Evaluation of the Impact of the Ergonomics of Technical Systems on the State of Health of a Human Operator with Regard to His Functional Reserve

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Abstract. The paper studies the impact of the ergonomics of technical systems on the emergence and development of occupational diseases of a human operator, taking into account the functional reserve of his body. In view of the complexity of the analytical description of the interaction mechanisms of the human-technical system, a methodology for the synthesis of hybrid fuzzy decision rules, focused on solving poorly formalized problems, was chosen as the mathematical apparatus of research.

Keywords: Ergonomics · Functional reserve · Health status · Membership functions · Fuzzy logic

1 Introduction

Numerous studies of scientists from different countries of the world show that the quality of work of biotechnical systems of various types and purposes largely depends on the ergonomics of technical systems that are in contact with a human operator. The indicators characterizing the ergonomics of technical systems have a significant impact on the functional state and human health. It has been established that long-term contact of a human operator with technical systems that do not have well thought out ergonomics leads to the emergence and development of professional socially significant diseases of the cardiovascular, respiratory, nervous and urinary systems, musculoskeletal system, etc. Reducing the negative factors affecting the health of people from their contact with technical systems is one of the main tasks of ergonomics.

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A lot of work has been devoted to studying the influence of technical systems and industrial facilities on people's health [1–7]. Analysis of numerous works in the field of ergonomics shows that the majority of researchers spend significant efforts on studying the mutual influence of specific technical systems and working conditions on specific types of diseases, and the results obtained are rather difficult and sometimes impossible to transfer to objects of other nature. That is, the whole complex of research, including the choice of an adequate mathematical apparatus when switching to another object of research, should be repeated almost completely without guarantee of obtaining positive results. From a mathematical point of view, the creation of a unified approach to the study of the influence of technical systems of various types and purposes on the emergence and development of various types of diseases is hampered by the fact that the ergonomic properties of the systems under study and indicators describing the functional state and health of a human operator are described by a heterogeneous system of signs, often the information is incomplete and fuzzy, and the classes used for the state of human health have a complex, poorly formalizable and strongly intersecting structure of classes [1, 4–16]. Under these conditions, as shown by numerous studies, it is advisable to use fuzzy logic of decision-making [8, 10–12, 15–19, 20]. In works [1, 2, 4–7] was shown that good practical results, when solving problems of assessing the impact of ergonomic technical systems on the functional state and health of a person, can be achieved using the synthesis methodology of hybrid fuzzy decision rules developed at the Department of Biomedical Engineering of South-West State University (Russian Federation) [8, 11, 12, 21, 22].

2 Methods

In works [1–7] was described the methods of synthesis of fuzzy rules for deciding the functional state and state of human health, taking into account the fact that one of the leading risk factors is the level of ergonomics of technical systems.

In general, view a fuzzy mathematical model of decision-making is described by the expression:

$$UPF_\ell = F_\ell(UPE_\ell, UPI_\ell, UPEK_\ell), \tag{1}$$

where UPF_ℓ - confidence in the decision on the class of the state of the human operator ω_ℓ; UPE_ℓ - confidence in the class ω_ℓ on group of ergonomic indicators; UPI_ℓ - on individual risk factors; $UPEK_\ell$ - on environmental risk factors; F_ℓ - aggregation function.

If each of the particular decision rules UPE_ℓ, UPI_ℓ and $UPEK_\ell$ increases the risk in the transition of a human operator to a class of states ω_ℓ, then the decisive rule (1) is modified into E. Shortliff storage system [8, 11, 12, 21]:

$$UPF_\ell(q+1) = UPF_\ell(q) + Q_{q+1}[1 - UPF(q)], \tag{2}$$

Where–iteration number; $UPF_\ell(1) = Q_1 = UPE_\ell$; $Q_2 = UPI_\ell$; $Q_3 = UPEK_\ell$.

Considering that the mechanisms for obtaining private decision rules and the choice of their aggregation method are described in detail in [1, 7–13, 15, 17–20], we will dwell in more detail on the method of assessing the level of functional reserve of the human body. From the physiological point of view the experts cannot exactly define the concepts value and a level of functional reserve. Many experts compare these concepts to the balance of an organism to environment, its readiness to work, to resist to the external adverse factors and etc. Taking into account the indistinct nature of "functional reserve" concept and its possible classification the theory of fuzzy logic of decision-making was selected as the main mathematical device. We selected two ways from this theory. The way based on the usage of accessory function to studied classes of a state ω_l the construction mechanism of which was described in L. Zadeh papers [15], and the way using the confidence coefficient in the hypothesis ω_l the receiving and calculation mechanism of which was suggested by Shortliff [13] and their modification [21, 22]. As initial signs defining the classification and the level of functional reserve (FR) of an organism and its subsystems the power characteristics of meridian structures being changed at level changes of FR [23–25]; the level of psycho emotional pressure (PEP); the level of physical exhaustion (LPE); the level of intellectual exhaustion (LIE); pulse rate (PR); the value of systolic arterial pressure (SAP) and diastolic arterial pressure (DAP) were selected on the expert level [27–29].

The medico-technical capabilities and the features of solved tasks can expand this list.

According to the recommendations [30] the selected (or other reasonably imposed) features xi, defined during the measurement or calculated with the help of appropriate methods, are determined before and after dosed physical and/or intellectual loadings. After that the ration of the measured index before loading (x_{i_0}) to the meaning of the same index measured after load test (x_{i_H}) are defined:

$$Y_i = \frac{x_{i_0}}{x_{i_H}} \tag{3}$$

The obtained indices Yi can be used as basic variables of an accessory function to different classes characterizing functional reserve of an organism and/or its subsystems. For example, the following classes characterizing FR of an organism can be selected:

ω_0 is an optimal functional reserve of a healthy person allowing normally and reliably function at reasonably raised loadings;

ω_1 is a satisfactory functional reserve allowing normally function at usual conditions without considerable loadings;

ω_2 is an unsatisfactory functional reserve at which the risk of emergence and disease developments and/or unforeseen failures at work because of lack of reserve opportunities of an organism are high.

The example is shown on the Fig. 1, where the graphs of accessory functions to the selected classes of FR with the base variable Yi are shown.

The value $\mu^m_{\omega_l} \leq 1,0$ limited the maximum meaning of the accessory function describes the experts' point of view that how reliable the index Y_i at the classification of FR can be. If the experts believe that the selected index reliably characterizes such a concept functional reserve of an organism, then $\mu^m_{\omega_l} = 1,0$.

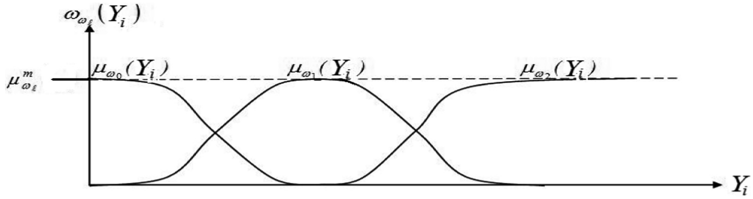

Fig. 1. The variants of distribution of an accessory function by the classes ω_l ($l = 0, 1, 2$ with the basic variable Y_i

In practical applications, a few indices defined from the ration (1) are used to estimate functional reserve and its classification. The confidence proportion at the given classification using one index can be small. If it happens, the task of reaching such certain (for each of used indices Y_i) accessory functions and ways of their aggregation which allow to get an acceptable quality of classifications for practice.

If the choice of indices and corresponding accessory functions is supplied in such a way that the usage of each does not reduce confidence in the accepted decision of the classification of FR, according to the recommendations [8, 12, 14, 29] the common confidence of studied hypothesizes ω_l can be defined by the Shortliff "accumulative" iterative expression:

$$\mathrm{QU\omega l(i+1) = \ QU\omega l\ (i) + \mu\omega l\ (Y * i + 1)[1 -\ QU\omega l\ (i)]}, \tag{4}$$

Where QUωl (i) is a confidence coefficient in the classification ω_l ($l = 0, 1, 2$) after i of Yi indices was analyzed; μωl (Y*i+1) is the value of an accessory function calculated for the basic variable with i+1 at the point Y*;QUωl (1) = μωl (Y*1).

Among the allocated classes of states and their corresponding accessory functions, the class of optimal functional reserve with the accessory function $\mu_{\omega_0}(Y_i)$ is of great interest. Let us select this accessory function in such a way that the more the meaning of Y_i lags behind the coordinate meaning of Y_{i_0} according to the experts' point of view corresponding to the concept optimal functional reserve, the smaller $\mu_{\omega_0}(Y_i)$ and the smaller the level of this reserve. Thus, the value $\mu_{\omega_0}(Y_i)$ can characterize the level of functional reserve of an organism. The $\mu_{\omega_0}(Y_i)$ accessory function made for the solution of classified tasks can match with the $\mu_U(Y_i)$ accessory function made for level determination of functional reserve but cannot match with it. If a few indices are used for level assessment of FR each of them allows to make a positive investment at level assessment of studied subsystems and the whole organism function, then as (4), the integrated levels of FR can be assessed by:

$$\mathrm{UF(i+1) = UF(i)} + \mu_{\omega_0}(Y*_{i+1})[1 - \mathrm{UF(i)}]; \tag{5}$$

$$\mathrm{UF(i+1) = UF(i)} + \mu_U(Y*_{i+1})[1 - \mathrm{UF(i)}]; \tag{6}$$

Where UF(i) is a level of functional reserve defined after adding i indices to the calculations: $\mu_{\omega_0}(Y*_{i+1})$ is a value of an accessory function to the ω_0 class. By the index with i+1 defined in the Y* point at the conditions that the classification of an accessory function to the ω_0 class used for the level assessment of FR; $\mu_U(Y*_{i+1})$ is an accessory function to the ω_0 class on purpose defined for the level assessment by the experts. The main characteristic of expressions (5) and (6) is their accumulative property consisting of that at every input to the calculations of each used indices Yi the increase of settlement level of FR is provided. In practice, such mechanism of level calculation of FR is not always acceptable. There is a possible variant of such an expert conclusion when the violation in functioning of one of the subsystems leads to the violation in functioning of the whole system and subsystems of higher level, then the level assessment of FR by the combined calculated parameters Yi characterizing the level of FR of subsystem with i should be carried out according to the following ration:

$$UF = \min_i(\mu_{\omega_0}(Y_\mathrm{i})) \tag{7}$$

$$UF = \min_i(\mu_U(Y_\mathrm{i})) \tag{8}$$

The conduct analysis of the original features at parameter determination Yi (exp. 1) shows that at carrying out load tests at first the change of xi takes place from xi0 to xih, and then the current meaning of xi with different speed (depending on the level of FR) heads to return to the meaning xi0. This tendency at the conduct of xi allowed the experts to come to the conclusion it is wise to include not only the ration (1) to the level calculation of FR, but also the indices of return dynamics of xi to xi0. In the given work paper the dynamic record of xi at level determination of FR is suggested to carry out by the input of two illegible corrections to $\mu_{\omega_0}(Y_i)$ or $\mu_U(Y_i)$ increasing the assessment precision of the studied level. To obtain the illegible corrections let us input two extra indices: thi is a supervision time, tbi is a return time of xito xi0 after load test. Supervision time is derived from reasonable restrictions on research time.

To obtain the illegible corrections for each parameter of Yi let us define the accessory function to the concepts of the maximum corrections of the chosen basic variable. As the first basic variable let us choose return time of xi to xi0, if tbi<thi. As the second basic variable Ci it is necessary to choose the value of difference size between xi and xi0, if tbi>thi . Taking into account that for different parameter types the meaning of xi can be as bigger as less of xi0, the size of the basic variable Cican be defined from the rations:

$$C_i = \begin{cases} \mathrm{x_{i0}} - \mathrm{x_i}, & \text{if} \quad \mathrm{x_{i0}} \geq \mathrm{x_i} \\ \mathrm{x}_i - \mathrm{x_{i0}}, & \text{if} \quad \mathrm{x_{i0}} < \mathrm{x_i} \end{cases} \tag{9}$$

The maximum meaning of μ_{1i}^m and μ_{2i}^m of the entered accessory functions of the first and the second basic variables will be defined as an experts' point of view of what maximum meaning the levels of FR defined by the accessory function of $\mu_{\omega_0}(Y_i)$ or $\mu_U(Y_i)$ can have if return dynamic of xi to xi0 is taken into account.

If creating the accessory function to the meaning of the maximum corrections of the basic variables of tbi ($\mu_P(t_{\mathrm{bi}})$) and Ci($\mu_P(C_i)$) the additional conditions are done, their current meaning reflects the experts' images about the current corrections to $\mu_{\omega_0}(Y_i)$ or $\mu_U(Y_i)$, then the accessory function defining the level of functional reserve by Yi parameter can be corrected by the ration of algebraic sum:

$$\mu \overset{*}{U}(Y_i) = \begin{cases} \mu_U(Y_i) + \mu_P(t_{bi}) - \mu_U(Y_i) \cdot \mu_P(t_{bi}), & if\ t_b \le t_h \\ \mu_U(Y_i) + \mu_P(C_i) - \mu_U(Y_i) \cdot \mu_P(C_i), & if\ t_b > t_h \end{cases} \quad (10)$$

The accessory function of $\mu_{\omega_0}(Y_i)$ is corrected the same way.

Considering that a high level of functional reserve prevents the emergence and development of the state ω_l, the UF indicator should be considered as a measure of mistrust to the classification ω_l [12–14]. Since the level of functional reserve for different classes of state ω_l affects this state differently and, basically, is nonlinear, we introduce the concept of the function of belonging to the concept of a high level of protection in a class ω_l with a basic variable UF − $\mu_{Z\ell}(UF)$.

Taking into account $\mu_{Z\ell}(UF)$ the certainty UW_ℓ that the subject is in class ω_l in accordance with the recommendations [4, 5, 12, 13] is determined by the expression:

$$UW_\ell = \begin{cases} UPE_\ell - \mu_{Z\ell}(UF),\ if\ UPE_\ell > \mu_{Z\ell}(UF); \\ 0,\ if\ UPE_\ell \le \mu_{Z\ell}(UF). \end{cases} \quad (11)$$

3 Results

As a specific example the Problem of the Mathematical Model prediction synthesis nervous system diseases provoked ergonomics Russian manufacture tractor according to individual risk factors and the functional reserve of the organism. The primary features used to assess the level of ergonomics of the tractor cab at the expert level were: temperature in the cab (x1); cabin noise level (x2); the average level of load on the hands (x3); the average level of load on the legs (x4), vibration of the whole body (x5), vibration on the hands (x6), vibration on the legs (x7), angle of inclination of the seat (x8), seat height (x9), distance to the main controls (x10); the level of psycho-emotional stress associated with professional activity (x11) and the level of chronic physical fatigue (x_{12}) [1, 2, 7, 31, 32]. The signs x_{11} and x_{12} characterize the individual properties of a person, but since they "strongly depend" on the level of ergonomics of technical systems with which the operator contacts, they can indirectly characterize the level of ergonomics. Therefore, experts in the appropriate block of signs of ergonomics included these signs.

For the construction of private functions of the level of ergonomics on the signs x_1, …, x_{10}, two approaches were chosen: the method of psychophysical scaling and the construction of specialized test questionnaires.

Signs x_1, …, x_{10} are measured using appropriate technical means and computer questionnaires.

Levels of psycho emotional stress x_{11} and fatigue x_{12} are determined by the methods described in [12, 23, 19, 32].

In accordance with the general methodology for the synthesis of hybrid fuzzy decision rules in conditions of poor formalization, it is advisable to use the interactive package RUMM 2020, the use of which is described in [8, 12] in conditions of poor formalization.

In the course of evaluating the information content, six informative features x_2, x_5, x_6, x_7, x_{11} and x_{12} were selected from the entire set of features describing the tractor cabin ergonomics for the task of predicting the onset of nervous diseases.

1. The sign x_2 was measured with an electronic device in decibels. For a quantitative assessment of signs x_5, x_6 and x_7, a specially designed questionnaire with a point estimate was used.
2. Working conditions are not connected with vibration $x_5 = 0$.
3. Working conditions are associated with low-intensity physically poorly perceptible vibration without causing physical discomfort $x_5 = 1$.
4. Working conditions are associated with noticeable tangible vibration without causing physical discomfort $x_5 = 2$.
5. Working conditions are associated with a well-perceptible vibration causing some physical discomfort by the end of the day, but over time there is a feeling that the discomfort "does not accumulate" $x_5 = 3$.
6. Working conditions are associated with significant vibration, which causes pain to the end of the work shift and with significant work experience (over 25 years) leads to pathological changes $x_5 = 3$.

Using these characteristics as basic variables in accordance with the recommendations [12, 13, 19, 23], the membership functions $\mu_H(x_2)$, $\mu_H(x_5)$, $\mu_H(x_6)$, $\mu_H(x_7)$, $\mu_H(x_{11})$ and $\mu_H(x_{12})$ were constructed to class ω_H "high risk of diseases of the nervous system."

In accordance with the recommendations [8, 10, 12, 16–18], a fuzzy model was built to predict the occurrence and development of nervous diseases from human contact with a machine (tractor):

$$UPF_H^*(p+1) = UPF_H^*(p) + \mu_H\left(x_{j+1}^*\right)\left[1 - UPF_H^*(p)\right], \quad (12)$$

Where $UPF_H^*(1) = \mu_H^*(x_2)$; $x_2^* = x_5$; $x_3^* = x_6$; $x_4^* = x_7$; $x_5^* = x_{11}$; $x_6^* = x_{12}$;; j = 1, 2, …,5.

Considering that a significant risk factor for the class of risk of the onset and development of diseases of the nervous system is the work experience, taking into account the recommendations [2, 4, 5, 12, 13], was obtained the function of time accounting $\gamma_{E_H}\left(t_p\right)$ with basic variable t_p – work experience.

Confidence in the appearance and development of nervous diseases from contact with a tractor for expressions (1) and (2) with due regard for recommendations [4, 5, 12, 33] and work experience is determined by the expression:

$$UPF_H = \gamma_{EH}\left(t_p\right) \cdot UPF_H^*, \tag{13}$$

For the indicator UPI_H of expressions (1) and (2), at the expert level, the following composition of informative features was determined; medications that have a harmful effect on the nervous system; alcohol intake; diseases of the nervous system in close relatives; imbalance of the energy characteristics of the meridian biologically active points (BAP) associated with the situation of the disease of the nervous system (points P9, G5, V43, V60, R9, VC7).

In accordance with the recommendations [8–10, 12, 13], a predictive model of the form was synthesized for this group of characters:

$$UPI_H(q+1) = UPI_H(q) + R(q+1)[1 - UPI_H(q)], \tag{14}$$

where $UPI_H(1) = \mu_H(L_s)$; $R(2) = \mu_H(AL)$; $R(3) = \mu_H(Br)$; $R(4) = UB_H$; Ls – a sign describing the conditions for taking medicines; AL – alcohol consumption; Br – diseases of the nervous system in close relatives; UB_H – confidence in the appearance and development of diseases of the nervous system, determined by the energy characteristics of the BAP in accordance with the recommendations [23–27].

Considering the fact that the studies were conducted in a relatively clean ecological region of the Kursk region (Russia), the component $UPEK_l$ for expressions (1) and (2) was not determined.

When assessing the level of functional reserve by the method described in the work using expression (5), the membership function $\mu_{ZH}(UF)$ is:

$$\mu_{ZH}(UF) = \begin{cases} 0, \ if\ UF < 0,1 \\ 1,28\, UF \ - \ 0,13, \ if\ 0,1 \le UF < 0,8 \\ 0,9, \ if\ UF \ge 0,8 \end{cases}. \tag{15}$$

In the course of the conducted clinical trials on control representative samples according to the method described in [4, 5, 12], it was shown that the number of erroneous forecasts using mathematical models of type (2) is 0,86, and using model (10) – 0,94.

Thus, the simultaneous consideration of ergonomic risk factors and functional reserves of the human body in the considered example allows to increase the quality of the forecast by 8%.

4 Conclusion

The reliability of human-machine systems is largely determined by the ergonomics of technical systems, which in the long run can lead to deterioration in the functional state and health of a human operator. Moreover, having an appropriate functional reserve, the human body can significantly reduce the harmful effect not only of technical systems with which it contacts for a long time, but also from other environmental factors (environmental factors). The paper proposes a method for the synthesis of hybrid fuzzy decision rules, which allows to take into account the influence of heterogeneous risk factors on the human body, taking into account its protective properties evaluated through a functional reserve. On a practical example (forecast of the onset and development of diseases of the nervous system) it is shown that the simultaneous consideration of ergonomic risk factors and the size of the functional reserve allows to improve the quality of decisions made about the state of health of the human body.

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