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Experimental identification of a mathematical model of human operator working under mental stress

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In engineering the human is considered as one of the system elements. In most studies, his/her model remains unchanged due to the external factors. The present study shows that a relation between the mental stress and human dynamics cannot be neglected. The dynamic characteristics of the operator model change due to external stimuli, i.e., mental stress. The aim of this study was to present identification of a mathematical human model and measurement methodology of the mental stress level. To determine the level of human response to external stimuli, the electrocardiography (ECG) and electromyography (EMG) methods were applied. The results showed difference in model parameters that cannot be neglected during the modeling of the human operator. The present study points to the need of developing simplified human models, taking into account external stimuli that have direct impact on his/her effectiveness. Some interdisplinary investigation provide may benefits combining part of the automation and ergonomics research areas.

Key words: *human operator, model, identification, EMG, ECG*

List of symbols

EMG	–	electromyography
ECG	–	electrocardiography
HRV	–	heart rate variability
$H(s)$	–	human transfer function
ζ	–	damping ratio
$1/T_w$	–	natural frequency
K	–	gain
T_z	–	lead time
T_d	–	delay time
RMS	–	root mean square
mRR	–	mean RR intervals during the sinus rhythm
SDNN	–	standard deviation of RR intervals
rMSSD	–	root – mean-square differences of successive RR intervals
pNN50	–	percentage of differences between adjacent filtered RR (NN) intervals
LF	–	low-frequency power of RR intervals (0.04 to 0.15 Hz)
HF	–	high-frequency power of RR intervals (0.15 to 0.4 Hz)
LF/HF	–	ratio of low frequency to high frequency power

1. Introduction

In spite of the fact that advanced automation and robotics become more and more common, the human still remains a crucial element in a large number of cases he/she is involved. Therefore, like in other studies [1]–[5] in the current investigation the human is considered as an element of the man-machine system. The fundamental problem in the research, from the control viewpoint, is that humans are very unpredictable elements [6]. Therefore, the knowledge of human behavior under difficult conditions is a key element in predicting the activity of a whole man –machine system. The main feature of the humans is lack of reproducibility. That main difference between humans and machines makes simulations of the man–machine system complicated. In the research [1]–[3] the impact of psychophysical aspects on parameters in human mathematical model has

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been hardly ever considered. In majority of studies the human operator is taken as an invariable element. Such an assumption clearly simplifies the model. That means that the existing models of human operators lately developed, can be improved by adding a factor corresponding to the operator's physiological state [7]. The hypothesis of the present study is that human operator is very susceptible to external stimuli. The pressure and increasing mental stress may affect effectiveness of the controlled object. To determine the operator's state during the task performance the electrocardiography (ECG) and electromyography (EMG) methods were applied [8], [12], [29]. In the wide literature [22]–[24] the biofeedback is used as a tool for operator's state assessment. There are several measurement methods, but the EKG [21], EMG [12], [30] and EEG [19], [20] are the most common. It has been proved that the human body response might be represented within the analysis of those signals. In paper [11], it has been presented that the heart rate variability (HRV) is a reaction of the human organism to external stimuli. The advantage of ECG analysis is that heart rate variability reaction is very quick. The fact that presented experiment took a short time, the ECG seems to be the most suitable measure. In paper [18] it has been proved that the human response to external stressors increases the tension in muscles. In the present study the mental stress is defined as a factor that impacts on the humans actions [28]. The mental burden is to be a parameter that should be included into a human model.

1.1. Pilot study

The presented research was proceeded by a pilot study, verifying the experiment methodology and software. The previous experiment was a simple tracking task widely used in similar investigations [25]–[27]. During the task performance no physical parameters were measured. The satisfactory results obtained from the pilot study confirmed the hypothesis that a human control effectiveness as the difficulty level of task raises. The human model identification method and software have been validated. However, the pilot study did not prove the impact of external stimuli on the operator control strategy.

2. Methods and materials

The experiment conducted was based on a simple tracking task. Using a joystick an operator was to follow the signal appearing on the screen. Such an approach is frequently used in similar investigations [9], [10]. A subject had to repeat the short task (120 sec.) twice. First task (reference task) was to track a simple pulse signal with the constant amplitude and frequency. The second task (distraction task) was similar, but the amplitude and frequency of the input signal varied. One of the assumptions taken was that the second task would affect the operator's mental state.

2.1. Study group

The study was carried out on 10 subjects, 20–27 years old. All of the subjects were male, one of them was left-handed. The subjects did not suffer any heart, muscle or postural diseases. Due to the fact that subjects were examined with the use of ECG and EMG methods, special permission from the bioethics commission was obtained. For the ECG analysis one subject was eliminated due to a very low cardiac rhythm.

2.2. Software and hardware

The study was conducted at the Central Institute for Labour Protection, National Research Institute, Warsaw, Poland. The test stand for the operator consisted of: a stable chair, a 17-inch screen, a laptop with the software (Matlab/Simulink), a joystick, ECG/EMG devices, electrodes, and headphones.

The screen on which the signal was displayed was fixed to the plane in front of the operator. On the same plane joystick was fixed, so that it could not move during the experiment. Fixing of the elements, including chair position, was necessary to maintain the same posture of subject during the reference and distraction tasks, respectively. The dedicated software written for the purpose of this study in MatLab/Simulink allowed a tracking task to be conducted with the use of joystick in real time.

2.3.1. EMG measurement

For the measurements and registration of raw EMG signal the Bagnoli-16 device was used. The EMG signal was registered using the software EMG Works 3.5. The EMG signal was sampled at a frequency of 4 kHz. The EMG signal was recorded using the surface electrodes [12]. The skin on which the electrodes were attached, had been cleaned and disinfected with alcohol. The muscle selection was made by the involvement into the hand motion, necessary for the task evaluation (Fig. 1). During the experiment the tension in the following muscles was measured: flexor carpi ulnaris (FC), trapezius (TR), bicepsc brachii (BB), deltoiudeus anterior (DA), deltoiudeus posterior (DP).

To have signals fitted to the tracking task, it was necessary to synchronize EMG signal with tracking task. Each operator after the signal appeared on the screen had to move his arm strongly forward/backward.

2.3.2. ECG measurement

To register the ECG signal the Medilog Oxford MR45 series tape recorder was used. For the ECG analysis the Oxford Medical Systems – Medilog Optima equipment was used. The device meets the requirements for the quality of HRV analysis, established by the European Society of Cardiology and the North American Society of Pacing and Electrophysiology [13]. The ECG records were analyzed using stationary analysis system. The ECG signal was recorded continuously by the "beat by beat" method, allowing information to be obtained about duration of each subsequent evolution of the heart. The real-time ECG tracking and manual recording of the task events by the supervisor, allowed in referencing the cardiovascular reaction and muscular system to specific situations during the study. Similarly as in the EMG procedure, the skin on which the electrodes were attached, had been cleaned and disinfected with alcohol.

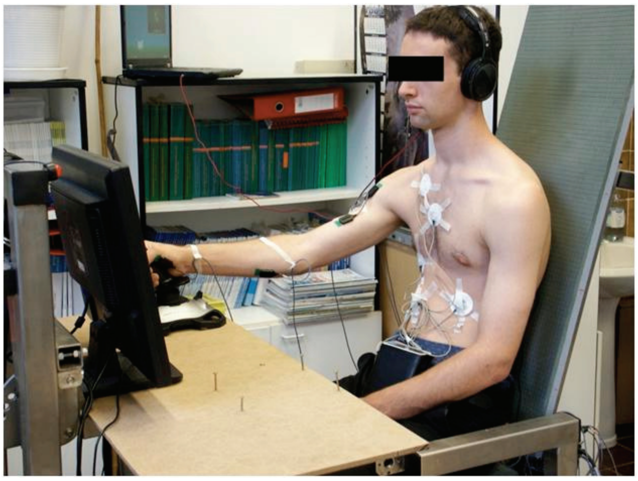

Fig. 1. An operator with the electrodes during the experiment

2.4. Experimental procedure

The experiment was divided into three phases. First, the subject had some time to get acquainted with the software and dynamics of the joystick. Prior to the next phase, the subject was become listening to the relaxing music for 3 minutes to stabilize the physical parameters. Subsequently, the subject had to follow the signal appearing on the screen. The shape of the signal was a repeating pulse one with a fixed amplitude and the frequency. The task duration was 120 seconds. This phase was called the reference task. At the end of this task, subject had to take a 3 minute brake (relaxing music). The measurement was performed within the scheme presented in Fig. 2.

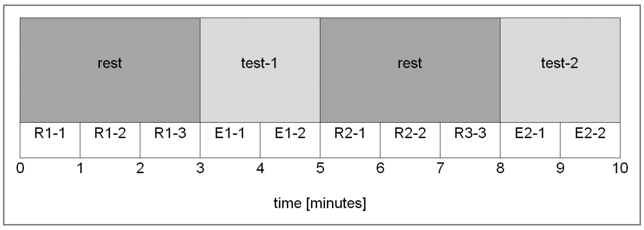

Fig. 2. ECG registration scheme; R1 -1, R1-2 and R1-3 are the adjacent minutes of registration for rest, E1-1 and E1-2 are two following minutes for the reference task. The next 5 minutes are for the rest 2 and distraction task

In the second task, the signal to track was a random one with varying amplitude and frequency (120 seconds). This phase was called a distraction task (Fig. 3). Higher frequency and varying amplitude was necessary to create more difficult work conditions.

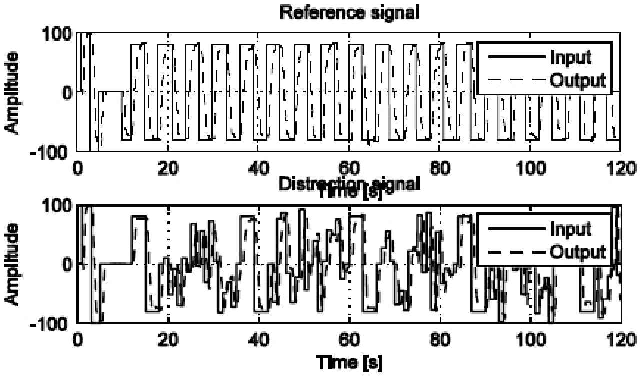

Fig. 3. Example of the tracking task; top – reference signal, bottom – distraction signal

One can easily predict that the more difficult task is evaluated the lower control effectiveness will be. To avoid a misleading in this aspect, the distraction task was supplemented with the same pulse signal (with the same amplitude and frequency as in the reference task) five times in 10th, 36th, 60th, 84th and 108th second of the signal, respectively. Further analysis of the identified models base only on those selected time intervals.

2.5. Model identification

The human dynamic model was adopted from [14]. Such form of human model is used frequently in, e.g., [9], [15]. In paper [2], the model characteristic is developed. It is clear that such model is simplified representation of human activity. In our research the model had a form of proper approximation of the human's action considered as a controlling element. The model is as follows

$$H(s) = \frac{K(1+T_z s)e^{-T_d s}}{(T_w^2 s^2 + 2\zeta\, T_w s + 1)}. \tag{1}$$

The input signal to the human model element is trajectory of the signal that the subject had to follow. The output signal is a response of the operator to the input signal. Those three data (input/output signal, human model) allowed to conduct a human model identification. The joystick inertia was negligible. In similar research [16] the ARX/ARMAX method was used. However, for the purpose of the current experiment the Process Model Identification (MatLab toolbox [17]) was applied. Such a method was more appropriate since the form of the model is known. The identification process was made 5 time intervals. For each subject, five models have been identified. The final model was an average one Such a procedure was repeated twice, for the reference and distraction task. Finally, each subject was represented by two models the reference and distraction.

3. Results

3.1. Human operator models

The identification methods, based on the literature and the MatLab tools allowed the human operator models to be identified properly. The aim of the study was to verify the hypothesis that the subjects response would drop down under the more difficult work condition. It is obvious that more difficult task increase higher stress. However this assumption was not confirmed, but it seems that raising the signal frequency affects strongly the operator's behavior. The models of the operators have been analyzed by comparing main parameters of the obtained transfer functions. The result of identification for one subject is presented below:

$$H_{ref}(s) = \frac{2.384(1+13.57s)e^{-0.183s}}{(s^2+10.92s+33.36)}, \tag{2}$$

$$H_{distr}(s) = \frac{1.7(1+24.72s)e^{-0.292s}}{(s^2+9.822s+43.81)}. \tag{3}$$

The following procedure was necessary to analyze models using the step response characteristics. Only two models obtained for each operator were compared. The main criteria of the operator's effectiveness were: the smallest overshoot and the shortest rise time.

Based on the model analysis of control task and established criteria, it was observed that overshoot had increased (Table 1).

Table 1. Overshoot coefficient for the identified models

Subject No.	Reference model [%]	Distraction model [%]
1	0.0130	3.2323
2	0.0082	5.0498
3	1.0449	5.7501
4	0.0935	8.3534
5	0.5909	2.6569
6	6.4774	11.0340
7	8.7299	5.0246
8	8.1238	7.7228
9	3.0187	9.5791
10	1.4105	5.6185

Such a result of the increasing overshoot was expected. In the distraction task, an operator moved joystick faster, so the accuracy was poorer. This result was also confirmed by the second parameter of the human model response analysis. The rise time which represents the reaction rate almost in all the cases decreased significantly (Table 2).

Table 2. Rise time coefficient for the identified models

Subject No.	Rise time for reference model [sec]	Rise time for distraction model [sec]
1	0.4986	0.3284
2	0.5583	0.3037
3	0.5766	0.3537
4	0.4496	0.3231
5	0.9618	0.5189
6	0.2106	0.1853
7	0.1125	0.2011
8	0.4185	0.4093
9	0.7415	0.6993
10	0.7607	0.5499

3.2. EMG signal analysis

The main assumption of EMG analysis was to compare the values of muscle tension recorded during the distraction task to the values obtained in reference one, as represented by the following equation

$$\frac{x^i_{\text{distr}}}{x^i_{\text{ref}}} > 1, \tag{4}$$

where:

x_{distr} – average tension values for 10th, 36th, 60th, 84th and 108th seconds of distraction task,

x_{ref} – average tension values for 10th, 36th, 60th, 84th and 108th seconds of reference task.

The approach presented in the study is based on a dimensionless parameter, so the differences have no impact on the results. The registered signals represent raw EMG values. The RMS (root–mean-square) method was used to smooth EMG signal (4). The EMG signal was divided into windows (moving window) with 0.25 s (1000 samples) intervals. From each window the RMS parameter was calculated,

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} X_i^2}{N}}, \tag{5}$$

where:

N – number of samples in one window (1000),

X – values of analyzed signal.

Next step consisted in selecting the five particular time intervals (10th, 36th, 60th, 84th and 108th second of the signal). These are the intervals where the tracking signal was identical for reference and distraction tasks. Based on those signals the tensions (RMS) developed by the muscles between tasks were compared. For each time interval the average value for the tension was calculated. Consequently, for each subject the average ratio from 5 intervals was calculated. The hypothesis was that during the distraction task the muscle tension will increase. Consequently, the muscle tension ratio has to satisfy the assumption represented by equation (4).

3.3. Results of EMG measurement

Analysis of the calculated ratios are presented in Table 3. Deltoideus posterior for each of the analyzed cases and trapezius for most of the analyzed cases satisfy condition (4). Deltoiudeus anterior and flexor carpi ulnaris shows that for half of subjects condition (4) is also satisfied. The only muscle which does not go in line with the hypothesis is biceps brachii muscle. It may be interpreted that this muscle was not involved directly into the task. However, presented results of EMG analysis confirm the hypothesis that in the distraction task the muscle tension would be greater.

Table 3. Muscle ratio – distr/ref for each muscle

Subject No.	Flexor carpi	Trapezius	Biceps brachii	Deltoiudeus anterior	Deltoiudeus posterior
1	1.14	1.35	0.46	1.99	1.23
2	0.71	0.89	2.43	0.89	2.59
3	0.94	0.90	0.95	0.91	1.01
4	0.99	1.02	1.03	0.91	1.02
5	0.96	0.95	0.34	1.31	1.13
6	1.53	1.10	0.95	0.98	1.63
7	0.83	1.82	0.72	1.00	1.13
8	1.32	1.57	1.62	1.42	1.06
9	1.03	1.19	0.70	1.04	1.34
10	1.14	3.33	0.76	1.11	1.01

3.4. ECG signal analysis

Heart Rate Variability (HRV) was analyzed in accordance with the standards described in [13]. The analysis was done for RR intervals from one-minute parts of the ECG signal. For the HRV analysis, which allow to assess the autonomic control of heart rhythm only sinus stimulation were used. Hence the ventricular and supraventricular pacing were eliminated. Finally, the artifacts were filtered from the ECG signal [11].

Table 4. The physiological interpretation of parameters describing the mechanism of cardiovascular control

Domain	Parameter	Physiological interpretation
Length of the RR intervals	mRR (ms)	Autonomic nervous system activity
	SDNN (ms)	
Differences between adjacent RR intervals	pNN50 (%)	Vagal activity
Periodic variation of RR intervals	LF (ms^2)	Sympathetic nervous system activity
	HF (ms^2)	Parasympathetic nervous system activity
	LF/HF	Sympathetic – vagal balance

HRV analysis was done in the time domain and frequency domain. The power spectrum was determined by FFT method (Fast Fourier Transformation). For the time domain analysis following parameters have been selected: mRR time [ms], SDNN [ms], rMSSD [ms], and pNN50 [%]. In frequency domain the following parameters were analyzed: low – frequency (LF) and high – frequency (HF) power spectrum [ms^2], and finally the ratio between the spectral powers: sympathetic and vagal balance (LF/HF). Table 4 presents the physiological interpretation of the selected parameters.

3.4.1. Statistical analysis

To verify whether the results of the same parameter differ in adjacent minutes of the experiment the analysis of variance – ANOVA Friedman was used. Comparison of the results, obtained at different minutes showed statistically significant differences in mRR variable ($\chi^2 = 17.630$, $p < 0.04$). For the comparison of the values obtained in two different moments of the experiment, the pair sequence Wilcoxon's test was applied. Statistical analysis and graphical presentation of the results was made in STATISTICA6PL program.

3.4.2. Results

Table 5 presents the results of statistical analysis for variable in the time and frequency domain taken from the sample of 9 participants at different stages of the experiment. In the presented tables the first line from the registration is considered as a reference value, relax time before the main tasks (R1-1).

The results of HRV analysis in the time and frequency domains are presented in Fig. 4 and Fig. 5. For the comparison of the results the Wilcoxon signed rank test was used. Only the pairs with statistically significant differences are marked.

The mRR parameter showed the most significant changes during the experiment. Using the values for the first minutes of experiment (R1-1) as a reference, there was a significant increase in the mRR during tasks performance (E1-1 E1-2 and E2-1, E2-2). It was also found that the mRR value in the reference task (E1-2) were significantly lower than the values in the first minute at distraction tasks (E2-1). The pNN50 parameter showed a significant increase in the second minute of reference task (E1-2) as compared to the first minute of relax (R1-1). Such a growth indicates the increased activity of the parasympathetic regulation of heart rate. Changes in the LF parameter may indicate a gradual reduction in the subsequent minutes of experiment. During the first minute of reference task (E1-1) the LF power spectrum significantly ($p < 0.05$) decreased, as compared to the last minute before the relax (R1-3). A significant decrease in LF power spectrum in the distraction task (E2-2) as compared to the first task (E1-2), ($p < 0.05$), indicates a further decrease in the sympathetic activity of heart rate regulation. The power spectrum of high-frequency (HF), indicating the rate of parasympathetic activation and sympathetic – vagal balance (LF/HF) did not change significantly during distraction tasks. In the final minutes of the experiment (E2-1 and E2-2) the

Table 5. HRV in the time domain the sample of 9 participants

Mean	Median	Minimum	Maximum	Standard deviation	ANOVA Friedman
mRR (ms)					
854.2	869.0	735.8	1002.4	80.54	$\chi^2 = 17.630$ $p < 0.04$
SDNN (ms)					
178.383	81	32.99	421.91	159.826	$\chi^2 = 9.606$ $p < 0.383$
pNN50					
11.348	9.485	3.390	20.00	6.172	$\chi^2 = 8.071$ $p < 0.527$
LF (ms^2)					
2828.9	1379.6	239.5	6936.4	2549.9	$\chi^2 = 9.121$ $p < 0.426$
HF (ms^2)					
358.222	247.400	66.3	629.20	228.507	$\chi^2 = 5.556$ $p < 0.783$
LF/HF					
10.043	8.898	0.968	27.61	8.862	$\chi^2 = 6.368$ $p < 0.703$

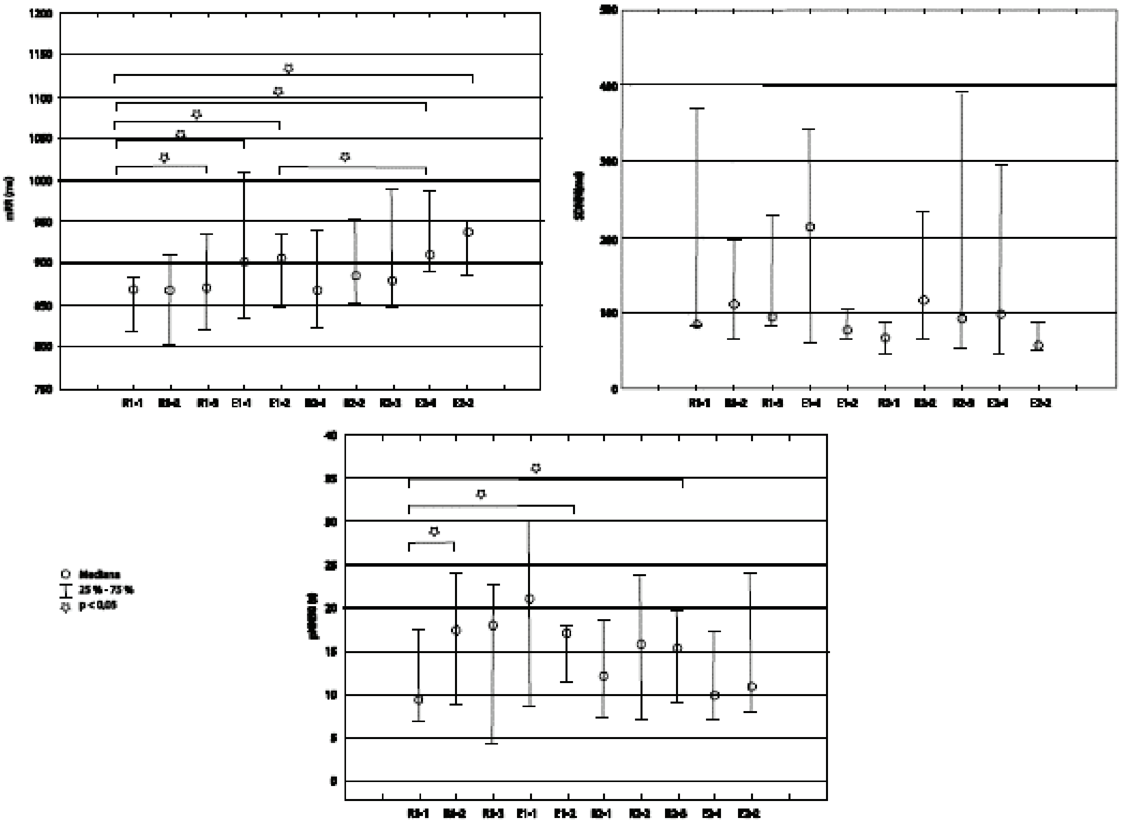

Fig. 4. Values of the parameters reflecting HRV in the time domain at different moments of experiment in the sample of $n = 9$ participants. Top left – mRR, top right - SDNN, bottom – pNN50

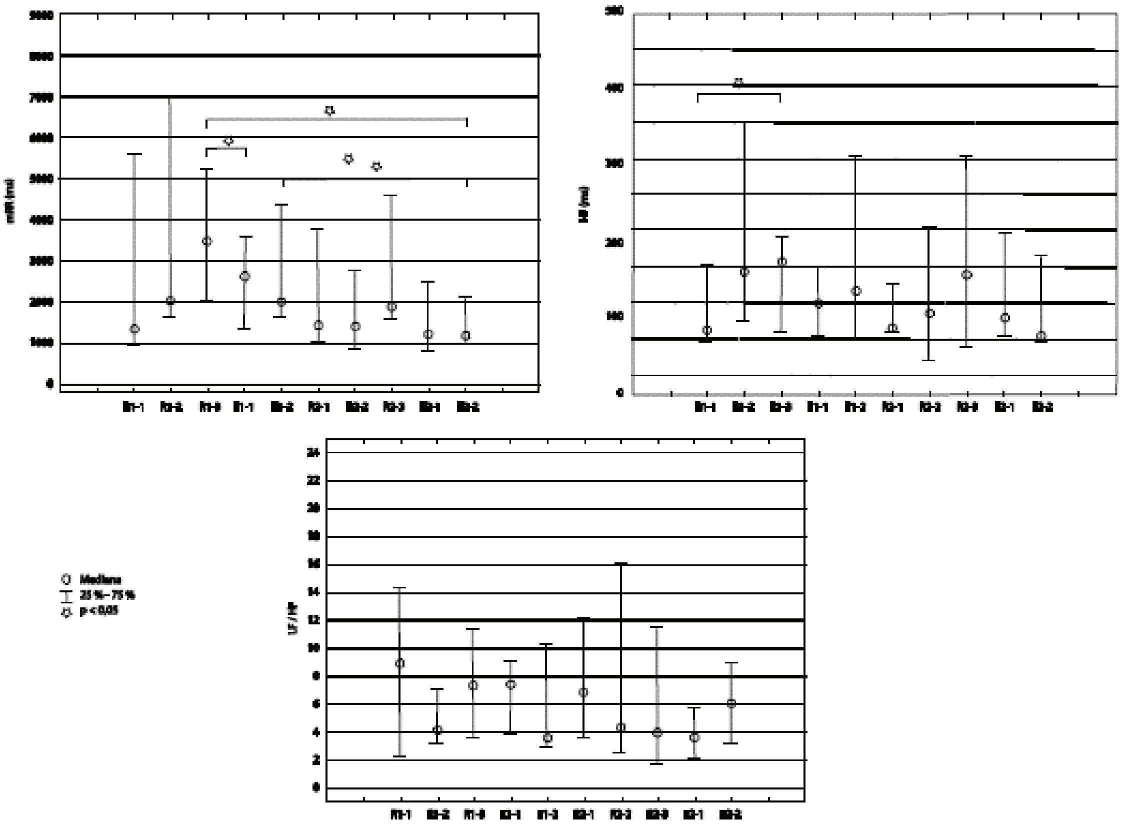

Fig. 5. Parameters reflecting HRV at different minutes of the experiment in the sample of $n = 9$ participants. Top left – HF, top right – LF, bottom – LF/HF

lowest values of the sympathetic – vagal balance, (LF/HF) are noticeable. The increase of the mRR value, during the task performance may be caused by a decreased sympathetic system activity compared to the parasympathetic one. It is a consequence of a decrease of the sympathetic parameter (LF). At the same time, the lack of significant changes in the HF is noticed. The values of sympathetic-vagal balance were the lowest in the two minutes of the distraction task. It can be summarized that reference task resulted in a significant decrease in the sympathetic lead in regulating heart rhythm.

4. Discussion

As was shown above, the distraction task models are weaker as compared to those obtained from the reference one. The model analysis confirmed the assumed hypothesis. It can be stated that the rise time and damping ratio are directly affected by the state of the operator. Despite one-to-one comparison the general tendency is also possible to notice. The response of the majority of models is weaker (for the criteria established). The rise time significantly decreased for 90% results in distraction task compared to reference one. Similar tendency can be observed in overshoot (that might be interpreted as subjects control precision). 80% of the results show the increased overshoot in distraction task. This is clearly in line with the expectations, so the operator response is less precise. The experiment showed that effectiveness of the operator decreases when the external factors act on the subject. From the automation viewpoint, the operator model changes significantly. The experiment showed that changes in operator model in the tracking task are susceptible to external stimuli. It means that considering an operator model as a fixed-parameter model simplifies the problem too much.

The methodology of using ECG and EMG signals as a tool for assessment of the human organism reaction to the mental stress is reliable. The research results show that the methodology presented could be applied to more advanced studies, i.e., pilot-aircraft situations, where mental stress is much stronger and pressure on the pilot is higher. There would be definitely difficulties with integration of the biosignal registration, data filtration and proper synchronization. The identification process of the model parameters would be challenging to apply in on-line system, however, such research into a more advanced application would be interesting.

For the purpose of simulation of man-machine systems it is worth taking into consideration the development of operator model. Those are more complex and susceptible to external factors. Especially, in the domains with the operator being strongly affected by the mental stress.

Acknowledgements

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