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Application of Vibraimage Technology and System for Analysis of Motor Activity and Study of Functional State of the Human Body

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Introduction

The history of discussion about motion information content dates back to Aristotle's declaration of correlation between motion and life of biological objects. This correlation includes connection of locomotor activity with psychophysiological state. Ivan Mikhailovich Sechenov in his work *Cerebral Reflexes* published in 1863 declared that all external features of cerebral activity can be manifested as muscular motion. This declaration illustrates a correlation between thinking and muscular motion. Charles Darwin in his book *The Expression of the Emotions in Man and Animals* published in 1872 declared that reflexes represented emotions. Conrad Lorenz, Nobel Prize winner and a prominent biologist and physiologist of the XXth century, in his book *Aggression* published in 1966 declared that measurement of reflection motion intensity and amplitude would provide measurement of aggression intensity.

In spite of direct correlation of emotional and functional states with parameters of reflex-controlled motion, until recent time there were no quantitative and informative parameters of human body movement. This is primarily due to the fact that most researchers of motion physiology (N. A. Bernshtein [1], Mira-y-Lopez [2]) studied human body micromobility, which was a sophisticated mathematical problem.

It was shown in [3] that vertical equilibrium of the human head was controlled by the vestibular system and was described by vestibular reflex function. Equilibrium of the human head controlled by the vestibular system can be also regarded as a particular case of locomotor activity (head micromobility). There are advantages of head micromobility analysis over analysis of other types of human body reflex-controlled mobility. Movements of human head are the most frequently repeated motions of human body during life. The two-month-old child begins to poise the head. Vertical head position in older children and adults is controlled by the vestibular system. This includes continuous micromobility (hundreds of micrometers per sec) of head or the head is sloped to a support.

From the physical standpoint, mechanical head oscillations are a vibration process, whose parameters provide quantitative correlation between energy and object mobility. Integral information about head mobility parameters can be obtained using vibraimaging technology [4]. Vibraimaging technology provides quantitative information about periodic movements of any point of the object. Video image is the primary image, each point of which represents object mobility parameters. Like biomedical images (ultrasonic, NMR, IR, X-ray), video image represents a specific physical property. Vibraimage provides information similar to information obtained using point-by-point biomedical methods: EEG, galvanocutaneous reaction, ECG. The physical model of head micromobility analysis based on vibraimage technology and thermodynamic laws was suggested in [5]. This model introduces a new term, vestibular emotional reflex or vestibular energy reflex (VER).

Methods

Various active tests and video systems are used for analysis and diagnosis of vestibular functions [6]. Most tests include force movement of the patient's body or head. The technology of vibraimaging for testing vestibular functions determines real-time trajectory of each point of patient head in natural equilibrium with maximum accuracy. Virtually any movement of the human body is controlled by the sensory system. Vestibular cor-

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rection is not an exception to this rule. Bernshtein studied time component of these processes [1, 7]. Time constant of these processes (0.1 sec) makes it possible to use low-frequency video cameras (frame rate, 10-20 Hz) for increasing accuracy of micromovement monitoring.

Basic specifications of these video cameras are:

– resolution, elements: 640 × 480;
– frequency, frame/sec: 15.0;
– dynamic range, dB, no less than: 80;
– object working illuminance, lx, no less than: 100;
– objective angle, deg: 10;
– distance to object, m: 3;
– distance to computer, m, no more than: 5;
– digital signal interface: USB 1.0, 2.0;
– climate adaptation: UHL2;
– power line voltage (USB), V: 5.

Video-to-vibraimage conversion provides real-time determination of integral and local parameters of human head movement associated with functional state of the human body. Initial matrices for integral parameter calculation are represented by amplitude and frequency vibraimages calculated from equations derived in [4].

The amplitude component of each point of the vibraimage is calculated from:

$$A_{x,y} = \frac{1}{N}\sum_{i=1}^{N}\left|U_{x,y,i} - U_{x,y,(i+1)}\right|, \qquad (1)$$

where x, y are coordinates of point; $U_{x,y,i}$ is signal amplitude at points x, y in i-th frame; $U_{x,y(i+1)}$ is signal amplitude at points x, y in $(i + 1)$-th frame; N is number of frames for averaging amplitude component of vibraimage.

Frequency component of each point of vibraimage is calculated from:

$$F_{x,y} = \frac{F_{in}}{N}\sum_{i=1}^{N}\begin{cases}\left|U_{x,y,i} - U_{x,y,(i+1)}\right| > 0:1\\ \text{otherwise: } 0\end{cases}, \qquad (2)$$

where F_{in} is processing frequency of video image.

To obtain a clear vibraimage, the patient's face should be uniformly illuminated and located in front of the video camera [4]. Patient-to-camera distance depends on objective parameters. The patient's head should be accommodated to the camera raster. This provides maximum resolution of the video camera for minimal vibrations and movements.

The modern digital video camera is a highly accurate metering instrument. This instrument allows parameters of human body micromovements to be determined provided that necessary recommendations are observed and necessary software is used.

Results

The studies of the human body functional state were directed toward elucidation of emotional state [3]. The algorithms of determination of emotional state are based on mathematical statistic apparatus [8], principles of movement coordination, behavioral psychology logic, and comparative tests. Vibraimage with frequency scale is shown in Fig. 1a. Thermal image is the closest physical analog of vibraimage. Thermal image of the human body with a pseudocolor temperature scale is shown in Fig. 1b.

Amplitude and Frequency Vibraimages

Amplitude and frequency parameters of human head vibrations are determined at each point and displayed on a monitor screen as a pseudocolor image. Integral processing of vibration parameters at each point provides general information about human body mobility. Vibraimages of the human head calculated from Eqs. (1) and (2) are shown in Fig. 2a and 2b, respectively.

Each point (pixel) of amplitude vibraimage (Fig. 2a) represents relative object displacement within a certain time interval (at insignificant displacement of inter-frame

a b

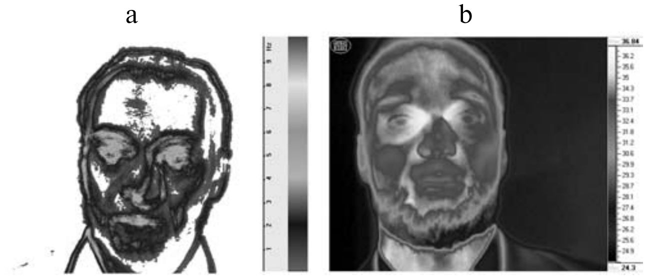

Fig. 1. Vibraimage with frequency scale (a); thermal image with temperature scale (b).

a b

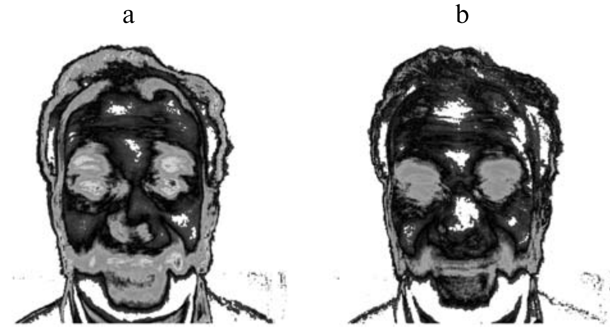

Fig. 2. Vibraimages of the human head representing amplitude (a) and frequency (b) vibration distribution.

difference this is proportional to object movement [9]). Distance to object and camera objective working angle should be known to convert relative object displacement into absolute object displacement. Then, pseudocolor scale can be graduated in mm or μm. However, uniform relative scale is automatically set at similar positions of the human head on monitor screen. Therefore, information obtained for different persons can be comparatively processed.

In contrast to amplitude vibraimage, dimension of each point of frequency vibraimage is frequency dimension (Hz). Violet color of frequency vibraimage represents vibration range 0-1 Hz. Blue color of frequency vibraimage represents vibration range 0-4 Hz. Green color of frequency vibraimage represents vibration range 4-8 Hz. Red color of frequency vibraimage represents vibration range 8-10 Hz.

Two similar primary images (matrices 640 × 480 × 8) allow more than 20 integral parameters of the vibraimage to be determined. These parameters have minimal mutual correlation and fall into four groups of vibraimage parameters: amplitude, frequency, symmetry, and vibration processing [3].

The information value of the primary vibraimages can be increased using special software Vibraimage [10]. The software provides real-time conversion of amplitude and frequency vibraimages into external vibraimage of the patient's face. The color of the external vibraimage represents maximal signal line frequency. The size of the external vibraimage represents mean signal line amplitude. Resulting external vibraimage provides information about frequency and amplitude components of the vibraimage. This information increases the probability of correct diagnosis of functional state of the human body.

In addition to visual evaluation of vibraimage, the Vibraimage software provides real-time viewing of histograms of vibraimage amplitude and frequency as well as vibraimage spectra.

Frequency Histogram

The frequency histogram demonstrates distribution of movement frequency at any point within a certain time interval (by default, 10 sec). Actual frequency histograms at various psychophysiological states are shown in Figs. 3a and 3b.

Bottom curves are close to normal (Gaussian) distribution; bottom curves represent normal psychophysiological state of the patient. Top curves (bimodal and exponential frequency distribution) represent psychophysiological pathology. Mathematical expectation of distribution curve is shifted along the horizontal axis (frequency) depending on emotional state and fatigue. Minimal distribution amplitude is observed in the state of fatigue and rest. The histogram is shifted toward a higher frequency in the state of excitation and pain. If mathematical expectation of distribution curve depends on psychophysiological state of the patient, the distribution curve shape would depend on physiological factors.

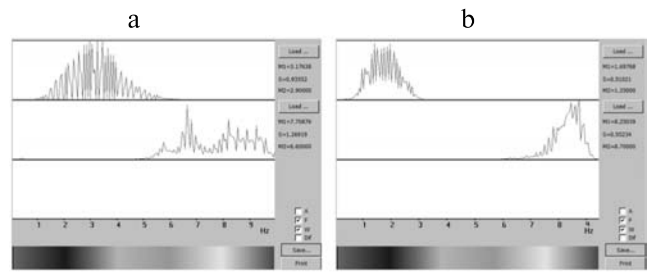

Fig. 3. Histogram (program window) of vibration frequency distribution in the human body in normal psychophysiological state (a, top curve) and pathological psychophysiological state (a, bottom curve); patient with strong tooth pain. Bottom curve (b) measured in patient with high temperature 38.5°C and symptoms of influenza; top curve (b) measured in patient with low temperature 35.5°C after outbreak of influenza.

Each distribution curve (frequency histogram) is determined by the following mathematical characteristics: mathematical expectation M1 (arithmetic mean over distribution curve); mean-square deviation S (MSD) is a characteristic of distribution curve width; frequency of distribution curve maximum M2. It follows from Fig. 3 that mathematical characteristics of distribution curve depend on patient state. Distribution curve can be described using new informative mathematical characteristics.

Spectral Analysis

Spectral analysis of high-speed vibraimage signals (analysis of frame-to-frame difference using neighboring frames) demonstrates psychophysiological characteristics of patient. The spectrum of high-frequency vibraimage (amplitude and frequency) is measured using real-time fast Fourier transform (FFT).

The amplitude of the low-frequency component of vibration spectrum in a patient in normal psychophysiological state is several times larger than in a patient in alarm-aggressive state or in state of physiological pathology. The spectrum of vibraimage signal (program window) of a patient in normal state (top curve) and in anxiety state (bottom curve) is shown in Fig. 4.

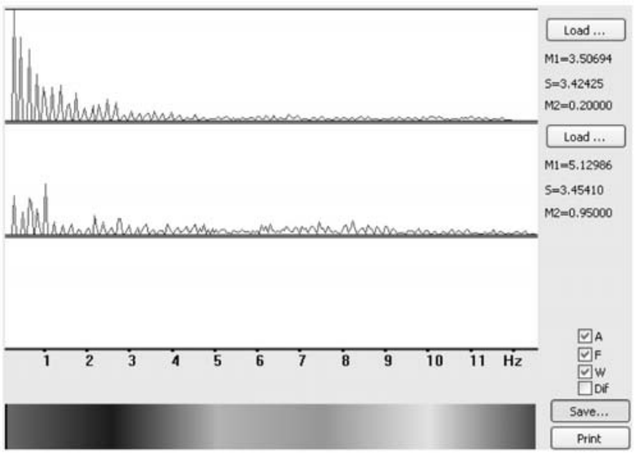

Fig. 4. Spectrum of vibraimage signal (program window) of patient in normal state (top curve) and in anxiety state (bottom curve).

It follows from Fig. 4 that the vibration frequency spectrum of patient in quiet state can be approximated with an exponential curve, whereas vibration frequency spectrum of patient in pathological psychophysiological state can be approximated with more elaborate combination of distribution curves.

Discussion

Vibraimaging is used in security systems for detecting potentially dangerous passengers in aviation and airports. Automatic vibraimaging system determines the level of aggression, stress, and anxiety of people within 10 sec of observation. The resulting signal of potentially aggressive or dangerous person is transmitted to security service (profiler). Preliminary testing in Pulkovo-2 airport (St. Petersburg) demonstrated that, according to VIPK MVD of Russian Federation method, the probability of erroneous detection of potentially dangerous passengers was 8% [11].

Kinetic principles declare that movement coordination depends on emotional state and physiological state [12]. The pathology origin is difficult to diagnose. The solution of most primary problems is not required in security systems. People in abnormal states should be detected for further more careful investigation. Similar principles are used in medicine. Early diagnosis of most diseases is important for successful therapy. Body temperature is a common diagnostic parameter. Body temperature increases in most diseases (often, too late for effective therapy). The human vestibular system receives information from virtually all parts of body. This information is used to support human body balance, and any significant signal disturbs the balance. Parameters of human head micromobility (frequency) in addition to body temperature and HR, are essential indicators of human health. Thermoregulation is an integral parameter. Significant changes are required to modify human body temperature. Heart functions are determined by many factors. It is fairly improbable that HR and cardiac rhythm are modified at early disease stages. In contrast to HR and cardiac rhythm, vestibular system reaction is detectable at early disease stages.

Simple use of vibraimaging system makes it a health state indicator. Any computer user can use this indicator. In this case computer user should have computer, application software, and an inexpensive WEB camera. Vibraimaging system can also be used in professional monitoring for early disease diagnosis. Vibraimaging system can be used for diagnosing vestibular dysfunctions, mental diseases, and various functional pathology of central nervous system. Preliminary testing revealed efficacy of the system in early diagnosis of Alzheimer's disease, Parkinson's disease, and multiple sclerosis.

Conclusions

Vibraimaging technology provides quantitative information about periodic movements of any point of the object, thereby providing functional and physiological diagnosis, which is very promising. Simple use of vibraimaging system makes it possible to perform extended clinical testing of vestibular emotional reflex without huge material expenses. In spite of promising theoretical implications, medical diagnostic applications of vibraimaging system can be implemented after standard clinical tests.

It is important to discuss information value of human body mobility, because prominent researchers have studied this problem at length. Modern technological progress allows quantitative information about human body mobility to be converted into adequate health diagnosis.

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