DOI: https://doi.org/10.15407/kvt210.04.060

FAINZILBERG L.S., DSc. (Engineering), Professor,
[1]Chief researcher of Intelligent Automatic Systems Department
[2]Professor of the Department of Biomedical Cybernetics,
https://orcid.org/ 0000-0002-3092-0794, e-mail: fainzilberg@gmail.com

[1] International Research and Training Center for Information Technologies
and Systems of the National Academy of Sciences of Ukraine
and Ministry of Education and Science of Ukraine,
40, Acad. Glushkov av., Kiyv, 03187, Ukraine
[2] National Technical University of Ukraine
"Ihor Sikorsky Kyiv Polytechnic Institute»
37, Peremogy av., Kiyv, 03056, Ukraine

MOBILE INFORMATION TECHNOLOGY FOR ASSESSING THE ADAPTATION CAPABILITIES OF THE HUMAN BODY UNDER CONDITIONS OF INCREASED LOADS

Introduction. *An important role in assessing the body's adaptive reserves under conditions of physical and emotional stress is played by information obtained with the help of special tests. Such tests should be convenient enough to quickly obtain the result, including at home and in the field.*

The purpose *of the paper is to develop the principles of building mobile IT for the operational assessment of the adaptive capabilities of the human body in the field and at home and the implementation of IT on a smartphone.*

Methods. *To assess tolerance to physical and emotional stress, a cognitive graphical image is constructed that integrally characterizes the regulatory patterns of changes in the physiological parameters of the heart rate, calculated in three states: at rest, at the height of the load and during restitution.*

Results. *It is shown that reliable information about the pulse wave (finger photoplethysmogram) during testing can be obtained using the built-in camera of a smartphone without additional technical means based on the developed original computational procedures that provide for the selection of reliable and unreliable cycles. To manage the physical load on the internal processor of the smartphone, a virtual teacher animation procedure is implemented, which demonstrates the correct technique and sets the required pace of the load. The emotional load management module is based on the Stroop effect and boils down to doing mental work under time pressure. The experiments confirmed that the cognitive graphic image makes it possible almost instantly to identify physiological indicators that demonstrate an inadequate response of the body to the load and rest after it.*

Conclusions. *The developed technology for assessing the adaptive capabilities of the human body under conditions of increased physical and emotional stress provides reliable testing in the field and at home, and the test results can be interpreted by a person without special medical education.*

Keywords: *information technology on a smartphone, regulatory patterns, body tolerance to physical and emotional stress.*

INTRODUCTION

Adaptation ensures that the body adapts to constantly changing environmental conditions. The process of adaptation is carried out in a reflex and humoral way [1]. Both mechanisms are interconnected and constitute a single neurohumoral mechanism that ensures self-regulation of the physiological functions of the body (the so-called sympathovagal balance).

One of the well-known methods for assessing the sympathovagal balance is based on mathematical methods for analyzing heart rate variability (HRV) [2, 3]. In clinical practice, most researchers use the standard proposed in 1996 [4], which provides recommendations on the use of this method.

An important role in assessing the body's adaptive reserves under conditions of physical and emotional stress is played by information obtained with the help of special tests. Such tests should be convenient enough to quickly obtain the result, including at home and in the field.

The generally accepted methods for evaluating test results are most often based on the analysis of the dynamics of heart rate (HR) and blood pressure (BP) under exercise. However, it is known [5, 6] that such an assessment does not always provide the required reliability of decision-making on the body's tolerance to stress. When quantifying the response to loads it is impossible to know for sure whether the detected deviations reflect the functional state of the heart or whether such deviations are associated with the features of the autonomic regulation of cardiac activity [7].

Therefore, it is useful to supplement a quantitative assessment with a qualitative analysis of the individual characteristics of the dynamics of changes in body parameters, in particular, statistical and spectral HRV indicators in the process of performing functional tests.

Traditionally, for the practical implementation of mathematical methods for HRV analysis in clinical conditions, special medical systems are used based on computer analysis of an electrocardiogram [8] or photoplethysmogram [9]. However, the complexity of these systems limits their use for mass preventive examinations in the field and at home.

The rapid development of smartphone technology has led to the emergence of new medical technologies. According to experts, a promising direction is the creation of modern mobile technologies for recording a pulse wave using the built-in camera of a smartphone without additional technical means [10–13]. However, on the way to implement such an attractive approach, there are a number of difficulties [14], which limit the scope of its practical application.

One of the main problems is due to the "masking" of true bursts of the pulse wave generated by heart beats, and the appearance of false bursts caused by random distortions and artifacts [15]. If these problems are not taken into account and signal processing is carried out using trivial algorithms, then another "toy" that is useless in the medical aspect will appear as a result, which smartphone users have already encountered more than once. It is not for nothing that such inefficient and sometimes dangerous applications have recently been removed from Google Play.

Let us show that the use of a new class of information technologies — intelligent IT, which has the properties of natural intelligence, can significantly reduce the likelihood of target miss errors and false alarms when assessing the dynamic series of cardio intervals and thereby increase the reliability of assessing the adaptive reserves of the body to increased physical and emotional stress.

The purpose of the article is to develop the principles of building mobile IT for the operational assessment of the adaptive capabilities of the human body in the field and at home and the implementation of IT on a smartphone.

THE BASIC IDEA OF THE PROPOUSED INFORMATION TECHNOLOGY

Intelligent IT is becoming more and more widespread in solving applied problems. Unlike traditional IT based on computational procedures of data analysis, intelligent IT operates with generalized concepts — images that provide more complete information about the external environment, and the analysis of such images generates a holistic picture of the phenomena being studied.

A useful tool for figurative representation of a problem is cognitive computer graphics, which allows you to either immediately see the solution to the problem or get a hint for finding it [16, 17]. Such possibilities of cognitive graphics are due to the fact that the human brain (unlike a computer) perceives and interprets a graphic image much easier than the numerical data that gave rise to it.

For example, even an experienced cardiologist is unlikely to be able to make a correct diagnosis by analyzing only a sequence of numbers (discrete readings) reflecting the process of changing the electrical activity of the heart over time. But when the same readings are presented to the doctor in the form of an electrocardiogram graph, then when interpreting it, the mechanism of figurative perception of information is activated, which is based on analogies, previous experience and the intuition of a specialist.

One of the successful examples of the use of a cognitive graphic image for the analysis and interpretation of ECG, which laid the foundation for an innovative method in cardiology — the phasegraphy method, was proposed by us in [18].

Let us now demonstrate the advantages of cognitive computer graphics using the example of building mobile IT to assess the adaptive reserves and tolerance of the body to physical and emotional stress.

On the Figure 1 is a simplified IT block diagram that implements the proposed testing methodology. To assess the adaptive capabilities of a person, it is proposed to automatically determine three groups of heart rate indicators:

$$x_i^{(1)},\ x_i^{(2)},\ x_i^{(3)},\ i = 1,\dots,N, \tag{1}$$

which are calculated at rest, immediately after exercise and after a 3-minute rest.

As such indicators, we will use, in particular: HR — heart rate (bpm); $SDNN$ — standard deviation of the array of cardiointervals (ms); CV — Pearson's coefficient of variation (%); AMo — amplitude of the cardiointervalogram mode (%); LF/HF — sympathovagal index, *Baev.Ind.* — Baevsky stress index.

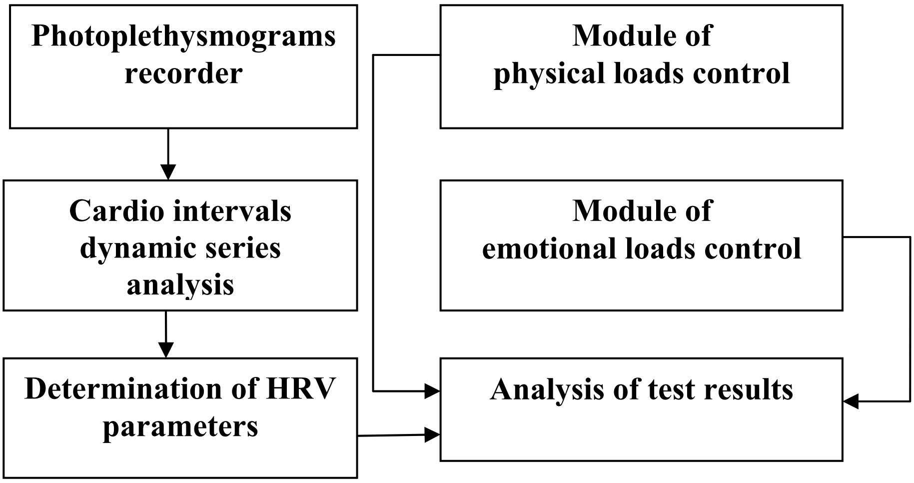


Fig. 1. Structural diagram of information technology

A qualitative assessment of the body's response to the load is carried out as follows. Each triple of indicators $\left\langle x_i^{(1)}, x_i^{(2)}, x_i^{(3)} \right\rangle$ $i = 1,...,N$, forms one of the five classes of patterns that characterize the dynamics of changes in the i-th indicator under load and during restitution [19]:

class 1 "Maximum", if (2)

$$(x_i^{(2)} - x_i^{(1)}) > h_i \ \wedge \ (x_i^{(2)} - x_i^{(3)}) > h_i,$$

class 2 "Minimum", if (3)

$$(x_i^{(1)} - x_i^{(2)}) > h_i \ \wedge \ (x_i^{(3)} - x_i^{(2)}) > h_i,$$

class 3 "Increase", if (4)

$$(x_i^{(2)} - x_i^{(1)}) > h_i \vee (x_i^{(3)} - x_i^{(2)}) > h_i \vee (x_i^{(3)} - x_i^{(1)}) > h_i,$$

class 3 "Decrease", if (5)

$$(x_i^{(1)} - x_i^{(2)}) > h_i \vee (x_i^{(2)} - x_i^{(3)}) > h_i \vee (x_i^{(1)} - x_i^{(3)}) > h_i,$$

class 5 "Permanent", if relations (2)-(5) are not met, (6)

where h_i – threshold of insensitivity to the value changes of the i-th indicator.

The patterns "Maximum" and "Minimum" characterize the situation in which the value of the indicator increased (decreased) immediately after the load, and more or less returned to the value at rest during the restitution period. These patterns are physiological, that is, typical for an adequate response of the body to any type of load and rest after it.

The patterns "Increase" and "Decrease" describe indicators, the value of which after rest becomes greater (less) than its value at rest. In other words, such patterns characterize the dynamics of the indicator for an increase (decrease) during testing. And, finally, the “Permanent” pattern describes the absence of visible dynamics in the values of indicators, regardless of the load. The last three patterns indicate inadequate dynamics of the load indicator.

Note that, in accordance with (2–6), there are various forms of each class of patterns. For illustration, Figure 2 shows possible variants of the form of the "Increase" pattern, which determines by condition (4).

A joint analysis of the all patterns forms in accordance with the patent of Ukraine for inventions [20] makes it possible to form a cognitive graphical image that provides visual qualitative information about the results of testing a particular subject. As it will be shown below, such an image is quite convenient for an integral assessment of the result and can be interpreted by a person who does not have a special medical education.

To receive a signal that carries information about the pulse wave, the user covers the smartphone camera with the phalanx of his finger, which is illuminated by a built-in flashlight (Fig. 3). As a result, a sequence of images of the phalanx of the finger is formed (video series):

$$\Psi_{\kappa m1}(x,y),\ \Psi_{\kappa m2}(x,y),\ \Psi_{\kappa m3}(x,y),\ldots, \tag{7}$$

where $\Psi_{\kappa mz}(x,y)$ is the function characterizes the brightness of pixels with coordinates.

Due to the influx of blood into the capillaries of the finger, the brightness of the frames changes (pulsates). Average frame brightness:

$$q_z = \frac{1}{Q_x Q_y}\sum_{k=1}^{Q_x}\sum_{m=1}^{Q_y}\Psi_{kmz}(x,y), \quad z = 1,2,\ldots\ , \tag{8}$$

where Q_x, Q_y are the number of pixels in the finger image of the horizontally and vertically respectively forms a sequence of discrete values $q_1, q_2, \ldots, q_N$ of the pulse wave at discrete points of time $z = 1,2,\ldots$.

Observations have shown that as a result of finger tremor, the initial pulse wave has a low-frequency trend. Therefore, the first stage of processing $q_1, q_2, \ldots, q_N$ is to using of adaptive algorithm that allows to automatically removing of the trend from the original sequence.

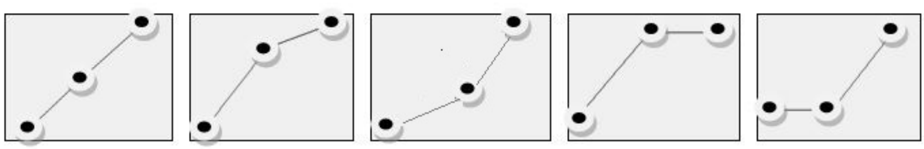


Fig. 2. Variants of the "Increase" pattern forms

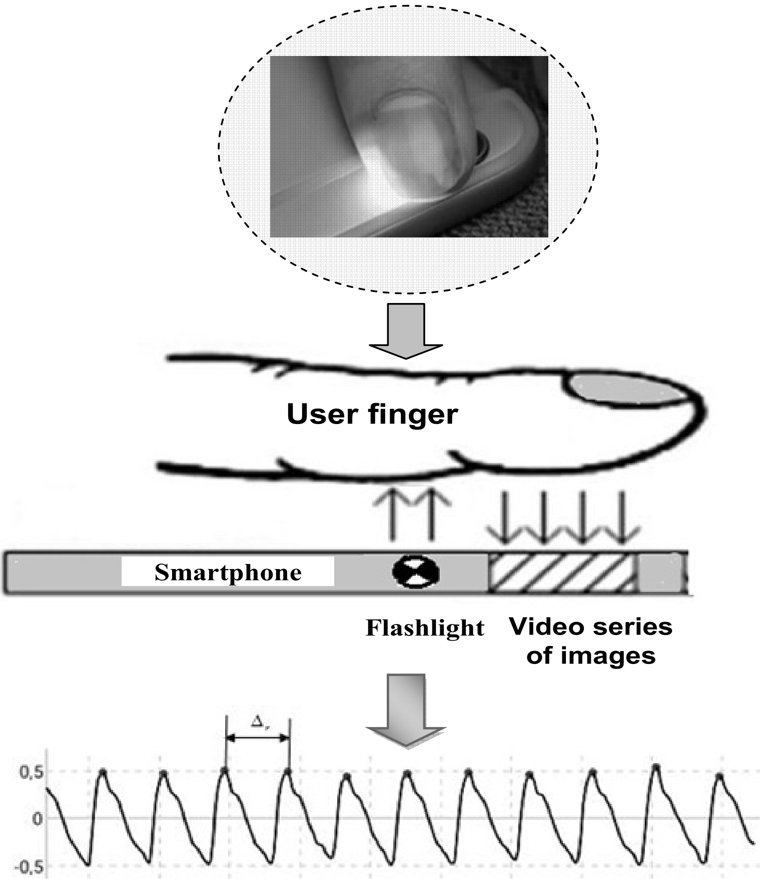


Fig. 3. The principle of a pulse wave registering using a smartphone camera

To do this, using the recursive procedure

$$G_z = G_{z-1} + \frac{1}{\Omega}(q_z - q_{z-\Omega}), \qquad z \in [\Omega + 1 \ , N] \tag{9}$$

we evaluate the trend of the observed sequence of the pulse wave discrete values $q_1, q_2, ..., q_N$ which is modified by follow:

$$\tilde{q}_z = q_z - G_z . \tag{10}$$

As a result the trend is automatically removed from the registered pulse wave.

The next stage of signal processing is the determination of the local maxima of the pulse wave. The use of a special procedure allows, against the background of possible distortions, to determine the characteristic points of the pulse wave, which divide each cardiac cycle into anacrotic and dicrotic limbs of the pulse waveform. These points are used to calculate the initial dynamic series of cardiointervals Δ_r, $r = 1,2,...$.

As already noted, in real situations, when registering a pulse wave, due to random disturbances, false bursts or the loss of true bursts of a pulse wave generated by heart beats may appear. Therefore, in order to improve the reliability and accuracy of determining HRV indicators from real signals, developed IT implemented original computational procedures for filtering and selecting cycles. This process is implemented in two stages.

The first stage (online procedure) makes it possible to automatically correct the initial dynamic series of cardiointervals Δ_1, Δ_2, … , Δ_N, , … in the process of recording a pulse wave in accordance with the patent for the invention [21]. To do this, the first five Δ_1, Δ_2, Δ_3, Δ_4, Δ_5 values are stored in a sliding buffer and are ranked in ascending or descending order. For example, if the following initial values of cardio intervals are:

$$\Delta_1 = 0{,}86\,\text{s};\ \Delta_2 = 1{,}31\ \text{s};\ \Delta_3 = 0{,}87\ \text{s};\ \Delta_4 = 0{,}81\ \text{s};\ \Delta_5 = 0{,}85\,\text{s}, \tag{11}$$

then after ranking in descending order, the following values will be placed in the sliding buffer

$$d_1 = 1{,}31\ \text{s};\ d_2 = 0{,}87\ \text{s};\ d_3 = 0{,}86\ \text{s};\ d_4 = 0{,}85\ \text{s};\ d_5 = 0{,}81\,\text{s}. \tag{12}$$

The first and last of the ranked values (12) are ignored and the remaining three values are averaged according to the formula

$$\delta_3 = \frac{d_2 + d_3 + d_4}{3}. \tag{13}$$

The value δ_3 calculated according to (13) determines the first element of the modified dynamic series of cardiointervals.

When the next element Δ_6 is defined the five values Δ_2, Δ_3, Δ_4, Δ_5, Δ_6 are ranked again, the first and last of the ranked values are ignored, and the remaining three values d_3, d_4, d_4 are averaged according to the formula

$$\delta_4 = \frac{d_3 + d_4 + d_5}{3}, \tag{14}$$

which forms the next value δ_4 of the modified dynamic series of cardiointervals. The process of modifying cardiointervals continues in a similar way in real time until the last value Δ_N from the initial dynamic series of cardiointervals is determined.

As a result, if single random outliers of values of cardio intervals are observed, then after ranking the Δ_{j-2}, Δ_{j-1}, Δ_j, Δ_{j+1}, Δ_{j+2}, $j = 3,...N-2$ such false values will either be in the first or last place of the ranked values d_{j-2}, d_{j-1}, d_j, d_{j+1}, d_{j+2}, $j = 3,...N-2$ of the sliding buffer. The current value of the modified cardio intervals is determined by the formula:

$$\delta_j = \frac{d_{j-1} + d_j + d_{j+1}}{3}, \quad j = 3,...N-2. \tag{15}$$

So the false values of the original dynamic series of cardiointervals are automatically deleted.

For example, the value $\Delta_2 = 1{,}31$ s, which is significantly different from the other values in the first five of the initial series of cardiointervals (11), after ranking will be in first place ($d_1 = 1{,}31$ s) and will not participate in the averaging procedure. So, according to (13), the first element of the modified dynamic series of cardiointervals will obtain the value $\delta_3 = 0{,}86$ s.

The considered adaptive filtering procedure combines the advantages of median filtering and moving average. As a result, the reliability of the formation of a dynamic series of cardiointervals upon possible artifacts is increased.

The second stage of processing (offline procedure) provides recognition of typical and atypical cycles of the recorded pulse wave, which further increases the accuracy and reliability of calculating HRV indicators. The procedure implements the intellectual property of generalization, making the transition from specific objects (in this case, pulse wave cycles) to the abstract classes "typical" and "atypical" cycles.

One of the classical approaches to solving the classification problem is based on the search for generalizing features that characterize class objects. Often such generalizing features are formed by machine learning methods based on precedents — representatives of individual classes collected in a training sample of observations.

However, when classifying pulse wave cycles, this approach turned out to be unsuitable. The fact is that the form of an atypical pulse wave cycle of one person can be typical for another and vice versa. It follows that it is impossible to build a reliable classification procedure based on an analytical description of the shape of cycles, which means that it is useless to look for generalizing features of typical and atypical cycles using machine learning methods.

Therefore, the developed IT implements an original computational procedure for classifying cycles [22], which is based on a single assumption: the number N_B of atypical cycles is much less than the total number N of cycles of the registered pulse wave, i.e.

$$N_B << N. \tag{16}$$

Otherwise, the concept of a "typical" cycle loses its meaning.

The procedure is based on calculating the distances between all pairs of cycles. To simplify the calculation of distances $L_{\mu\nu}$ between the μ-th $(\mu = 1,..., N)$ and ν-th $(\nu = 1,..., N)$ cycles, fragments $q_n^{(i)}$ of the anacrotic ($i = I_1$) and dicrotic ($i = I_2$) phases of each n-th cycle are modified based on the operator transformation

$$q_0^{(i)}(t) = a_n^{(i)} q_n^{(i)}\left(\frac{t}{b_n^{(i)}}\right), \quad n = 1,2,..., \quad i \in \{I_1, I_2\}, \tag{17}$$

where $a_n^{(i)}$, $b_n^{(i)}$ are parameters of linear stretching (compression) in amplitude and time. This modification made it possible to estimate the proximity of the cycles by the sum of the absolute values of the difference in the discrete values of the signal.

Calculated distances $L_{\mu\nu}$ form a square matrix

$$\Lambda = \begin{pmatrix} L_{11} & L_{12} \ldots & L_{1N} \\ L_{21} & L_{22} \ldots & L_{2N} \\ & \ldots & \\ L_{N1} & L_{N2} \ldots & L_{NN} \end{pmatrix}. \tag{18}$$

The matrix Λ allows to determine the most typical pulse wave cycle (reference cycle) by the formula

$$S_0 = \arg\min_{1 \le \nu \le N} \sum_{\mu=1}^{N} L_{\mu\nu}, \tag{19}$$

which, by virtue of condition (16), can rightfully be considered typical.

This made it possible to automatically classify typical and atypical cycles according to ordered distances

$$\Re = L(S_0, S_\lambda), \quad \lambda = 1,...N-1 \tag{20}$$

between the reference cycle S_0 and the remaining $N-1$ cycles of the registered pulse wave.

The point that corresponds to a jump or a sharp change in the slope of the graph of function (20) determines the threshold $\Re_0$, on the basis of which the set of all cycles is divided into two subsets:

$$\text{Typical cycles, when } \Re \le \Re_0; \tag{21}$$

$$\text{Atypical cycles, when } \Re > \Re_0. \tag{22}$$

The threshold value $\Re_0$ is automatically determined using a special search procedure implemented in IT software. Experiments confirmed the effectiveness of the proposed approach: the results of automatic analysis of statistical and spectral HRV indicators coincided with the data obtained from parallel observations using professional medical systems (Fig. 4).

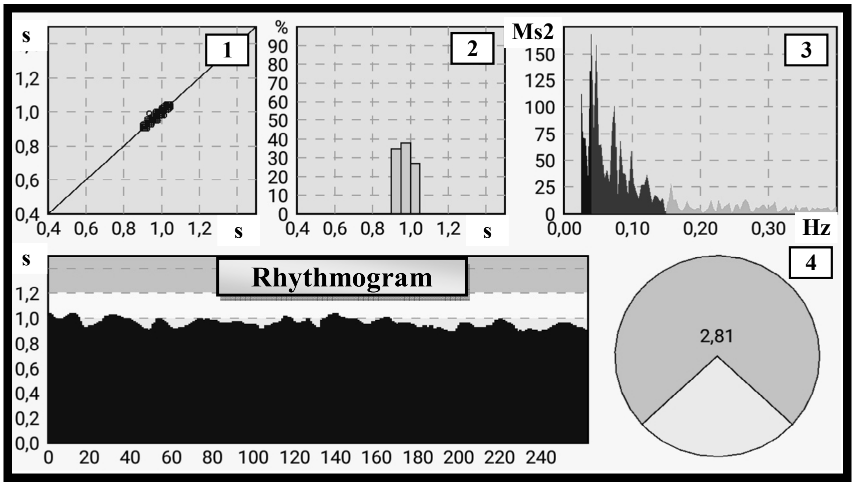


Fig. 4. Graphical interpretation of the results of the assessment of HRV indicators: scatterogram (1), histogram (2), spectrogram (3) and power balance diagram (4)

MODULE OF PHYSICAL LOADS CONTROL

In clinical practice, exercise tests are used to detect cardiac pathologies in the early stages [23]. In medical conditions, studies are carried out using special tools — a bicycle-ergometer and a treadmill. However, such products are not suitable for testing in the field and at home, while playing sports and in the workplace. This requires not only portable tools, but also simple methods that allow you to quickly get test results in a convenient and understandable form.

There are quite a lot of simplified methods for assessing the adaptive capabilities of a person under load: functional tests by Rufier, Gorinevsky, Letunov, Kotov-Denish, Martinet-Kushelevsky and others [24], in which the assessment of the recovery processes of the cardiovascular system under load by measuring heart rate (HR) and blood pressure (BP).

In the same time numerous observations of sports doctors testify [25] that the analysis of changes in heart rate to physical activity does not give an unambiguous answer to the question of the adaptive capabilities of the body. Not without reason, in modern recommendations for monitoring the training process, the catch phrase appeared: “Do not be a prisoner of heart rate!” [26].

Usually, during exercise, an increase in heart rate occurs as a result of a decrease in vagal tone and an increase in sympathetic stimulation of the heart. At the same time, the adaptation of the heart of a trained person to the load occurs to a greater extent due to an increase in stroke volume and to a lesser extent — as a result of an increase in heart rate, and in an insufficiently trained person — on the contrary: mainly with an increase in heart rate and to a lesser extent with an increase in stroke volume.

Some people’s heart rate increases only slightly, in response to exercise, which may indicate a violation of the sinus node function. There are also paradoxical dynamics of changes under load: the pulse increased during exercise falls below the initial level of rest (the effect of the negative phase of the pulse).

Fig. 5. Module of physical loads control window

Some researchers regard the effect of the negative phase of the pulse as an unfavorable sign associated with the insufficiency of the activity of different parts of the nervous system, which leads to a change in the sequence of recovery processes. Most often, such deviations occur in individuals with a labile nervous system and after neuropsychic overstrain. Other scientists associate the effect of the negative phase of the pulse with an improvement in the performance of the cardiovascular system.

It follows from the above that it is useful to supplement the assessment of the dynamics of heart rate under exercise with an assessment of changes in other indicators, in particular, statistical and spectral indicators of heart rate variability.

Exactly this possibility that is implemented in the developed IT using the software module of physical loads control, which ensures the implementation of the simplest and most accessible test in the form of deep squats, which is used in the Rufier test. By default, the standard load is 20 squats in 30 seconds. To provide greater flexibility, the developed module allows you to set the required number of sit-ups for a certain period of time. This allows you to adjust the desired pace of squats individually, taking into account the age and fitness level of the person being tested.

According to [27], reproducibility of test results can be achieved only if the squat test is performed correctly. To ensure this requirement, the module implements a procedure for animating a virtual teacher who demonstrates the correct technique and sets the required squatting pace (Fig. 5.)

The software of the virtual instructor animation is implemented by sequentially demonstrating pre-prepared images of individual phases of the squat on the smartphone screen. The display time of one frame is automatically calculated by the formula

$$\tau = \frac{\theta N_v}{N_\theta}, \tag{23}$$

where θ is the user-specified test execution time (s), N_θ is the user-specified number of squats that must be completed during time θ, and $N_v = \text{const}$ is the total number of frames that ensures the animation is realistic. The values of the variables θ and N_θ are set using the settings. The test-taker must perform squats in sync with the virtual teacher according to the sound signals of the metronome.

MODULE OF EMOTIONAL LOADS CONTROL

In modern conditions, human life and activity is characterized by a rapid pace, information overload, a decrease in physical activity, and an increased level of social conflicts. These negative phenomena lead to the increasing in the level of emotional stress of the individual [28]. Although stress most often causes only a change in the body's physiological reactions that do not go beyond normal conditions, in some cases it has quite serious negative consequences [29].

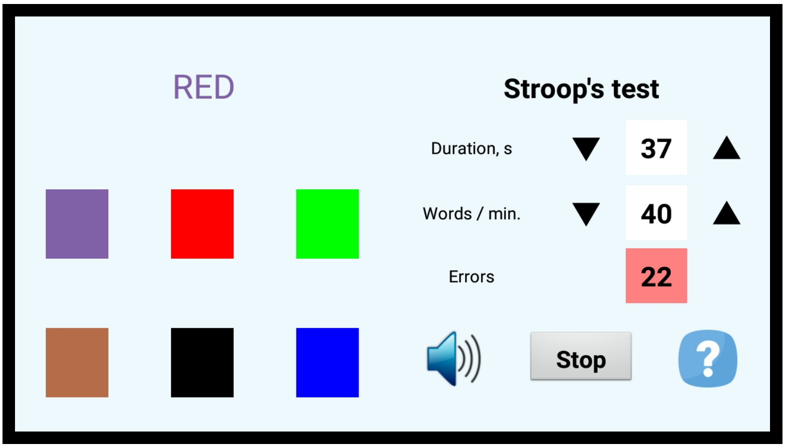
All this gave rise to a number of new scientific directions in medicine, psychology, sociology, computer science and other fields. One of these areas is the creation of modern computer tools that provide assessment and assistance in restoring the adaptive reserves of the body to overcome emotional stress [30].

One of the methods for assessing the body's adaptive reserves for emotional stress is based on the performance of special tests in a state of physical rest, which boil down to the performance of mental work under time pressure. To build such a test in the developed IT, a software module based on the so-called Stroop effect was created [31, 32].

The Stroop test is based on the properties of the human brain to save resources, which leads to the effect of a contradiction between the information read and seen. It is believed that separate parts of the brain process relevant and irrelevant information in parallel, but compete for entry into a single central "processor" during the choice of an answer. It has been established that the brain reads words faster than it recognizes the color of letters, since the brain's ability to process text is much faster than it recognizes color. Therefore, in situations where there is a conflict in the interpretation of words and colors, information about the word comes to the decision-making stage faster than information about the color, which creates confusion during processing [33].

According to the theory of selective attention, color recognition, in contrast to reading a word, requires more attention, which may be the result of a number of distractions that are not appropriate responses. In order to effectively solve these two different problems, not only different parts of the human brain, but also various specific ways of transmitting information developed in the process of evolution.

Therefore, if you write the word "RED" in a different color, for example, the color "VIOLET" and ask you to name the color of the letters, then most often the answer will be "RED", although the correct answer is "VIOLET". This happens because when we see a word in a familiar language, we automatically read it and a ready-made answer appears in our head. In other words, the brain saves resources and solves the problem like this: why think and recognize the color of letters if the answer is already there?



Fug. 6. Module of emotional loads control window

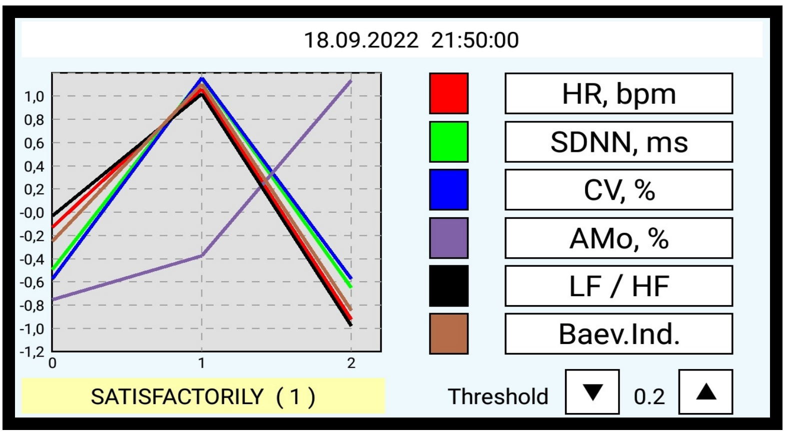


Fig. 7. Example of cognitive graphic images

Based on the Stroop effect, lightweight and enhanced versions of the Stroop's tests are programmatically implemented in the emotional load management module. Words written in one of six colors appear on the tablet screen at a given pace: "RED", "GREEN", "BLUE", "VIOLET", "BLACK", "BROWN" (Fig. 6). The subject must indicate the color of the letters by touching the square of the corresponding color. If the color of the word and the square do not match, an error occurs, the number of which is automatically calculated during the test.

The number of errors of the tested person is displayed on the smartphone screen. At the same time, a characteristic sound signal occurs. Signaling about the appearance of errors when performing a test imitates a stressful situation, as a result of which the values of physiological indicators change in emotional people.

The reinforced version of the test has an additional complexity: when the next word appears, the positions of the squares indicating the correct color of the text randomly change their position on the screen, which increases the emotional load.

The module interface provides settings for the duration of the test and the rate of occurrence of words. It is also possible to enable or disable the formation of characteristic sound signals during testing.

Evaluation of classes of regulatory patterns of physiological parameters in accordance with expressions (2) – (6) makes it possible to assess the adequacy of the reaction of the tested to the emotional load.

MODULE FOR INTEGRAL ASSESSMENT OF TEST RESULTS

The above set of five classes of graphical patterns that characterize the dynamics of individual physiological parameters under load forms a complete group of random events in the understanding that one of these classes will be unambiguously determined by successive testing of conditions (2) – (6) during each test.

As already noted, the patterns "Maximum" (grade 1) and "Minimum" (grade 2) characterize an adequate response of the body to the load, when three minutes after the end of the load, the value of corresponding physiological indicator returns to the original one. Therefore, these patterns can be used as physiological "standards" of adequate dynamics of the change in the indicator during testing.

It is clear that as a result of testing, some indicators may turn out to be physiological, while others may not. The final decision on the set of indicators can be made on the basis of a direct analysis of their values calculated during the testing process. However, it is more convenient to make a decision based on a cognitive graphic image that visually displays this data.

To build such an image, it is proposed:

• invert the value of indicators that generated the "Minimum" pattern as a result of testing in order to ensure the same direction of physiological patterns - convexity upwards;

• before forming a graphical pattern, normalize the value of each i-th indicator in the j-th state using the formula

$$\hat{x}_i^{(j)} = \frac{x_i^{(j)} - \frac{1}{3}\sum_{j=1}^{3} x_i^{(j)}}{\sqrt{\frac{1}{2}\sum_{j=1}^{3}\left(x_i^{(j)} - \frac{1}{3}\sum_{j=1}^{3} x_i^{(j)}\right)^2}}, \quad i = 1,\dots,N, \quad j = 1,2,3, \qquad (24)$$

the numerator of which determines the centered values of the indicator at rest, at the height of the load and during the restitution period, and the denominator is the standard deviation of the indicator during the testing period.

As a result of this modification, the set of patterns of all indicators is displayed on the same scale and generates a cognitive graphical image that is convenient for interpreting test results according to the voting rule [20, 34] shown in Table 1.

Visual analysis of a cognitive graphical image makes it possible to almost instantly identify indicators whose graphs do not have an upward bulge (Fig. 7.) The appearance of such graphs requires attention from the person who conducts the test, since this indicates that the corresponding indicator has not returned to its original value after the rest.

Table 1. Rule for qualitative interpretation of test results

Pattern classes	Description of the cognitive image	The load tolerance
Patterns of all indicators correspond to the physiological class	All graphs are convex upwards	Adequate
One of patterns not correspond to the physiological class	One of the graphs does not have an upward bulge	Satisfactorily
Two or more patterns not correspond to the physiological class	Two or more graphs do not have an upward bulge	Reduced

However, it should be noted that the detection of such “suspicious” indicators does not always indicate a decrease in exercise tolerance. Experiments have shown that in some people, after loads, the values of some indicators may be better than before loads. Most likely, such situations are associated with the individual characteristics of the autonomic nervous system of the subject or occur with an insufficient level of load. Of course, to confirm this hypothesis, additional studies are required to develop a methodology for adaptive load management for concrete person.

In any case, in order to make an informed decision, it is advisable to supplement the qualitative interpretation of the results based on a cognitive graphic image with a quantitative analysis of the triple $\left\langle x_i^{(1)},\, x_i^{(2)}, x_i^{(3)} \right\rangle$ of values of the "suspicious" indicator, which, by request of the user, are displayed on the smartphone screen.

CONCLUSIONS

A prototype of a mobile information technology has been developed for a personalized assessment of a person's adaptive capabilities under conditions of increased physical and/or emotional stress. The technology allows testing based on the Rufier’s and Stroop’s tests. Load control is carried out using software modules that are implemented on a smartphone running the ANDROID operating system.

The proposed technology has advantages over existing analogues, including:

• registration of the pulse wave is carried out using the built-in camera of a smartphone without additional technical means,

• original processing algorithms made it possible to increase the reliability of determining the parameters of cardiac cycle variability in real conditions,

• load control software modules implemented on the internal processor of the smartphone provide convenient testing in the field and at home,

• test results are provided in the form of a cognitive graphic image that can be interpreted by a person without special medical education.

Further research should be aimed at improving testing methods, in particular, developing an adaptive Stroop’s test that adapts to the individual characteristics of the user. It is also advisable to conduct further research aimed at expanding the functionality of the technology, in particular, improving the technology by constructing and analyzing graphical patterns that characterize the dynamics of blood vessel tone based on intelligent computer procedures that provide an estimate of speed of the pulse wave propagation.

REFERENCES

1. Lazurenko S. I., Biloshitskyi S. V., Semenov A. M. Adaptation and adaptive capabilities of man. Actual problems of education and upbringing of people with special needs. *Collection of scientific works*. 2013, No. 11(13), pp.194–207. http://ap.uu.edu.ua/article/32 (In Ukrainian).
2. Korkushko O. V., Pisaruk A. V., Shatilo V. G., Lishnevskaya V. Yu., Chebotarev N. D., Analysis of heart rate variability in clinical practiceю. Age aspects. K: Institute of Gerontology of the Academy of Medical Sciences, 2002. 189 p. (In Russian).
3. Corr P.B., Yamada K.A.,Witkowski F.V. Mechanisms controlling cardiac autonomic function and their relation to arihythmogenesis. The Heart and Cardiovascular System. N-Y: Raven Press, 1986, pp. 1343–1403.
4. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart Rate Variability. Standards of Measurement, Physiological Interpretation and Clinical Use. Circulation. 1996, Vol. 93, pp. 1043–1065.
5. Prokopiev N.Ya., Kolunin E.T., Gurtovaya M.N., Mitasov D.I. Physiological approaches to the evaluation of functional stress tests. *Basic research*. 2014, No. 2, pp. 146–150. (In Russian).
6. Sidorov S.P., Perkhurov A.M., Stefan O.S. The significance of the correct implementation of the functional test methodology with 20 squats in assessing the state of the cardiovascular system of young athletes. *Physical education in prevention, treatment and rehabilitation*. 2009, No. 2 (29), pp. 39–44. (In Russian).
7. Minina E.N., Fainzilberg L.S., Orikhovskaya K.B. Qualitative assessment of the adaptive reserves of the cardiovascular system based on the regulatory patterns of the reference cycle of a single-channel ECG. *J. Modern Science. Topical issues of theory and practice. Series natural and technical sciences*. 2016, No. 8. pp. 103–113. (In Russian).
8. Baevsky R.M., Ivanov G.G., Chireikin L.V. Analysis of heart rate variability using various electrocardiographic systems (guidelines). *Bulletin of arrhythmology*. 2001, No. 24, pp. 65–87. (In Russian).
9. Alian A.A., Shelley K.H. Photoplethysmography. Best Practice & Research. *Clinical Anaesthesiology*. 2014, Vol. 28, No. 4, pp. 395–406. https://doi.org/10.1016/j.bpa.2014.08.006.
10. Papon M.T.I., Ahmad I., Saquib N., Rahman A. Non-invasive heart rate measuring smartphone applications using on-board cameras: A short survey. *Proc. of 2015 International Conference on Networking Systems and Security*. Dhaka, 2015, pp. 1–6.
11. Laure D., I. Paramonov I. Improved Algorithm for Heart Rate Measurement Using Mobile Phone Camera. *Proc. of the 13th Conference of Open Innovations Association FRUCT and 2nd Seminar on e-Tourism for Karelia and Oulu Region*. 2013, pp. 8593. https://doi.org/10.23919/FRUCT.2013.8124232
12. Boland P. The emerging role of cell phone technology in ambulatory care. *Journal of Ambulatory Care Management*. 2007, Vol. 30, No. 2, pp. 126–133. doi: 10.1097/01.JAC.0000264602.19629.84.
13. Jonathan E., Leahy M. Investigating a smartphone imaging unit for photoplethysmography. *Physiol Measurements*. 2010, Vol. 31, No. 11, pp. 79–83. doi: 10.1088/0967-3334/31/11/N01. Epub 2010 Sep 24.
14. Rong-Chao Peng. Investigation of Five Algorithms for Selection of the Optimal Region of Interest in Smartphone Photoplethysmography. *Journal of Sensors*. Volume 2016, Article ID 6830152. https://doi.org/10.1155/2016/6830152
15. Trofimov P.A., Purtov K.S., Kublanov V.S. Measuring human heart rate variability using a smartphone camera. Computer Image Analysis: Intelligent Solutions in Industrial Networks (CAI-2016): *Collection of scientific papers based on the materials of the International Conference* May 5-6, 2016. Ekaterinburg: UMC UPI, 2016, pp. 134–137.

16. Zenkin A.A. Cognitive computer graphics. M.: Nauka, 1991. 192 p. (In Russian).
17. Pospelov D.A. Cognitive graphics are a window to a new world. *Software products and systems*. 1992, No. 2, pp. 4–6. (In Russian).
18. Fainzilberg L., Potapova T. Computer Analysis and Recognition of Cognitive Phase Spase Electro-Cardio Graphic Image. *Proc. of the 6th Int. Conf. on Computer Analysis of Images and Patterns (CAIPS'95)*. Prague (Czech Republic). 1995, pp. 668–673.
19. Fainzilberg L.S., Orikhovskaya K.B. Information technology for assessing the adaptive reserves of the body in the field. *Cybernetics and computer technology*. 2015, Issue. 181, pp. 4–22.
20. Fainzilberg L.S. A method of assessing the adequacy of the body's response to stress. Patent of Ukraine for the invention No. 116548. Bull. No. 27, 2018. (In Ukrainian).
21. Fainzilberg L.S. The method of obtaining a dynamic series of cardio intervals based on the pulse wave. Patent of Ukraine for the invention No. 126520. Bull. No. 43, 2022. (In Ukrainian).
22. Fainzilberg L.S. Intelligent digital medicine tools for home use. *Clinical informatics and telemedicine.* 2020, Vol. 15, Issue 16, pp. 45–56. (In Russian). http://doi.org/10.31071/kit2020.16.03.
23. Lupanov VP, Nuraliev EYu, Sergienko IV. Funkcionalnye nagruzochnye proby v diagnostike ishemicheskoj bolezni serdcza, ocenke riska oslozhnenij i prognoza. 2016. M.: Izd-vo OOO «PatiSS». (In Russian)
24. Aronov D.M., Lupanov V.P. Functional tests in cardiology. M.: Medpress-inform, 2002. 296 p. (In Russian)
25. Halson S.L., Jeukendrup A.E. Does Overtraining Exist? An Analysis of Overreaching and Overtraining Research. *Sports Med*. 2004, Vol. 34, No. 14, pp. 967–981. doi: 10.2165/00007256-200434140-00003.
26. Prokopiev N.Ya., Kolunin E.T., Gurtovaya M.N. Physiological approaches to the assessment of functional stress tests. *Basic research*. 2014, No. 2, pp. 146–150. (In Russian)
27. Sidorov S.P., Perkhurov A.M., Stefan O.S. The value of the correct implementation of the functional test technique with 20 squats in assessing the state of the cardiovascular system of young athletes. *Physical education in prevention, treatment and rehabilitation*. 2009, No. 2, pp. 39–44. (In Russian)
28. Trigranyan R.A. Stress and its importance for the body. M.: Nauka, 1988. 176 p. (In Russian)
29. Kornatsky V.M. Tretyak I.V. Influx of psychoemotional disorders on the development and overcoming of cardiovascular pathology. *Ukrainian Cardiology Journal "Ukrcardio"*.2008, No. 6, pp. 94–100. (In Russian)
30. Fainzilberg L.S., Kondratyuk T.V., Semergey N.A. ANTISTRESS is a new information technology for managing the regulatory systems of the human body based on biofeedback. *Control systems and machines*. 2011, No. 3, pp. 62–72. (In Russian)
31. Williams, J.M.G., Mathews, A., MacLeod, C. The emotional Stroop task and psychopathology. *Psychol. Bull*. 1996, No. 120, pp. 3–24. https://doi.org/10.1037/0033-2909.120.1.3.
32. Esgalhado G, Pereira H., Silva P.Adaptation of an Emotional Stroop Test for Screening of Suicidal Ideation in Portugal. *Behav. Sci*. 2022, No. 12, pp. 281–292. https://doi.org/10.3390/bs12080281
33. Lamers M.J.M., Roelofs A., Rabeling-Keus I.M. Selective attention and response set in the Stroop task. *Memory & Cognition*. 2010, No. 38, pp. 893–904. https://doi.org/10.3758/MC.38.7.893
34. Gritsenko V.I., Fainzilberg L.S., Kravchenko A.N., Korchinskaya Z.A., Orikhovskaya K.B., Pasko V.S., Stanislavskaya S.S. Cognitive graphic images in the task of evaluating the body's response to stress by the phasegraphy method. *Control systems and machines*. 2016, No. 6, pp. 24–33. http://dspace.nbuv.gov.ua/handle/123456789/117310. (In Russian).

Received 16.09.2022

ЛІТЕРАТУРА

1. Лазуренко С. І., Білошицький С. В., Семенов А. М. Адаптація та адаптаційні можливості людини. Актуальні проблеми навчання та виховання людей з особливими потребами. *Збірник наукових праць*. 2013. № 11(13). С.194–207. http://ap.uu.edu.ua/article/32
2. Коркушко О.В., Писарук А.В., Шатило В.Г., Лишневская В.Ю., Чеботарев Н.Д., Погорецкий Ю.Н. Анализ вариабельности ритма сердца в клинической практике. Возрастные аспекты. К: Институт геронтологии АМН, 2002. 189 с.
3. Corr P.B., Yamada K.A.,Witkowski F.V. Mechanisms controlling cardiac autonomic function and their relation to arihythmogenesis. The Heart and Cardiovascular System. 1986. N-Y:Raven Press. 1343–1403.
4. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart Rate Variability. Standards of Measurement, Physiological Interpretation and Clinical Use. Circulation. 1996. Vol. 93. P. 1043–1065.
5. Прокопьев Н.Я., Колунин Е.Т., Гуртовая М.Н., Д.И. Митасов Физиологические подходы к оценке функциональных нагрузочных проб. *Фундаментальные исследования*. 2014. № 2. С. 146–150.
6. Сидоров С.П., Перхуров А.М., Штефан О.С. Значение корректного выполнения методики функциональной пробы с 20 приседаниями при оценке состояния сердечно-сосудистой системы юных спортсменов. *Физкультура в профилактике, лечении и реабилитации.* 2009. № 2 (29). С. 39–44.
7. Минина Е.Н., Файнзильберг Л.С., Ориховская К.Б. Качественная оценка адаптационных резервов сердечно-сосудистой системы на основе регуляторных паттернов эталонного цикла одноканальной ЭКГ. *Журнал «Современная наука. Актуальные вопросы теории и практики. Серия естественные и технические науки»*. 2016. № 8. С. 103–113.
8. Баевский Р.М., Иванов Г.Г., Чирейкин Л.В. и др. Анализ вариабельности сердечного ритма при использовании различных электрокардиографических систем (методические рекомендации). *Вестник аритмологии*. 2001. № 24. С. 65–87.
9. Alian A.A., Shelley K.H. Photoplethysmography. Best Practice & Research. *Clinical Anaesthesiology*. 2014. Vol. 28, No. 4. P. 395–406. https://doi.org/10.1016/j.bpa.2014.08.006.
10. Papon M.T.I., Ahmad I., Saquib N., Rahman A. Non-invasive heart rate measuring smartphone applications using on-board cameras: A short survey. *Proc. of 2015 International Conference on Networking Systems and Security*. Dhaka, 2015. P. 1–6.
11. Laure D., I. Paramonov I. Improved Algorithm for Heart Rate Measurement Using Mobile Phone Camera. *Proc. of the 13[th] Conference of Open Innovations Association FRUCT and 2[nd] Seminar on e-Tourism for Karelia and Oulu Region*. 2013. P. 8593. https://doi.org/10.23919/FRUCT.2013.8124232
12. Boland P. The emerging role of cell phone technology in ambulatory care. *Journal of Ambulatory Care Management*. 2007. Vol. 30. No. 2. P. 126–133. doi: 10.1097/ 01.JAC.0000264602.19629.84.
13. Jonathan E., Leahy M. Investigating a smartphone imaging unit for photoplethysmography. *Physiol Measurements*. 2010. Vol. 31. No. 11. P. 79–83. doi: 10.1088/0967-3334/31/11/N01. Epub 2010 Sep 24.
14. Rong-Chao Peng et al. Investigation of Five Algorithms for Selection of the Optimal Region of Interest in Smartphone Photoplethysmography. *Journal of Sensors*. Volume 2016. Article ID 6830152. https://doi.org/10.1155/2016/6830152
15. Трофимов П.А., Пуртов К.С., Кубланов В.С. Измерение вариабельности сердечного ритма человека с помощью камеры смартфона. Компьютерный анализ изображений: Интеллектуальные решения в промышленных сетях (CAI-2016) : *Сборник научных трудов по материалам Международной конференции* 5–6 мая 2016 г. Екатеринбург: УМЦ УПИ, 2016. С. 134–137.
16. Зенкин А.А. Когнитивная компьютерная графика. М.: Наука, 1991. 192 с.
17. Поспелов Д.А. Когнитивная графика — окно в новый мир. *Программные продукты и системы.* 1992. № 2. С. 4–6.

18. Fainzilberg L., Potapova T. Computer Analysis and Recognition of Cognitive Phase Spase Electro-Cardio Graphic Image. *Proc. of the 6th Int. Conf. on Computer Analysis of Images and Patterns (CAIPS'95)*. Prague (Czech Republic). 1995. P. 668–673.
19. Файнзильберг Л.С., Ориховская К.Б. Информационная технология оценки адаптационных резервов организма в полевых условиях. *Кибернетика и вычислительная техника*. 2015. Вып. 181.С. 4–22.
20. Файнзільберг Л.С. Спосіб отримання динамічного ряду кардіоінтервалів пульсовою хвилею. Патент України на винахід № 126520. Бюл. № 43, 2022 р.
21. Файнзільберг Л.С. Спосіб отримання динамічного ряду кардіоінтервалів за пульсовою хвилею. Висновок про відповідність винаходу за заявкою а 2019 07936 умовам патентоздатності за результатами кваліфікаційної експертизи від 25 квітня 2022.
22. Файнзильберг Л.С. Интеллектуальные средства цифровой медицины для домашнего применения. *Клиническая информатика и телемедицина*. 2020. Т. 15. Вып. 16. С. 45–56. http://doi.org/10.31071/kit2020.16.03
23. Лупанов В.П., Нуралиев Э.Ю., Сергиенко И.В. Функциональные нагрузочные пробы в диагностике ишемической болезни сердца, оценке риска осложнений и прогноза. М.: Издво ООО «ПатиСС», 2016.
24. Аронов Д.М., Лупанов В.П. Функциональные пробы в кардиологии. М.: Медпресс-информ, 2002. 296 с.
25. Halson S.L., Jeukendrup A.E. Does Overtraining Exist?An Analysis of Overreaching and Overtraining Research. *Sports Med*. 2004. Vol. 34, No. 14. P. 967–981. doi: 10.2165/00007256-200434140-00003.
26. Прокопьев Н.Я., Колунин Е.Т., Гуртовая М.Н. Физиологические подходы к оценке функциональных нагрузочных проб. *Фундаментальные исследования*. 2014. № 2. С. 146–150.
27. Сидоров С.П., Перхуров А.М., Штефан О.С. Значение корректного выполнения методики функциональной пробы с 20 приседаниями при оценке состояния сердечно-сосудистой системы юных спортсменов. *Физкультура в профилактике, лечении и реабилитации.* 2009. № 2. С. 39–44.
28. Тригранян Р.А. Стресс и его значение для организма . М.: Наука, 1988. 176с.
29. Корнацький В.М. Третяк І.В. Вплив психоемоційних порушень на розвиток і перебіг серцево-судинної патології. *Український кардіологічний журнал «Укркардіо»*. 2008. № 6. С. 94–100.
30. Файнзильберг Л.С., Кондратюк Т.В., Семергей Н.А. АНТИСТРЕСС – новая информационная технология управления регуляторными системами организма человека на основе биологической обратной связи. *Управляющие системы и машины*. 2011. № 3. С. 62–72.
31. Williams, J.M.G., Mathews, A., MacLeod, C. The emotional Stroop task and psychopathology. *Psychol. Bull*. 1996. No. 120. P. 3–24.https://doi.org/10.1037/0033-2909.120.1.3.
32. Esgalhado G, Pereira H. , Silva P.Adaptation of an Emotional Stroop Test for Screening of Suicidal Ideation in Portugal. *Behav. Sci*. 2022. No. 12. P. 281–292. https://doi.org/10.3390/bs12080281
33. Lamers M.J.M., Roelofs A., Rabeling-Keus I.M. Selective attention and response set in the Stroop task. *Memory & Cognition*. 2010. No. 38. P. 893–904. https://doi.org/10.3758/MC.38.7.893
34. Гриценко В.И., Файнзильберг Л.С., Кравченко А.Н., Корчинская З.А., Ориховская К.Б, Пасько В.С., Станиславская С.С. Когнитивные графические образы в задаче оценки реакции организма на нагрузку методом фазаграфии. *Управляющие системы и машины*. 2016. № 6 С. 24–33. http://dspace.nbuv.gov.ua/handle/123456789/117310

Отримано 16.09.2022

Файнзільберг Л.С., д-р техн. наук, проф.,
[1]голов. наук. співроб. відд. інтелектуальних автоматичних систем,
[2]професор кафедри біомедичної кібернетики
https://orcid.org/0000-0002-3092-0794, e-mail: fainzilberg@gmail.com
[1] Міжнародний науково-навчальний центр інформаційних технологій та систем НАН України та МОН України,
40, пр. Акад. Глушкова, Київ, 03187, Україна
[2] Національний технічний університет України "Київський політехнічний інститут імені Ігоря Сікорського"
37, пр. Перемоги, м. Київ, 03056, Україна

МОБІЛЬНА ІНФОРМАЦІЙНА ТЕХНОЛОГІЯ ДЛЯ ОЦІНЮВАННЯ АДАПТАЦІЙНИХ МОЖЛИВОСТЕЙ ОРГАНІЗМУ ЛЮДИНИ В УМОВАХ ПІДВИЩЕНИХ НАВАНТАЖЕНЬ

Вступ. Важливу роль в оцінюванні адаптаційних резервів організму в умовах фізичних і емоційних навантажень має інформація, одержувана за допомогою спеціальних тестів. Такі тести мають бути досить зручними для оперативного отримання результату, зокрема, в домашніх та польових умовах.

Мета статті — розроблення принципів побудови мобільної ІТ для оперативного оцінювання у польових та домашніх умовах адаптаційних можливостей організму людини та реалізація ІТ на смартфоні.

Методи. Для оцінювання толерантності до фізичного та емоційного навантаження будується когнітивний графічний образ, який інтегрально характеризує регуляторні патерни змін фізіологічних показників серцевого ритму, обчислені у трьох станах: стані спокою, на висоті навантаження та в період реституції.

Результати. Показано, що надійну інформацію про пульсову хвилю (пальцеву фотоплетизмограму) у процесі тестування можна отримувати за допомогою вбудованої камери смартфона без додаткових технічних засобів на основі розроблених оригінальних обчислювальних процедур, які передбачають селекцію надійних та ненадійних циклів. Для керування фізичним навантаженням на внутрішньому процесорі смартфона реалізовано процедуру анімація віртуального вчителя, який демонструє правильну техніку і задає необхідний темп виконання навантаження. Модуль керування емоційним навантаженням основано на ефекті Струпа і зводиться до виконання розумової роботи в умовах дефіциту часу. Експерименти підтвердили, що когнітивний графічний образ дає можливість практично миттєво виявити фізіологічні показники, які демонструють неадекватну реакцію організму на навантаження та відпочинок після неї.

Висновки. Розроблена технологія оцінювання адаптаційних можливостей організму людини в умовах підвищених фізичних та емоційних навантажень забезпечує надійне тестування в польових та домашніх умовах, а результати тестування можуть бути інтерпретовано людиною без спеціальної медичної освіти.

Ключові слова: *інформаційна технологія на смартфоні, регуляторні патерни, толерантність організму до фізичного та емоційного навантажень.*