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Eliminating pain-induced risks of operator reliability via transcutaneous electroneurostimulation controlled by Patient's breathing

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ABSTRACT

The negative aspect of interactions in the man-machine systems is the formation of professional pain syndromes and musculoskeletal disorders that reduce the reliability of human operator and require prompt treatment. The paper analyzes the possibility of using the positive aspect of bidirectional human-machine interaction for such treatment. In particular, the approach to analgesic electroneurostimulation is proposed in which the interaction between the patient and the medical device is mediated through feedback signals from the patient's breathing rate. It provides automatic control of the parameters of the stimulating current in accordance with own physiological rhythm of the patient. Positive results of pilot testing of the technology in the conditions close to clinical are presented.

1. Introduction

One of the most important directions of modern human factors research is the problem of human operator reliability. It includes at least three aspects: personal, professional and functional reliability of specialist (Kruk, 2015). Functional specialist reliability is related to the risks of operator's failure as a result of illness, fatigue, drowsiness, stress, etc. and is actively investigated in the recent years. For example, it was established that in most human-machine systems the reliability and vigilance of human operator requires hard mental work and could induce stress states (Warm et al., 2008). Significant manifestations of the fatigue have been observed in servicemen-operators as a result of daily shift-work (Kalnish and Shvets, 2012). In cold and harsh conditions the cognitive performance of operator is the key factor of human error probabilities and associated risks (Noroozi et al., 2014).

Among various factors that have a negative impact on the functional reliability of the human operator, professional pain syndromes and musculoskeletal disorder risks acquire special attention in the last years (Oakman et al., 2016). Work-related musculoskeletal disorders among office workers with intensive computer use is widespread and the prevalence of symptoms is growing (Robertson et al., 2013). It is known that the operators of various technical devices and keyboards, computer programmers and car drivers often suffer from functional pain symptoms in the hands or neck reflecting the formation of musculoskeletal disorder (Yakhno and Kukushkin, 2012). Musculoskeletal disorders represent one of the leading causes of lost workdays in industry and are associated with major economic costs (Gallagher and Heberger, 2013). Workplace upper extremity musculoskeletal disorders are associated with repetitive and forceful exertions, high repetition, awkward postures, localized mechanical stress, and highly dynamic movements (Fan et al., 2014). As a result of pinching of the nerve endings there are pains in the arms and neck, swelling, numbness and violation of fine motor skill in the hand to the extent that an operator cannot pick up a cup, comb own hair, or subscribe to the document. Therefore, it is highly important to timely correct functional pain syndromes before they can progress to a sharp deterioration in the quality of life and the need for operator to change job.

To reduce acute pain, the most advanced and popular is the method of transcutaneous electrical nerve stimulation – TENS (Johnson et al., 2015). TENS is a non-pharmacological intervention that activates a complex neuronal network to reduce pain by activating descending inhibitory systems in the central nervous system (Vance et al., 2014). Among the obvious advantages of TENS there are its non-invasiveness, ease of use, portability of devices implementing the method, and the ability to use them to reduce the pain of various origins (Nizard et al., 2012). However, the effectiveness of existing TENS methods is limited by the phenomenon of habituation, in which the brain filters out constantly repeated stimulus (Johnson, 2014). As a result, during TENS treatments the user has to constantly increase the intensity of the electrical pulses, which entails damage to the skin and other negative

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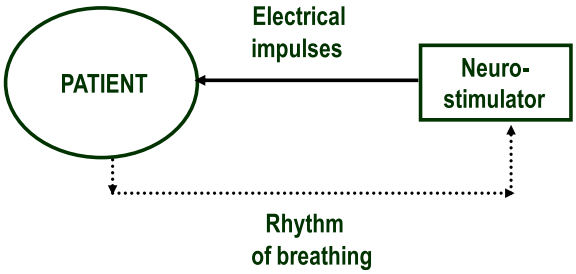

Fig. 1. Key elements of electroneurostimulation, controlled by patient's breathing rate.

consequences (Gladwell et al., 2016). Although numerous attempts to overcome habituation by varying one or more stimulation parameters have been made, the efficiency of available TENS methods remains questionable (DeSantana et al., 2008).

The described problem of habituation could be solved through the use of positive aspect of forward and backward interactions in the man-machine system. In particular, it seems promising to organize the interaction between the patient and the TENS device, where the feedback signals from patient's own endogenous rhythms will be used (Fedotchev et al., 2006). For example, automatic control of the parameters of stimulation via feedback signals from the patient's breathing is assumed to overcome habituation and to increase excitability of relevant brain structures under TENS (Fig. 1).

The objective of this study is technical implementation and pilot testing of treatment procedures to eliminate the risk of functional specialist reliability caused by pain via electroneurostimulation controlled by feedback signals from patient's breathing. For this aim, a working prototype of breathing-controlled TENS device for pain relief has been developed and tested in conditions close to clinical. The results of this pilot study are presented below.

2. Method

2.1. Overview

The study was conducted in two stages. The first stage included the development and testing of the device, which provides control of electrical impulses by patient's breathing rate. With this aim, a sensitive resistive respiration sensor fixed on subject's chest with self-adhering belt for monitoring respiration rate, waveform and amplitude has been developed. The sensor has been included into output circuit of serial transcutaneous electroneurostimulator "ETNS-100-01" (Russia) to provide automatic control of the amplitude of electrical impulses by patient's breathing rate. The amplitude of electrical impulses was maximal during inhalation and minimal during exhalation.

Preliminary testing of the device was held in a series of ascertaining experiments with experimentally induced risks of functional specialist reliability and their correction by electrostimulation, including necessary control condition (TENS without feedback). Students and post-graduates from Bauman Moscow State Technical University voluntarily participated in this stage. For the induction of specialist reliability risk, the task was used to click on computer keys at a maximum rate until to failure due to the emergence of pain in the hand and the increasing number of stray keystrokes. Immediately after subject's failure to continue the task, breathing-controlled TENS or control procedure (TENS without feedback) were carried out in random order. It was found that the degree of pain reduction was significantly higher after experimental procedures (breathing-controlled TENS) than after control procedures (TENS without feedback).

Results of the first stage were used in the second step of research, which attempted the experimental testing of the breathing-controlled TENS in the real conditions of specialist reliability risks.

2.2. Participants

The study involved 11 patients of clinic (3 females and 8 males aged from 34 to 60 years). There were professionals of highly responsible and high-tech kinds of activity, including 3 programmers, 5 PC operators and 3 drivers of passenger buses. They complained by professional pain syndromes (stress headaches, 4 cases, neck pain, 4 cases, and pain in the wrist, 3 cases) and gave informed consent to participate in the procedures of physiological state correction via electroneurostimulation controlled by the rhythm of their own breathing.

2.3. Materials and equipment

2.3.1. Background questionnaire

Initial level of pain has been evaluated for each patient using a standard test of subjective self-assessment of pain sensations on a 10-point scale (Brugnoli et al., 2005). Furthermore, the initial psychological testing was conducted by the test "SAN" (Doskin et al., 1973). This test allows subject to self-assess own current values of health, activity and mood. The test was carried out by marking on the proposed form the points from 1 to 7 in 30 presentations, 10 for each of three scales. The amounts of points for each scale were the indicators of health, activity and mood.

2.3.2. Background registration of physiological data

Recorded electrophysiological signals were amplified by a multichannel amplifier « Brainsys» (Hardsoft, Moscow) and digitized with a sampling frequency of 128 Hz. Monopolar EEG was recorded from left occipital lead (point O1 by international system 10–20%) with a combined ear reference. The filters were set on the upper cutoff frequency of 70 Hz and the time constant of 0.3 s. Specially designed modification of dynamic spectral analysis was used for EEG processing (Fedotchev et al., 2000). Simultaneously with EEG the electrophysiological reactions - electromyogram (EMG) of facial muscles, galvanic skin response (GSR) from the right hand and respiration pattern have been registered and processed.

2.3.3. Stimulation

Serial transcutaneous electroneurostimulator "ETNS-100-01" (Russia) with electrical pulses at a frequency of 4 Hz and a maximum intensity of 10 mA was used. The amplitude of electrical pulses was automatically modulated by own respiration rhythm of the patient within 0.1–10 mA through inclusion of feedback signals from the perimeter resistive respiration sensor fixed on the subject's chest to stimulator output circuit. The deeper was subject's inhalation, the more intensive was stimulation.

2.4. Procedure

After the initial psychological testing, subjects were installed with sensors for recording electrographic responses, as well as breath sensor and stimulating electrodes located near the source of maximal pain sensations. Then a 2-min recording of background electrographic responses (EEG, EMG, GSR and respiration pattern) has been made. After baseline recording, electrical stimulation was performed for 15 min. After stimulation, electrographic reactions have been repeatedly recorded. At the end of each experiment, repeated psychological testing and re-evaluation of pain level have been made.

2.5. Data analysis

Statistical data processing was performed using the statistical package « Origin 6.0». Average values (M), standard errors (m) and Student's t values have been used to determine the P levels.