalexhaustion). Different duration ECG parameters were used for the investigation of dynamic physiological processes in the heart during tests.

Algebraic Analysis Algorithm

In this section, we present the concept of the rank of a sequence and its application for the ECG parameter analysis.

Let us consider a sequence: $y_0, y_1, ... := (y_j;\, j \in Z_0)$ where elements y_j can be real or complex numbers. Then, a sequence of Hankel matrices reads:

$$H_n := (y_{i+j-2})_{1 \le i,j \le n} = \begin{bmatrix} y_0 & y_1 & \cdots & y_{n-1} \\ y_1 & y_2 & \cdots & y_n \\ & & \cdots & \\ y_{n-1} & y_n & \cdots & y_{2n-2} \end{bmatrix}, \quad n = 1,2,... \quad (1)$$

The sequence of determinants of Hankel matrices $(d_n; n \in N)$ reads:

$$d_n := \det H_n \quad (2)$$

Definition 1. The sequence $(y_j; j \in Z_0)$ has a rank $m \in Z_0; m < +\infty$:

$$Hr(y_j;\, j \in Z_0) = m \quad (3)$$

if the sequence of determinants of Hankel matrices has the following structure:

$$(d_1, d_2, ..., d_m, 0, 0, ...) \quad (4)$$

where $d_m \neq 0$ and $d_{m+1} = d_{m+2} = ... = 0$.

Definition 2. Let $Hr\left(y_j;\, j \in Z_0\right) = m$. Then the characteristic Hankel determinant for the sequence $(y_j; j \in Z_0)$ is defined as [9]

$$\hat{d}_m := \det \hat{H}_m := \begin{vmatrix} y_0 & y_1 & \cdots & y_m \\ y_1 & y_2 & \cdots & y_{m+1} \\ \cdots & \cdots & \cdots & \cdots \\ y_{m-1} & y_m & \cdots & y_{2m-1} \\ 1 & q & \cdots & q^m \end{vmatrix} = 0. \quad (5)$$

The expansion of the determinant in (5) yields an *m*-th order algebraic equation for the determination of roots of the characteristic equation:

$$A_m\rho^m + A_{m-1}\rho^{m-1} + ... + A_1\rho + A_0 = 0 \quad (6)$$

where $A_m \neq 0$ because $A_m = d_m \neq 0$.

We have assumed that $\mu_{rg}\binom{j}{g}q_r^{j-g} = 0$ if $\binom{j}{g} = 0$ that is true when $0 \le j < g$. Moreover, $0^0 = 1$; $0^1 = 0^2 = ... = 0$. Then the following theorem holds.

Theorem 1. Let $Hr(y_j; j \in Z_0) = m$ and the recurrence indices of roots $q_1, q_2, q_3, ..., q_c$ of the characteristic equation (6) are $m_1, m_2, ..., m_c$ $(c = 1,2,3,...)$ respectively; $\sum_{r=1}^{c} m_r = m$. Then the following equality holds true:

$$y_j = \sum_{r=1}^{c}\sum_{g=0}^{m_r-1}\mu_{rg}\binom{j}{g}q_r^{j-g} \quad (7)$$

where $\mu_{rg}, q_r \in C$; $\mu_{rm_r-1} \neq 0$.

Rigorous proof of this theorem is given in [9].

Corollary 1. In case when all roots of the characteristic equation are different, Eq. (7) obtains a more simple form:

$$y_j = \sum_{r=1}^{m}\mu_r q_r^j \quad (8)$$

Coefficients μ_{rg} (or just μ_r) can be found solving the linear algebraic system of equations ($\rho_1, \rho_2, ..., \rho_c$ are determined beforehand):

$$\sum_{r=1}^{c}\sum_{g=0}^{m_r-1}\binom{j}{g}q_r^{j-g}\mu_{rg} = y_j \text{ , } j = 0,1,..., m-1 \quad (9)$$

This linear system of algebraic equations has one and the only one solution [9].

Corollary 2. Let $Hr(y_j; j \in Z_0) = m$ and the first *2m* elements of that series are known. Then it is possible to use (6), (9) and (7) to calculate all elements of that sequence.

Definition 3. A sequence $(y_j; j \in Z_0)$ is an *algebraic progression* if elements of that sequence can be expressed in the form of (7).

III. ALGEBRAIC ALGORITHM FOR THE ECG PARAMETER ANALYSIS

If $Y = (y_0, y_1, ..., y_{N-1})$ that is the time series of ECG parameter of length *N* consisted of several segments of algebraic progressions (Eq. (7)),then *Y* could be segmented into *k* non-overlapping contiguous segments by using the segmentation method for algebraic progressions [7]. This method was proposed for sequences without noise. Unfortunately, time series of ECG parameters are noisy; thus, this method cannot be applied directly. The main problem is that the rank of a noisy sequence does not exist.

Let us consider that time series of ECG parameters *Y* is segmented manually into *k* non-overlapping contiguous segments (Fig. 2):

$$S := \bigcup_{l} S_l \text{ , } l = \overline{1,k}$$

where $S_l = S_l(u_l, v_l) = (y_{u_l}, y_{u_l+1}, ..., y_{v_l})$, $u_l \le v_l$, u_l is the start and v_l - the end position of segment $S_l, l = \overline{1,k}$.

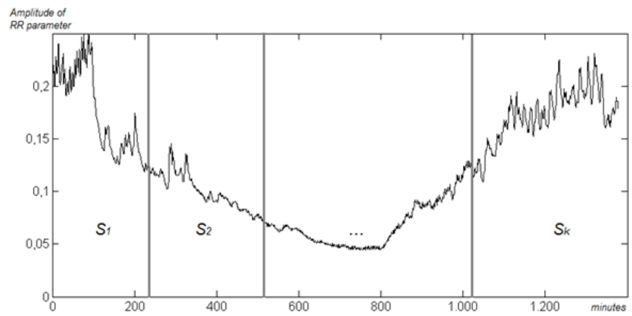

Fig. 2. ECG parameter segmentation into *k* segments.

The main task of the algorithm is to find an algebraic progression $\hat{y}_j^{(l)}, j = \overline{0, n_l}$, $n_l = v_l - u_l + 1$ of segment $S_l, l = \overline{1,k}$ with the condition:

$$\sqrt{\frac{1}{n_l}\sum_{j=0}^{n_l}\left(\hat{y}_j^{(l)} - y_j^{(l)}\right)^2} \le \varepsilon_1 \quad (10)$$

The detailed algorithm for algebraic progression $\left(\hat{y}_j^{(l)}, j = \overline{0, n_l}\right)$ construction is given in [6].

Let $\hat{y}_j^{(l)} = \sum_{r=1}^{c}\sum_{g=0}^{m_r-1}\mu_{rg}\binom{j}{g}q_r^{j-g}$, $j = \overline{0, n_l}$, $\mu_{rg}, q_r \in C$, $\mu_{rm_r-1} \neq 0$ bean algebraic progression of the segment $S_l, l = \overline{1,k}$. It has been noted in [6] that the algebraic progression consists of components:

$$\hat{y}_j^{(l)} = \omega_{j,-1}^{(l)} + \omega_{j,0}^{(l)} + \omega_{j,1}^{(l)},\ j \in Z_0 \quad (11)$$

Everycomponent represents (accordingly to parameter $\varepsilon_2 \ge 0$) the different nature of fluctuation: (b) inhibitory, (c) stationary and (d) stimulant:

$$\omega_{j,-1}^{(l)} = \sum_{t:|q_t| < 1\pm\varepsilon_2}\mu_t q_t^j,\ j \in Z_0, \text{(b)}$$

$$\omega_{j,0}^{(l)} = \sum_{t:|q_t| = 1\pm\varepsilon_2}\mu_t q_t^j,\ j \in Z_0, \text{(c)}$$

$$\omega_{j,1}^{(l)} = \sum_{t:|q_t| > 1\pm\varepsilon_2}\mu_t q_t^j,\ j \in Z_0 \text{(d)}$$

Imaginary and real parts of parameters are placed on the unit circle (Fig. 3, (a)). It can be noted that values of parameter inside the unit circle (Fig. 3 (b)) represent the inhibitory, on the unit circle – stationary (Fig. 3 (c)) and outside the unit circle – stimulant (Fig. 3 (d)) processes [6].

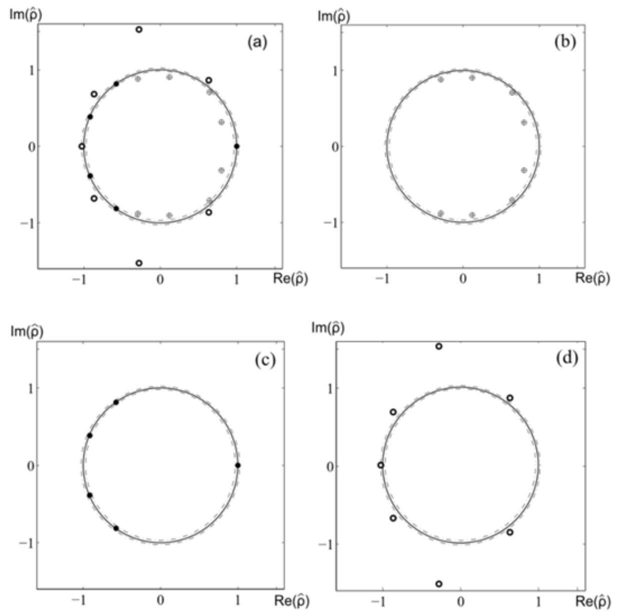

Fig. 3. Parameter values q_t of algebraic progression: (a) all; representing different nature of fluctuation: (b) inhibitory, (c) stationary, (d) stimulant

IV. RESULTS

In *Group1* participants' constant cycling power was *M* = 175 ± 30 W and time till volitional exhaustion was *M* = 23 ± 2.25min. During rest, load and recovery a time series of ECG parameters was evaluated: *RR* interval (the interval between two beats of the heart), *JT* interval (*JT* interval is associated with intensity of metabolic processes in heart), *QRS* complex (describes the inner heart regulation system). It is necessary to remind that the examined ECG parameters reveal different complexity levels, e.g., *RR* interval helps to characterize the state of the organism atits regulatory level, *JT* interval represents the metabolic reactions of the systems and the *QRS* parameter reflects the intrinsic regulatory state of the organ.

The length of the time series of each ECG parameter was individual. Time series were segmented into 9 segments: 1 - the *rest* minute, 2 - 4 minutes represent the *load* (2 is the moment in time when the subjects first reported *RPE* = 15), 3 – the minute between *PRE* = 15 and the end of the task, 4 - the last minute before the end of the load), 5 - 9 represents five minutes of recovery (Fig. 3-5 *x*-axes). Then algebraic progressions were constructed (with parameter $\varepsilon_1 = 0.01$) for each segment and accordingly to parameter $\varepsilon_2 = 0.01$ distinguished their components with different nature of fluctuation. The same procedure was repeatedly done for all times series of ECG parameters of all participants. Then for the every ECG parameter segment the total count of components and count of components with different nature of fluctuationwere calculated. Dividing counts of components of each process of each segment by the total number of components of the current segment, the normalized values of different processes (inhibitory (value – α), stationary (value - β) and stimulant (value – γ) (Fig. 4-6 *y*-axes) were calculated. The procedure to find normalized values of inhibitory, stationary, and stimulant processes was separately performed for *RR* interval (Fig.4), *JT* interval, (Fig. 5) and *QRS* interval (Fig. 6).

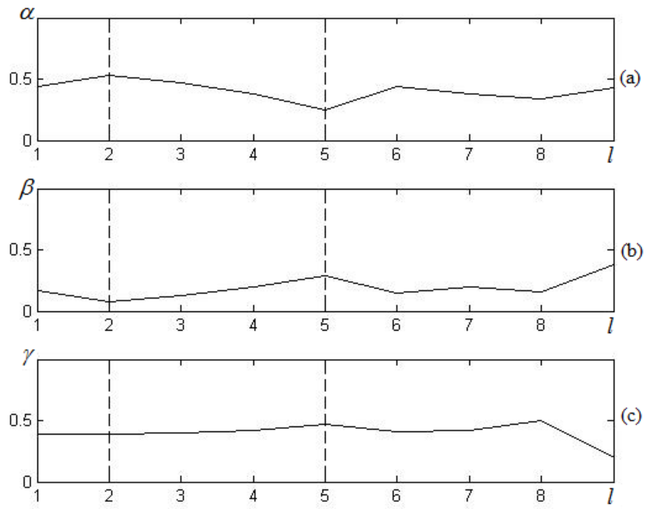

Fig. 4. Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *RR* interval dynamics during volitional exhaustion ergometry test. 1 is the *rest* minute, 2 is the moment in length of one minute when the subject reported *RPE* = 15 for the first time, 3 – middle minute between *PRE* = 15 and the end of the task, 4 – the last minute before the end of the load, 5 - 9 represents five minutes of recovery.

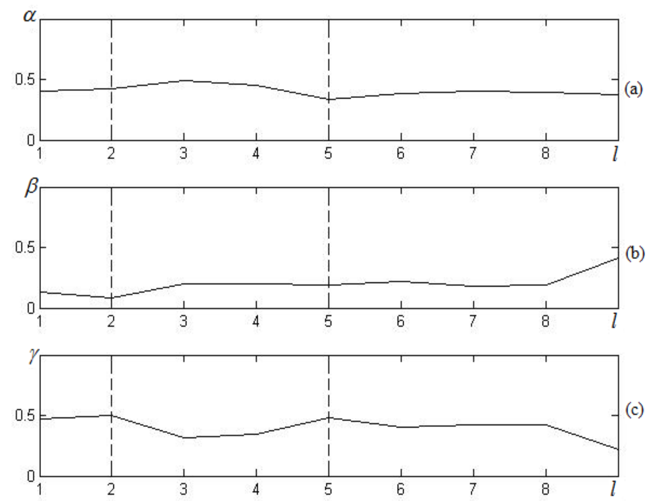

Fig. 5.Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *JT* interval dynamics during volitional exhaustion ergometry test. 1 is the *rest* minute, 2 is the moment in length of one minute when the subject reported *RPE* = 15 for the first time, 3 – middle minute between *PRE* = 15 and the end of the task, 4 – the last minute before the end of the load, 5 - 9 represents five minutes of recovery.

During the evaluation of fluctuations, greater attention was focused on the last 5 minutes of recovery in the dynamics of inhibitory, stationary and stimulatory process for *RR*, *JT* and *QRS* intervals. The dynamics of stationary and stimulatory processes showed moderately similar dynamics in recovery. At the end of recovery stage, there was a visible increase in stationary and decrease in stimulatory processes in *RR*, *JT* and *QRS* intervals. The inhibitory processes showed differing dynamics in RR, JT, and QRS intervals. While the *JT* interval remained relatively stable, *QRS* and *RR* intervals displayed unique characteristics. In the *QRS* interval, the inhibitory processes started to decrease in the 3rd recovery minute. These actions were antagonistic to what was seen in the *RR* interval where the inhibitory processes increased. This illustrates that recovery processes are not synchronous at different levels of the organism.

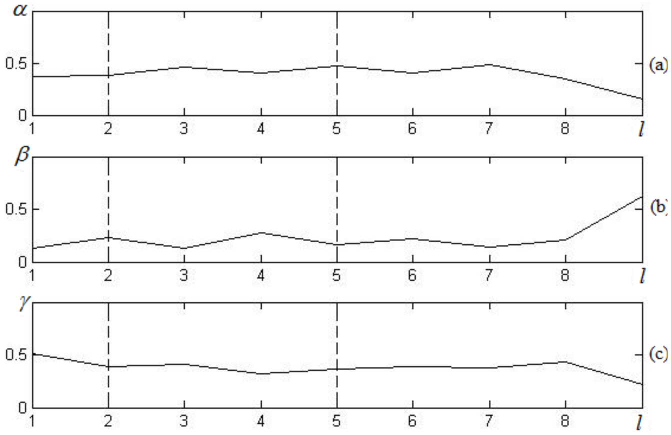

Fig. 6. Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *QRS* interval dynamics during volitional exhaustion ergometry test. 1 is the *rest* minute, 2 is the moment in length of one minute when the subject reported *RPE* = 15 for the first time, 3 – middle minute between *PRE* = 15 and the end of the task, 4 – the last minute before the end of the load, 5 - 9 represents five minutes of recovery.

In *Group2* the test was performed in eleven minuteswhere 1-2 minutes represented rest interval, 2-7 were the load minutes and 7-11 were the interval of recovery of the test (Fig. 7-9 x-axes). In every minute of the test the normalized values of those different processes (inhibitory (value - α), stationary (value - β) and stimulant (value - γ)) were calculated (y-axes) dividing counts of components of each process of each segment by the total number of components of the current segment. The procedure to find normalized values of inhibitory, stationary and stimulant process was separately performed for *RR* interval (Fig. 7), *JT* interval (Fig. 8) and *QRS* interval (Fig. 9).

In the last minute of load *RR* interval showed the overturned situation of influencing process – stimulant processes rapidly increased (Fig. 7(c) from 6-th to 7-th minute) while inhibitory process reacted (Fig. 7(a) from 6-th to 7-th minute) to opposite direction.

An interesting finding was related to complexity of ECG intervals RR, *JT* and *QRS* was the delay in recovery processes. For *JT* and *QRS* intervals there was a clearly expressed delay of stimulant processes in recovery interval (Fig. 8(c), Fig. 9(c) 7-th to 8-th minute). It can illustrate that recovery processes are not synchronous in different organism systems.

Stationary processes (Fig. 7(b), Fig. 8(b), Fig. 9(b)) varied insignificantly during the load and the first four minutes of recovery. They suddenly went up and reached their highest values at the last minute of recovery becoming the predominant processes influencing the *RR*, *JT* and *QRS* interval dynamics. This fact may confirm that the recovery processes are over.

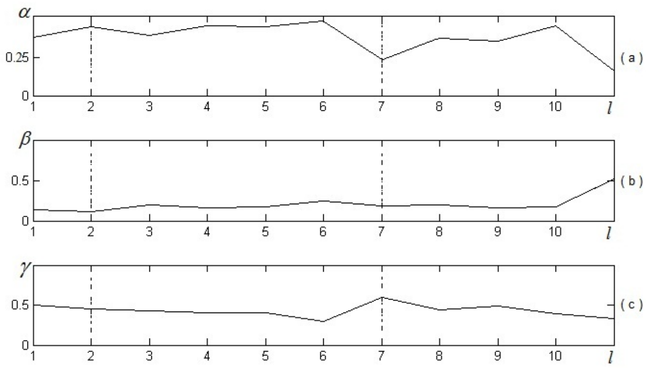

Fig. 7. Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *RR* interval dynamics during bicycle ergometry test.The test was performed in eleven minutes, where 1 minute represented a rest interval, 2-7 represented the load minutes and 7-11 represented the interval of recovery of the test (x-axes).

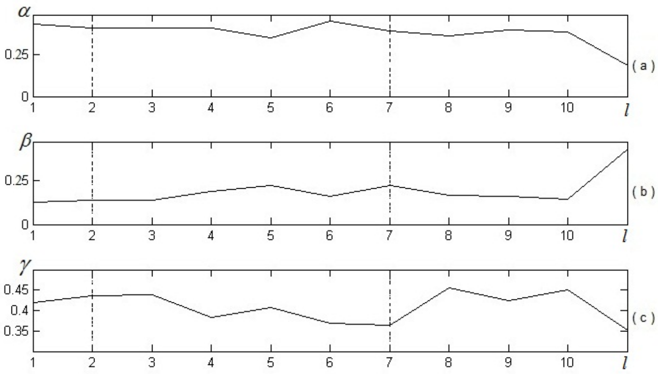

Fig. 8. Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *JT* interval dynamics during bicycle ergometry test.The test was performed in eleven minuteswhere 1 minute represented a rest interval, 2-7 represented the load minutes and 7-11 represented the interval of recovery of the test (x-axes).

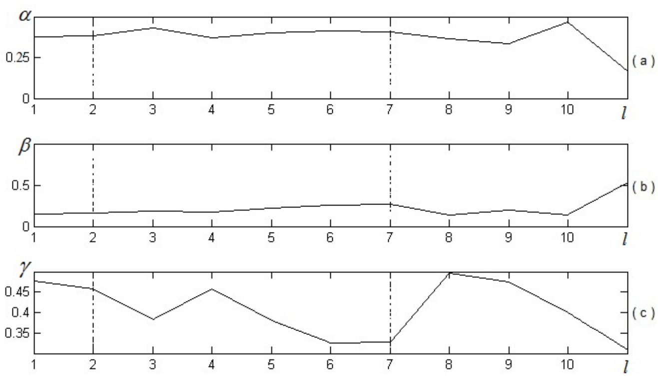

Fig. 9. Inhibitory (a), stationary (b) and stimulant (c) processes and their fluctuations in *QRS* interval dynamics during bicycle ergometry test.The test was performed in eleven minuteswhere 1 minute represented a rest interval, 2-7 represented the load minutes and 7-11 represented the interval of recovery of the test (x-axes).

V. Discussion

Even though the test duration in (Group1) was different and individual for all participants, the endpoint was achieved and subjects were volitionally exhausted at the last minute of pedalling. Special mathematical methods can be useful for extracting dynamics of physiological data during the recovery period (after physical load constant or incremental) using a combination of both objective and subjective methods. Inhibitory and stationary processes are at the same level, while in less exhausting tasks (incremental test) only the stationary processes predominate. A significant decrease in inhibitory processes was found during the first five recovery minutes. Results indicated that the changes in physiological conditions could be very rapid. Algebraic analysis reveals intervals with stable and/or unstable physiological features in different ECG functional parameters.

VI. Conclusions

In the analysis of medical or biological investigations it is important to separate data sequences into intervals where similar physiologic situations can be observed. In theliving organisms, changes of physiologic conditions can be very quick and application of statistical technologies or Fuorie analysis is not possible. The proposed algebraic analysis can be the technology, which can help in the analysis of short intervals of data, which allow revealing intervals with stable or unstable physiological features. The out-of-phase reactions were exhibitedin the results of ECG functional parameters. The peculiarities of physiologic processes at different fractal levels of organism in the human body after different tasks were caught with the proposed algebraic algorithm. We confirmed that the proposed algebraic algorithm could be effectively exploited for the analysis of ECG parameters during different tasks, although noisy time series were analysed.

References

[1] S. Bardauskiene, A. Daunoraviciene, A. Vainoras, E. Venskaityte, I. Muntianaite Dulkiniene, “Influence of short-term fasting on the changes in women’s cardiovascular functional parameters“, *Education, Physical Training, Sport*, no. 2 (81), 2011; p.p. 11-16, 2011.

[2] K. Berskiene, „Elektrokardiografiniu signalu parametru dinaminiu sasaju analize“: daktaro disertacija, 2010.

[3] A. Barnett, „Using recovery modalities between training sessions in elite athletes: does it help?“, *Sports Med* no. 36, p.p. 781-796, 2006.

[4] G. Borg, „Borg’s Perceived Exertion and Pain Scales Human Kinetics“ Champaign, IL (1998).

[5] J. Faulkner, R. Eston, “Overall and peripheral ratings of perceived exertion during a graded exercise test to volitional exhaustion in individuals of high and low fitness”, *European Journal of Applied Physiology*, no. 101, p.p. 613-620, 2007.

[6] D. Karaliene, Z. Navickas, A. Slapsinskaite, A. Vainoras, “Investigation of the stability of fluctuations in electrocardiography data”. *Journal of vibroengineering*, no. 15, p.p. 291-301, 2013.

[7] D. Karaliene, Z. Navickas, A. Vainoras, “Segmentation algorithm for algebraic progressions”. *Communications in Computer and Information Science*, *New York*: *Springer*, no. 319, p.p. 149-161, 2012.

[8] A. Leonaite, A. Vainoras, „Heart rate variability during two relaxation techniques in post-MI men“, *Electronics and electrical engineering*, no. 5(101), p.p. 107-110, 2010.

[9] Z. Navickas, L. Bikulciene, „Expressions of solutions of ordinary differential equations by standard functions“, *Mathematical Modeling and Analysis*, no. 11, p.p. 399-412, 2006.

[10] Z. Navickas, L. Bikulciene, M. Ragulskis, „Generalization of Exp-function and other standard function based methods“, *Applied Mathematics andComputations*, no. 216 (8), p.p. 2380-2393, 2010.

[11] Z. Navickas, M. Ragulskis, L. Bikulciene, „Special solutions of Huxley differential equation“, *Mathematical Modelling and Analysis*, no. 16(2), p.p. 248-259, 2011.

[12] Z. Navickas, R. Smidtaite, A. Vainoras, M. Ragulskis, „The explosive divergence in iterative maps of matrices“, *Communications in Nonlinear Science and Numerical Simulation*. *Elsevier*, no. 17(11), p.p. 4430 – 4438, 2012.

[13] M. Ragulskis, K. Lukoseviciute, Z. Navickas, R. Palivonaite, „Short-term time series forecasting based on the identification of skeleton algebraic sequences“, *Neurocomputing. Elsevier*, no. 64(10), p.p. 1735-1747, 2011.

[14] M. Ragulskis, Z. Navickas, „The rank of a sequence as an indicator of chaos in discrete nonlinear dynamical systems“, *Communications in Nonlinear Science and Numerical Simulation. Elsevier*, no.16, p.p. 2894-2906, 2011.

[15] M. Ragulskis, Z. Navickas, L. Bikulciene, “The solitary solution of the Liouville equation produced by the Exp-function method holds not for all initial conditions“, *Computers and Mathematics with Applications*, no. 62, p.p. 367-382, 2011.

[16] M. Ragulskis, Z. Navickas, R. Palivonaite, M. Landauskas, “Algebraic approach for the exploration of the onset of chaos in discrete nonlinear dynamical systems“, *Communications in Nonlinear Science and Numerical Simulation. Elsevier*, no. 17(11), p.p. 4304 – 4315, 2012.

[17] A. Vainoras, „Investigation of the heart repolariztion process during rest and bicycle ergometry (100 – lead and standard 12 – lead ECG data)“. *Synopsis of a D.Sc. habil. thesis*, Kaunas, 1996.

[18] A. Vainoras, „Functional model of human organism reaction to load – evaluation of sportsman training effect“, *Education, Physical Training, Sport*, no. 3 p.p. 88–93, 2002.

[19] R. Zumbakyte-Sermuksniene, A. Kajeniene, A. Vainoras, K. Berskiene, V. Augutiene, „Assessment of functional conditions of basketball and football players during the load by applying the model of integrated evaluation“, *Medicina (Kaunas)* 2010; no. 46 (6), p.p. 421-428, 2010.

Agne Slapsinskaite. In 2012 she received a bachelor diploma in rehabilitation (physical therapy specialty) at the Lithuanian University of Health and Science. In 2011 she was an Erasmus exchange student at the Norway University College. In 2012 she underwent scientific Erasmus practice at the National Institute of Physics of Catalonia (INEF), Barcelona (Spain). In 2012 she began her master studies in health rehabilitation through physical exercise. Complexity school courses in Macedonia and Spain.
She is a Member of the European Confederation of Physical Therapy Students (ECPTS); a Member of the Lithuanian Physical Therapy Association.
E-mail:agneslapsinskaite@gmail.com

Alfonsas Vainoras (Prof., dr.habilit.) in 1970 graduated from Kaunas Medical Institute, faculty of medicine, department of biophysics in Lithuania. In 1980 defended doctor thesis of "Automatization of diagnostics of heart rhythm and conduction disturbances". In 1996 defended dr. habilitatus thesis" Investigation of heart repolarization processes at rest and during physical load (using 100 point mapping and convenient ECG data)". From 1970 scientific co-worker, from - 1977 senior scientific co-worker in Automatised interpretation of electrophysiological processes laboratory, Institute of Cardiology, Kaunas Medical University. From 1992, from 2003 main scientific co-worker in lab. "Automatization of cardiovascular investigations", Institute of Cardiology, Institute of Cardiology, Kaunas Medical University. From 2011 - Head of department, "Kinesiology and sport medicine" Kaunas Medical University, professor of Sport Institute, Lithuanian University of Health Science, Medical Academy, main scientific co-worker in I-te of Human Health investigations, LUHS, Medical Academy. Professional interests: Diagnostic of heart diseases based on ECG analysis, it's formalization and alghoritmization; development of functional test evaluation, edification; investigation of human organism reactions to different influences, formalization of reactions, development of systems for integral evaluations; development of new type multiprocess monitoring systems – process recording and analysis, based on human organism complexity, investigation of interactions of different fractal levels in human organism; development of new technologies for e.Health systems in Lithuania and Europe. Country coordinator or participator in 9 international projects. With coauthors were published more than 360 papers.
E-mail: alfavain@gmail.com

Liepa Bikulčienė (Dr.) in 2000 graduated from Kaunas University of Technology (Applied mathematics) in Lithuania. In 2007 took a degree of doctor in field of Physical Sciences (Informatics, 01P). From 2006 to 2009 was a lecturer, since 2009 until now is associated professor at Kaunas University of Technology. Additionally from 2010 is a researcher in laboratory for Automation of Cardiovascular Investigation in Institute of Cardiology at Lithuanian University of Health Sciences. Professional interests: mathematical modeling, differential equations, complex systems, signal analysis. With coauthors were published more than 70 papers.
E-mail: liepa.bikulciene@ktu.lt

Agne Slapsinskaite, Alfonss Vainoras, Liepa Bikulciene. EKG sarežģītības analīze veloergometrijas testa laikā
Rakstā izklāstīts īpaša algebriska algoritma pielietojums EKG (elektrokardiogrāfijas) līkņu analīzei. Algoritms balstās uz laikā mainīgu procesu rangu analīzi. Algoritms izmantots, lai analizētu fizioloģiskos procesus diviem pielietojumiem (diviem protokoliem). Pirmais protokols (izturības) domāts veloergometrijas testam ar pastāvīgu slodzi. Otrais protokols (sprinta) domāts veloergometrijas testam ar augstu slodzi.
Datoranalīzei pakļautas EKG visas 12 novadījumu līknes veloergometrijas testa laikā jauniem veseliem vīriešiem. Eksperimenta mērķis – novērtēt EKG funkcionālo parametru svārstības katram sportistam individuāli. Par EKG parametriem izvēlēti: RR intervāls, JT intervāls, QRS intervāls. Pēc pirmā protokola slodze ir 175 ± 30 W, testa laiks 23 ± 2,25 min. Pēc otrā protokola testa laiks ir 11 min.
Testa slodzes, atpūtas un atjaunošanās laika intervālos notiek EKG minēto intervālu lielumu fiksācija un analīze. RR intervāls raksturo organisma stāvokli regulatīvā līmenī. JT intervāls raksturo metabolisko reakciju. QRS intervāls raksturo iekšējo regulācijas stāvokli.
Eksperimenta analīze rāda, ka EKG parametru maiņa var būt ļoti strauja un asinhrona dažādos līmeņos. Algebriskais algoritms ļauj atklāt stabilas un nestabilas intervālu izmaiņas. Līdz ar to metode kopumā var kalpot par tehnoloģiju laika intervālu analīzei, lai atklātu stabilas un nestabilas parametru izmaiņas slodzes testa apstākļos.

Агне Слапшинскайте, Алфонсас Вайнорас, Лиепа Бикулчиене. Анализ комплексности ЭКГ во время велоэргометрии.
В статье рассмотрены вопросы применения специального алгебраического алгоритма, основанного на понятии ранга последовательности. Он применялся для анализа физиологических процессов во время исполнения двух протоколов. Группа 1 (когорта выносливости) выполняет задачу постоянной езды, а Группа 2 (когорта спринта) едет с повышением нагрузки. Компьютерный анализ системой «Каунас - нагрузка» был применен для 12-ти отведений ЭКГ. Рейтинг воспринятого применения был использован для измерения каждого спортсмена индивидуально (субъективно) по личной переносимости нагрузки. Целью данного исследования было оценить колебания функциональных параметров ЭКГ для молодых физически активных мужчин при двух разных задачах эргометрии. Основное внимание уделялось динамике и комплексности функциональных параметров ЭКГ: RR интервалу, JT интервалу, QRS интервалу. В группе 1 сила езды участников 175 ± 30 Вт, а время езды - 23 ± 2,25 мин. В группе 2 тестирование проводилось 11 минут. Во время отдыха, нагрузки и восстановления авторы оценивали временной ряд параметров ЭКГ: RR интервала, интервала JT и QRS комплекса. Эти параметры ЭКГ показывает различные уровни комплексности, например, RR интервал помогает в характеристики состояния организма в нормативном уровне, JT интервал представляет метаболические реакций систем, а параметр QRS отражает внутренне регулирующие состояние органа. Экспериментальное исследование показало, что изменения в физиологических условиях могут быть очень быстрыми и асинхронными в разных уровнях организма. Тем не менее, алгебраический алгоритм анализа показывает интервалы со стабильными и/или нестабильными физиологическими особенностями в различных функциональных параметров ЭКГ. Предлагаемый алгебраический анализ является технологией, которая может помочь в анализе коротких интервалов данных и которая позволяет найти интервалов стабильной или нестабильной физиологической особенности.