A biofeedback system that uses the game to study electrical muscle activity

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***Abstract* — The aim of this project was to design a system that will allow performing repetitive muscle exercises using a biofeedback device. It is supposed to enhance the motivation and attractiveness of the performed tasks thanks to an interactive game developed for mobile devices with the Android operating system. The built-in calibration mechanisms enable the users to play a game that is independent of their abilities which evens out the level of all players. The data in the form of EMG signal is gathered directly from the patient's body's surface in real-time and is sent wirelessly for further processing. While testing the system's efficiency, two types of calibration processes used in the mobile application were carried out.**

Keywords—calibration, biofeedback, EMG, mobile game, muscle activity

I. INTRODUCTION

EMG signal is, along with ECG, the most used electric biosignal generated by motoneurons during muscle myofilaments activation. EMG enables an accurate monitoring of muscle activity through muscular potential record from the skin's surface over the examined muscle. The signal provides an enormous amount of information which can be used in rehabilitation, physiotherapy, and orthotics [1][2]. It extends the diagnostic possibilities of the gait disability [3] and quality evaluation of the training or its proper scheduling. In today's electronic world EMG represents a foundation for various biomedical applications which can be used not only as a source of information but also enable the conduction of diverse therapy types.

In the following article, the EMG biofeedback was applied - a mechanism that provides information regarding the muscles' state of a patient in the real-time. It is a type of feedback in which the biological signal is represented via visual or auditory impressions and is perfectly suitable to control the elements of an educational game. Such interactive applications are designed on personal computers [4][5][6] as well as on mobile devices [7]. The state of muscle activity (contraction and relaxation) and the duration of a specific phase can be visualized in the form of graphs or moving elements which illustrate the level of muscle contractions and relaxations. The patient will see the progress of muscles' activity in a comprehensible way and will attempt to influence the exercises' quality with greater commitment. The advantage of the games in the rehabilitation process is the opportunity to overcome own weaknesses, accomplish record-breaking results and also compete with other patients. The aim is to encourage the patient to perform the exercises correctly and on regular basis.

The EMG signal is characterized by very small amplitude value (which equals 5mV maximally) and the frequency in a range from 6 to 500Hz (with the highest power between 6 and 150Hz). Due to its arbitrary character, it is not likely to predict the next sample's value [8]. The amplitude majorly depends on the measurement conditions which mean that it can differ depending on the arrangement of the electrodes, patients' physical condition, skin condition and even during casual analyses in the same position with the same electrodes' placement. In order to correctly compare the level of electrical muscle activity of different patients, it is critical to apply the normalization [9] of the registered EMG signal. This process is usually performed by dividing the measured EMG signals during the exercises through the reference value obtained from

This work was supported by European Regional Development Fund concerning the project: UDA-POIG.01.03.01-22-139/09-03 -"Home assistance for elders and disabled – DOMESTIC", Innovative Economy 2007-2013, National Cohesion Strategy and partly from GUT Faculty of Electronics, Telecommunications and Informatics statue funds.

978-1-5386-5024-0/18/$31.00 ©2018 IEEE

the same muscle during the calibration procedure [10]. For this purpose, the process of initial measurements is performed before each exercise which enables the user to obtain the relevant reference values.

The aim of this article was to integrate the EMG biofeedback system with the visual feedback enabling the improvement of the attractiveness of performed exercises. The designed system is supposed to motivate the patient and instruct him to control the tension of the muscles by navigating the moving elements on the mobile device screen. The emerging obstacles are ought to be bypassed what is related to the number of scored points in direct proportion. Before each round, the calibration process must be performed which will adjust the amplification levels to individual possibilities of the trainee.

Two methods of calibration were proposed and examined in this article. It enabled the optimization of the exercises performed during the game and also the choice of an optimal algorithm determining the reference signal parameters.

II. METHODS

The proposed system consists of the EMG receiver, a game for the mobile devices and the EMG real-time monitor. All these elements are connected to each other wirelessly which simplifies the process of exercises and provides convenience for patients.

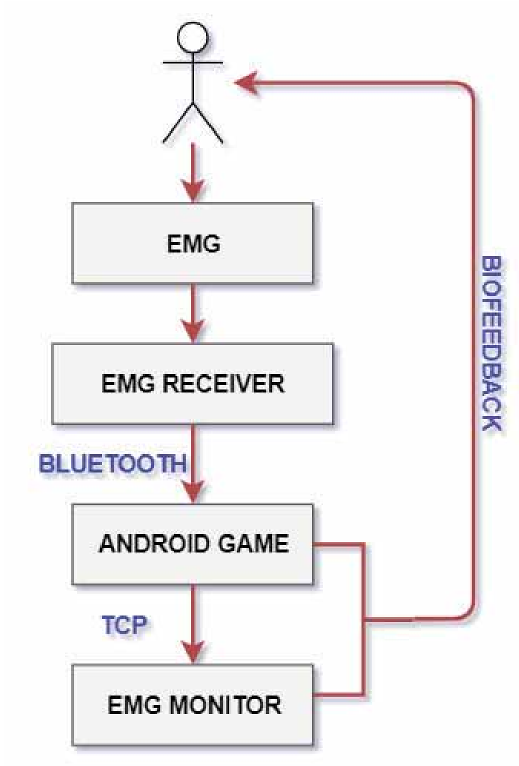

Fig. 1. Flow chart of the biofeedback system

The system construction was presented as a flow chart visible beneath on Fig. 1 and described precisely in subparagraphs.

A. EMG receiver

The EMG receiver is responsible for the reception of the signals deriving from the muscles. It complies with three fundamental assumptions: a wireless communication with the master device, miniature layout dimensions, and patient's safety obtained through isolation and appropriate power supply. The layout consists of four-layered PCB board, housing, and Li-Pol battery. The electronic part is divided into several essential blocks represented on the Fig. 2.

The most important element of the schema is the analog part. It consists of an instrumental amplifier [8] INA128 which is distinguished by high CMRR factor which rises up to 120dB and the ability to adjust the amplification through the single resistor. An implemented circuit that significantly removes noise is called Driven Right Leg (DRL). It introduces the common signal back to the patient's body. Afterward, the Butterworth active filters were applied: a fourth-order low-pass filter suppressing the signal 24dB/octave and an eight-order high-pass filter suppressing the signal 48dB/octave at 10Hz and 500Hz frequencies, respectively. In order to remove the noises derived from the power lines, the Robinson-Wien band-rejection filter with 50Hz cut-off frequency has been designed. In the next stage, the signal was amplified and the offset was added - equal to the half of the positive supply voltage. This way, only the positive values are placed on the input of the analog to digital converter.

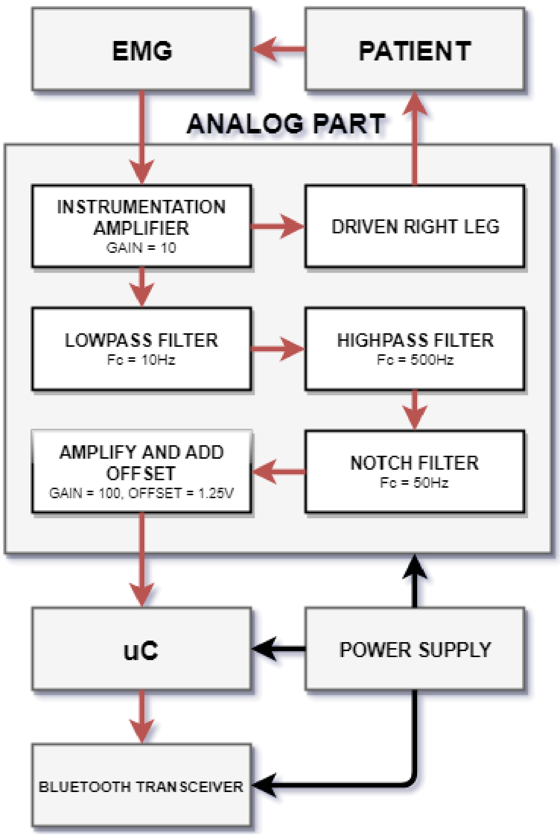

Fig. 2. Electronic system flow chart with added gain, frequency (F_c) and offset description.

The heart of the layout is microcontroller STM32F103 with a built-in 12-bit ADC converter for a high accuracy of measurements and a universal UART port providing a communication protocol. For the purpose of this project, the input signal is sampled at a frequency of 500Hz in order to ensure correct analysis of muscle activity. The microcontroller awaits the messages from the mobile application and thereafter sends the data in the form of packages of ten ADC values.

The packages contain up to 54 signs which is 540 bits. At a 50Hz frequency, the transmission speed stands at 27 000 bits/s. To avoid the unwanted loss of data, the baudrate parameter value was set up to 115200. The structure and exemplary frame were presented on the Fig. 3. The system responsible for wireless Bluetooth communication has been HC-06. To avoid the need to repeatedly remove and replace the battery, the charger has been used in this project. The lithium-polymer battery with a nominal voltage 3,7V and a capacity (C) of 240mAh is charged via LTC4053 integrated circuit. The current was set up to 0.5 * C (circa 120mA) in order not to destroy or overheat the battery in the charging process.

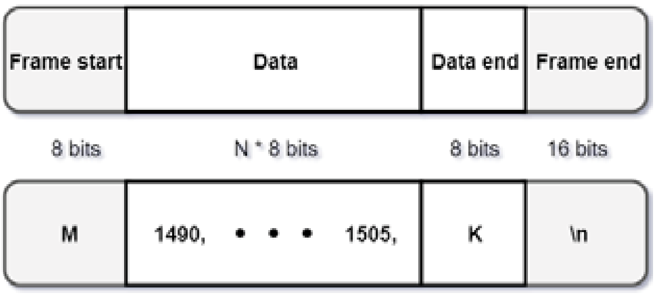

Fig. 3. The structure of data (the upper diagram) and exemplary data package as well as special characters (lower diagram)

The board has been closed in a sealed housing that provides complete isolation from electronic components. The end result is represented on Fig. 4.


Fig. 4. Complete system with the housing

B. Android game

The first stage of work with the system is to connect the EMG receiver with a selected mobile device equipped with Bluetooth interface, for instance, a smartphone or a tablet. Fig. 5 represents a simplified flowchart of the communication between the game and the receiver. Data from the receiver in the form of subsequent EMG signal values are continuously subjected to the Root Mean Square (RMS) algorithm [11]. It uses the moving window N which equals 60 samples which ensures sufficient smoothing of a signal. Each separate data window is calculated accordingly to this formula (1).

$$RMS = \sqrt{\frac{1}{N} * \sum_{k=1}^{N} EMG\_Value^2[k]} \qquad (1)$$

Studies are initialized by a seven seconds calibration process which aims to normalize the EMG signal during the game. In order to choose the most optimal exercise, which will be used while practice, three types of gestures have been used. The studies focused on the analysis of the M.deltoideus shoulder muscle. The complete calibration procedure was depicted on Fig. 5.

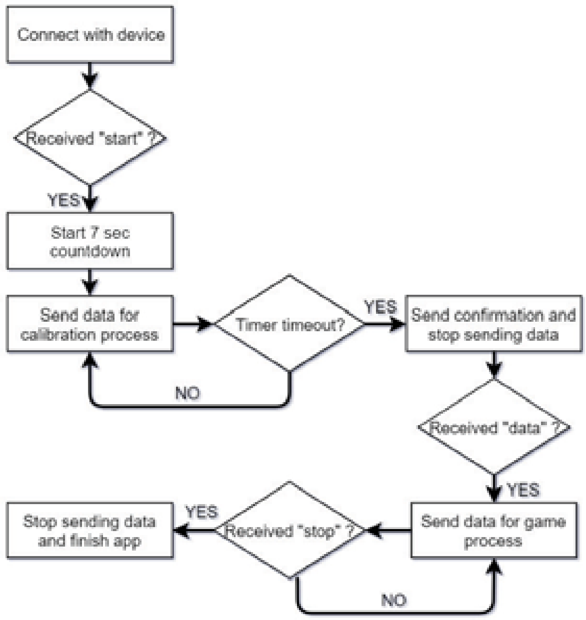

Fig. 5. The flow chart of Bluetooth communication

1) The appointed muscle was subjected to three types of exercises. Each trainee has made ten repeats of all types of gestures. Based on further analysis, it has been decided which of the exercises best reflected the repeatability of the results. In order to receive the best effect, an appropriate posture was required - a sitting position with back support. Backrest near the arm in a position close to 90º. The bilateral realization of the exercise ensures a balanced distribution of the force on the torso [12]. Each exercise had to be made in a uniform motion and the contraction should be maintained until the very end of the seven-seconds process. Following gestures were applied:

a) arms bent at the elbows raised to the sides until reaching a 90º angle between the shoulders and ribs,

b) straightened arms raised forward until reaching a 90º angle between the shoulder and the chest,

c) arms bent at the elbows raised upwards until they are entirely straightened up.

2) For each gesture selected in the first point, each patient performs the calibration process. After its completion, two reference values are calculated: mean value (2) and maximum RMS activity [12].

$$Mean = \frac{1}{n} * \sum_{i=1}^{n} RMS[i] \quad (2)$$

The normalization of these values allows reducing the signal variability between the successive trainees in comparison to the usage of raw data or when normalization of Maximum Voluntary Isometric Contraction (MVIC) is applied [13]. One of the limitations of using the MVIC is the patients' muscles' defects. It may be impossible for them to entirely use their muscles' strength. Dynamic methods based on mean and minimum muscle activity can ensure their better representation required for a specific exercise [14]. Normalization is based on the following formula (3):

$$Normalization = \frac{EMG\_Value}{Reference} * 100\% \quad (3)$$

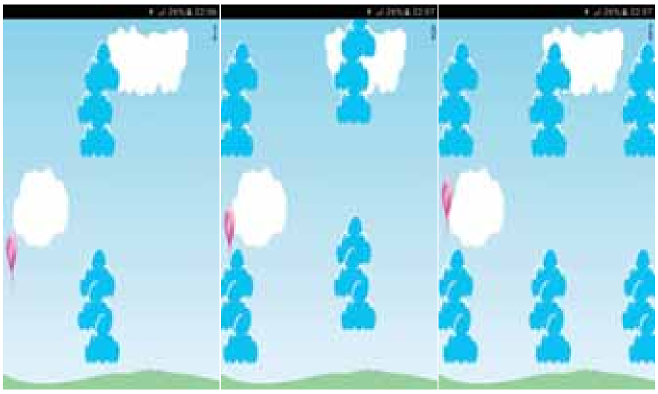

Fig. 6. Windows of the mobile game for easy, random and difficult modes, respectively. The screens display a pink balloon and blue clouds (obstacles) that must be crossed by flying between them.

During the game, the patient can choose between three modes, differing from each other in the type of exercise being performed:

- easy – short contraction, short relaxation,
- difficult – long contraction, short relaxation,
- random – dynamic exercises.

The normalized RMS signal is used to move the balloon. When the muscles are active, the moving element is given a positive acceleration directed upwards, while inactivity pulls it down. The patient is required to avoid further obstacles in the form of clouds by moving the balloon with the movement of the examined muscle. For each overpassed column, the trainee scores points which will consist the information regarding the effectiveness of a particular calibration method. The game process is depicted on the Fig. 6. In the case of contact between the balloon and the cloud, the collision is detected and the game is restarted.

C. EMG signal monitor

The EMG signal monitor gives the opportunity to observe the muscle activity of the patient on a regular basis. When analyzing the charts in real-time, it can be confirmed that the contractions were performed correctly and the system is working properly. Data on the desktop application are sent via the TCP protocol which connects the server sockets (EMG monitor) and client (mobile game). Each one of them is a communication identifier that consists of a port and IP address. It is guaranteed that the packages will be received in the same order in which they were sent out. At the same time, the data is also saved in separate text files for further processing in the Matlab program.

D. Data processing

In order to develop the optimal calibration method, the first step was to process in the Matlab environment. For that purpose, raw data gathered in the form of text files were imported to the software and subjected to the necessary processing. 1490 offset added at the stage of designing the electronic part was removed which is equivalent to the half of the positive power supply voltage which is 1.25V. Afterward, the negative values of the signal were reflected in regard to the axis of symmetry which will allow analyzing the entire EMG power. The data prepared in that way was subjected to the RMS algorithm with window width 60. The first type of calibration takes the maximum achieved value of the determined RMS signal. The second type sums up all the samples during muscle activity (amplitude greater than 80mV) and, thereafter, calculates the mean. Such procedure was conducted for all gestures and exercises tested.

Five healthy persons performed the M.deltoideus shoulder muscle exercises using the biofeedback device. Before starting the exercise, two electrodes were placed on the examined muscle to which EMG receiver was attached and the third, referential, one was attached near the tendon [15]. The system mounted on the body's surface and ready for operation is represented on Fig. 7.

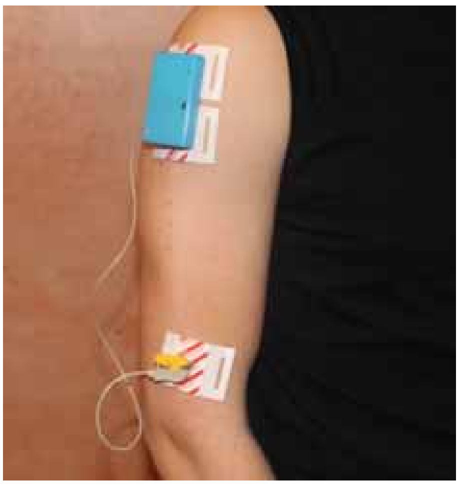

Fig. 7. EMG receiver prepared for starting the exercises

To start the game in the first step, it is required to connect to the desktop application and to the EMG receiver. Each trainee was instructed how to perform the exercises which allowed to get the correct results. Besides that, all system users had the access to a few-minutes test period that enabled them to adapt and learn about the possibilities of their muscles during the game. All the patients performed the calibration process ten times for three types of gestures. On the basis of obtained measurement results, a standard deviation (4) was determined which allowed deciding on the choice of a particular gesture.

$$\sigma = \sqrt{\frac{1}{N} * \sum_{i=1}^{N}(x_i - \mu)^2} \tag{4}$$

Afterward, the people being tested initialized the game process, starting with performing a single calibration process which resulted in two reference values. In the next step, the trainees realized the exercises for easy and difficult game modes using the already normalized EMG signal.

On the basis of the conducted exercises, the mean, minimum time needed to complete the tasks was determined. For easy mode, the time of contraction and relaxation was 2 and 2.5 seconds, however, in the case of difficult mode 6 and 4 seconds, respectively. The obtained results of patients in four games: easy mode with maximal (Easy Max) and mean (Easy Mean) reference value and difficult mode with maximal (Hard Max) and mean (Hard Mean) reference value were compared with the mean exercises times. The schema of exercises to be performed is depicted on Fig. 8.

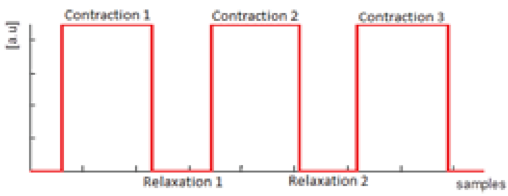

Fig. 8. The schema of performed exercises for all game types

For each correctly executed sequence, the patient received one point (TimePoints). To the final score, the points obtained for defeated obstacles were added (GamePoints). At the most, the patient was able to receive six points for a particular game mode. On the basis of the obtained results, the effectiveness (5) of a specific calibration process was determined.

$$Efficiency = \frac{(GamePoints + TimePoints)}{6} * 100\% \tag{5}$$

This way of determining the effectiveness allows stating whether a particular calibration mode enables the patient to provide adequate strength during the exercise and whether the trainee is able to maintain it for a certain period of time.

III. RESULTS

A. *The choice of an optimal gesture for calibration's requirements*

TABLE I presents maximal (Max) and mean (Mean) reference values of activity received during calibration process from five patients for three chosen gestures. Results are depicted in the form of mean values of ten calibration results combined with their standard deviations (SD).

Fig. 9 presents exemplary calibration figures performed for chosen gestures with marked maximal and mean activity values. Exercises where arms are raised to the sides and forward feature constant RMS value through the entire activity period. In case of raising the arms up, temporary amplitude increase appears and then it decreases and stabilizes. This kind of characteristics prevents proper exercise during the game.

TABLE I. MAXIMAL (MAX) AND MEAN (MEAN) REFERENCE VALUES WITH ITS STANDARD DEVIATIONS

	Arms to the sides		Arms forward		Arms up	
	Max	***Mean***	***Max***	***Mean***	***Max***	***Mean***
1	327.45±18.66	165.06±6.22	173.41±34.20	80.68±5.85	314.03±49.15	118.05±7.31
2	378.10±23.56	176.50±12.89	237.68±24.64	122.20±9.39	456.48±39.08	204.89±18.56
3	635.67±38.22	287.48±18.35	358.06±48.48	178.65±22.41	651.19±58.40	305.09±21.44
4	531.80±20.26	235.64±15.60	365.17±43.62	163.25±11.29	546.54±40.81	200.56±9.41
5	513.49±29.81	251.57±18.83	237.25±31.58	121.34±8.23	573.30±42.97	238.52±22.39

Values are mean±SD

As a result of the performed analysis, the first gesture was the optimal one - raising arms to the sides. For this type of exercise, the standard deviation criteria took the smallest values for the maximal activity, as well as the optimal for the mean activity. This denotes the smallest dispersion of all gestures types.

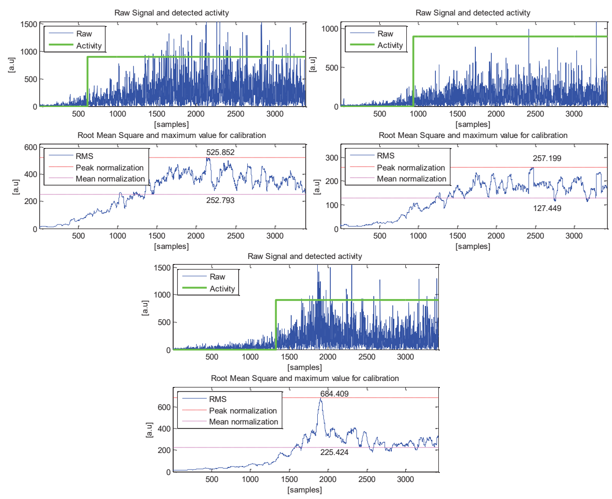

Fig. 9. The calibration figures for gestures: arms movement to the sides (upper left), forward arms movement (upper right) and arm movement upwards (bottom).

TABLE II. OBTAINED TIMES OF CONTRACTION AND RELAXATION FOR ALL TYPES OF GAME MODES PROVIDED IN SECONDS AND APPOINTED EFFECTIVENESS

		1			2			3			4			5			
Easy Max	**Contraction**	2.93	2.74	2.79	2.98	2.73	2.55	3.14	2.68	2.87	3.31	2.85	2.93	2.86	2.24	2.61	
	Relaxation		2.77	2.78		2.49	2.85		2.79	2.12		2.59	2.40		3.22	2.98	
Hard Max	**Contraction**	6.73	6.73	6.86	6.28	6.67	6.66	6.19	6.63	6.75	6.67	7.13	7.29	6.71	6.37	6.26	
	Relaxation		4.51	4.34		4.75	4.40		4.78	4.64		4.31	4.22		4.95	5.19	
Easy Mean	**Contraction**	2.36	2.50	2.63	2.77	2.28	2.97	2.72	2.58	2.45	3.45	3.04	2.82	3.99	2.40	2.46	
	Relaxation		2.74	2.86		3.19	2.52		3.24	2.77		2.55	1.85		2.82	2.84	
Hard Mean	**Contraction**	5.79	6.77	3.80	6.77	6.71	6.59	6.55	6.16	6.63	6.73	5.70	6.71	6.44	6.79	6.90	
	Relaxation		5.02	4.94		4.43	4.96		5.16	4.61		5.14	5.20		4.53	4.68	
Efficiency	**Max**	100.00%			100.00%			91.67%			100.00%			100.00%			**98.33%**
	Mean	75.00%			100.00%			100.00%			83.33%			100.00%			**91.67%**

B. The choice of an optimal algorithm for determining the calibration reference value

The results were obtained in the form of EMG signal charts received during the game process, times of contraction and relaxation, as well as the number of points scored. In TABLE II, all times were collected that five patients needed in order to perform contractions and relaxations in a particular exercise and their effectiveness. Fig. 10 shows an exemplary gameplay of one of the patients performed for all of the modes along with the appointed contraction and relaxation activities.

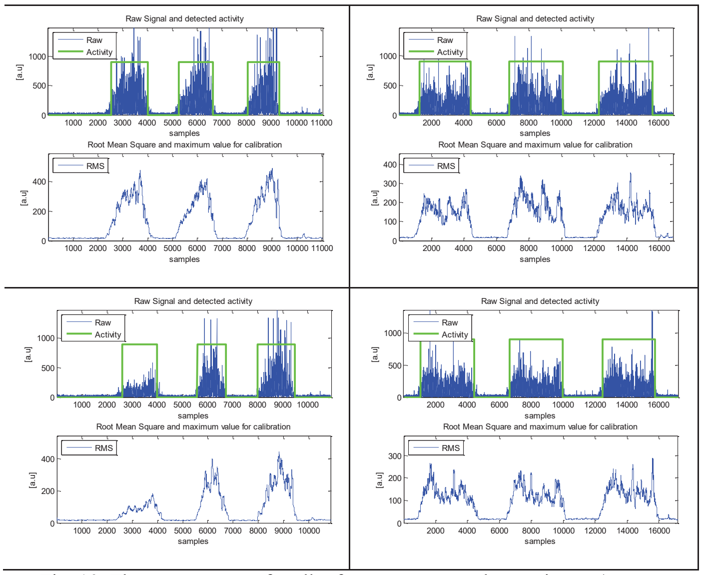

Fig. 10. The game process for all reference types: to the maximum (upper figures) and to the mean (bottom figures)

IV. DISCUSSION

According to the predictions, the normalization for both solutions provided different results in the form of signal amplitude level which can be seen on the figures on Fig. 9. More strength was required in order to raise the balloon when using the maximal reference value. The differences are also noticeable in the length of activity for easy and difficult modes. The analysis of the obtained data shows that both applied algorithms for determining the reference value support correctly the study of muscle activity. Their effectiveness is at a high level. however. the solution with the maximal activity value has achieved better results. which stands at 98.33%. According to the players' opinion. this mode allows for better control over the balloon being lifted. thanks to which the movement of the muscles was even. If the mean value was applied with effectiveness standing at 91.67%. the game required accuracy and caution from the patient. A slightly greater force applied meant that the trainee lost the control of the balloon which reacted very dynamically to the movement. This resulted in difficulty in overcoming further obstacles. especially in difficult mode. A properly performed calibration process and test period was very important for the results of the game. This allowed for better control of muscle capabilities which was visible in the regular balloon movement.

V. CONCLUSIONS

The designed system, which includes the EMG receiver and monitor, as well as the mobile game, allowed the selection of the most optimal calibration exercise and testing the effectiveness of two normalization algorithms. The selected gesture - raising the arms to the sides - is characterized by a small spread of obtained results supported by standard deviation criteria. The reference values obtained during calibration (maximal and mean activity) can be used to perform the exercises to examine electrical muscle activity. Thanks to the simple algorithm for detecting activity and its duration, it was possible to confirm the system's ability to perform specific exercises dictated by an application running on Android mobile devices.

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