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A Comparison of Methods of Controlling the Movement of an Exoskeleton, Supporting Movements of the Upper Limb Using Signals of Muscle Activity and Manual Controls

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Abstract: The paper presents the research methodology and the analysis of the results of the comparison test of two methods of controlling the exoskeleton of the upper limb using signals of muscle activity and manual control devices. The results show the advantage of the joystick method over EMG in terms of usability, task execution time, ease of use and comfort.
Keywords: exoskeleton, control method, EMG, joystick

1. INTRODUCTION

Exoskeletons are electromechanical devices that are worn by humans to increase their physical endurance. In the current exoskeletons available, control can be executed through the use of voice, thoughts, sensors of various types, but most of all manually with hands, feet or a joystick. From a research point of view, a very interesting way of controlling this type of device is through the use of the EMG signal. Mikulski [1] proposed a solution that uses exoskeleton movement control for physiotherapy and rehabilitation of the upper limbs. The design of the exoskeleton assumes a degree of freedom of movement, allowing flexion and extension in the elbow joint. In addition, for the convenience of use, the possibility of forearm rotation is provided, which is achieved through a rotating handle. EMG signals from the muscles responsible for flexion and extension in the elbow joint, i.e. bicep and tricep muscles, was used for movement analysis. The control system was constructed on the basis of a proportional algorithm and a threshold algorithm. Tests of proportional and threshold algorithms based only on a signal from a single channel indicating forearm flexion, have shown that the user cannot obtain sufficient control. With this in mind, a two-channel differential threshold algorithm was proposed, combining two antagonistic muscle groups responsible for flexion and extension movements. The difference in the relative muscle tone of the two-headed and three-headed arm muscles was taken into account. Another example of the use of EMG signals in exoskeleton control was presented in the work of Yagi et al. [2], who used the EMG signal coming from the muscles as a trigger. A signal of a certain magnitude and duration informed about the activation of the muscles involved in a specific movement. The authors of the work developed a model of an exoskeleton to assist in lifting loads while working in agriculture. The assumption of the robot function was to support and relieve the work of arm and shoulder muscles while lifting grain bags.

The load that the subjects were subjected to was estimated on the basis of data collected from strain gauges, the position of the limbs indicated by potentiometers, and information about flexion or extension in the elbow joint and shoulder joint using the EMG signal. The EMG signal coming from the biceps and triceps was registered. Its value indicated movement in the elbow joint, while the flexion and extension in the shoulder joint were controlled by a signal from the anterior and posterior deltoid muscles. Based on the signal, the RMS value was calculated, defining the moment of muscle activity.

It was assumed that when the sum of the changes in signal amplitude (in 200 ms time intervals) is greater than or equal to 0.2 mV, muscle tension occurs, and the signal triggering muscle activity is registered.

Lenzi et al. [3] developed a proportional control system based on the EMG signal, which was used to control the exoskeleton supporting movements in the elbow joint during its flexion and extension. The signal coming from the flexor and extensor muscles of the elbow joint was registered.

The signal was subjected to automatic transformation, rectification and filtration, and then the LE (linear envelope) signal analysis. Lu et al. [4] have developed an EMG-assisted hand exoskeleton for the rehabilitation of stroke survivors. Detection and recognition of user movements is based on electromyography. The exoskeleton is mounted on the forearm so that all fingers can be moved freely. The device allows all five fingers to bend and extend. The hand movement control system analysed muscle activity during the performance of six variants of movement: closing the hand, opening the hand, squeezing the fingertips of the thumb, index and middle fingers (tripod pinch), opening these three fingers, closing the middle and two smaller fingers (the so-called gun sign) and opening (straightening) those fingers. On this basis, the system recognized muscle activity and determined certain patterns indicating the patient's intention to perform a given movement, which translated into helping to perform the movement in real time during a therapeutic session. The registered signal came from the forearm muscles, i.e. dorsal interosseous muscles, superficial finger flexor, deep finger flexor, short finger extensor, long thumb abductor, little finger extensor, and long thumb extensor. The analysis was based on EMG signals registered in a processing window with a length of 200 ms. The processing was performed every 100 ms so that the recognition result could be updated at a frequency of 10 Hz, which is acceptable for real time control. First, a motion detection algorithm was performed to determine if the processing window contained EMG signals that were responsible for the voluntary movements of the user. The mean absolute value (MAV) was calculated. If the MAV was less than the specified threshold (80% of the mean MAV EMG of the signal recorded at the medium strength level), no further processing and recognition was performed. The result was the lack of movement. Otherwise, movement was considered because one or more muscles were active. For the recognition of motion patterns, the SVM supporting vector machine classifier was used, which was taught on the basis of a set of features, i.e. RMS, WL, ARC (fourth-order autoregression coefficients). The classifier output was mapped to a control command and sent to the hand exoskeleton.

The above examples show the implementation of the use of signals of muscle activity based on EMG sensors in the control of the wearable device. Similar solutions were adopted in the functional exoskeleton model developed at Central Institute for Labour Protection (Warsaw, Poland) in order to compare it with the control based on information from the joystick.

2. A FUNCTIONAL MODEL OF THE EXOSKELETON

The description of the functional model has been presented in the article [5].

2.1. Design

The upper limb exoskeleton Fig. 1 consists of a segment rigidly connected to the frame (handles, battery power and control section) and a manipulator ending with a highly rigid joystick.

The task of the mobile exoskeleton is to support the user in the scope of generated force of up to 30 N. The basic dedicated group of recipients are people with a deficit in this area and for tasks requiring increased strength in order to reduce fatigue, e.g. during long and monotonous assembly works or warehouse works in the field of supporting movements in the elbow joint and, to a limited extent, in the shoulder joint.

Fig. 1. Functional model of the exoskeleton of the upper limbs (only right hand active)

2.2. Manipulator control method controllers

A controller used in the exoskeleton control method using information on the muscular activity of the upper limb consists of the developed EMG signal measurement recorder (EMG controller) and a wristband recognizing gestures (Fig. 2 c).

As a result of testing the EMG signal recorder developed at an earlier stage of the project, the use of EMG signals from the muscles of the shoulder was abandoned due to the contact of these sensors with the exoskeleton structure.

For this reason, a new EMG signal recorder (Fig. 2 a, b) was developed for two muscles, i.e. the long head of the biceps brachii and the long head of the triceps brachii. The sensors used are DFRobot Gravity - analogue dry-type EMG sensors.

This sensor was modified in order to reduce the distance between the sensor and its integral amplifier system. The housing and the microprocessor-based measuring system were designed. The microprocessor samples the signal from two sensors at a frequency of 1 kHz, processes it accordingly and then sends it wirelessly at a frequency of about 60 Hz (an nRF24L01 system was used). Due to the low power consumption, the radio system used allows the recorder to work continuously for at least four hours using a 240 mAh battery. Additionally, a dedicated recorder receiver was designed, which communicates with the exoskeleton computer via the USB serial port.

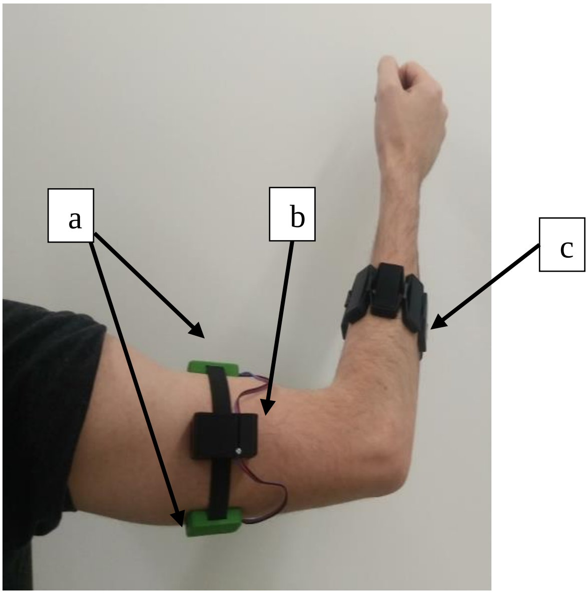

Fig. 2. EMG signal recorder: a) dry-type electrodes, b) measuring and transmitting system, c) Thalmic Labs wristband

In addition to the above recorder, we used equipment which recognized gestures based on EMG signals from the forearm muscles in the form of a Thalmic Labs wristband, consisting of eight sensors. The use of this wristband requires prior calibration, which consists of registering EMG signals in the course of performing five recognized gestures.

The joystick-type controller was presented in the publication [5] (Fig. 3).

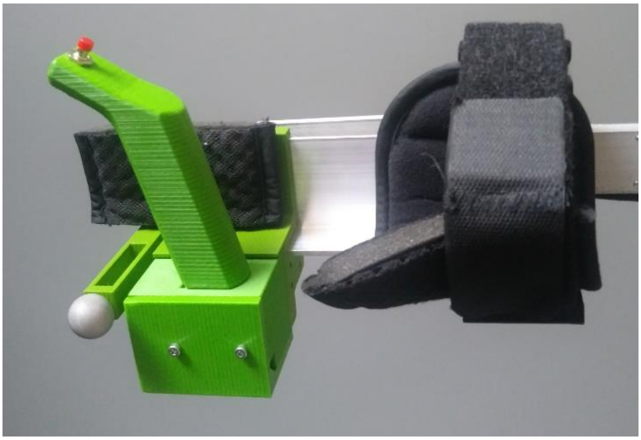

Fig. 3 Joystick

2.3. Control methods

Two control methods have been developed in the work. The first method uses signals about the user's muscle activity based on information from two muscles and information about the operator's hand gestures. The first component of the method is based on the EMG signal threshold analysis.

In the case of this algorithm, only the current amplitude of the registered muscle signal is taken into account, which, after exceeding the set threshold value, initiates a change in the angular position of the servo motor responsible for the movement of only the forearm. In the final version of the algorithm, the change in the angular position of the motor was determined experimentally and was constant regardless of the degree of exceeding the threshold value. The threshold values for individual muscles must be determined individually for each user and each muscle, at least due to differences in body structure and high individual variability of the EMG signal strength. When isometric tensions are detected, during which the antagonistic muscles are tensed in a way that stiffens the position of the joint, (without making any movement) the movement of the servo motor is blocked. The forearm movement above is performed only when the control system receives information that the hand clench gesture has been performed.

The information about the wrist flexing and straightening gestures is used to implement the horizontal movement of the effector (zooming in and out, respectively). In this situation, information about the current position of the motors is obtained in each cycle of the program loop. Based on this information, a simple kinematics problem is solved to determine the position of the effector. The proposed horizontal shift of the effector is introduced to the thus determined position of the effector. Having information about the new location of the effector, we solve the opposite problem for the mechanism with two rotational degrees of freedom and send information to the drives about the new angular settings of the drives.

The second method uses the information registered by the joystick. They also have threshold characteristics, i.e. after setting a threshold for the vertical or horizontal direction, the position of the exoskeleton effector changes. By exerting force on the joystick, the user determines the direction of the exoskeleton effector position in space. The direction of changes is determined locally in relation to the current position of the manipulator's forearm. As in the EMG method, pulling or pressing the joystick by the user in the direction perpendicular to the forearm initiates a change in the angular position of the servo motor responsible for the movement of only the forearm. On the other hand, performing an adduction or abduction movement with the hand clamped on the joystick initiates the movement in the horizontal direction. Information about the current position of the motors is obtained in each cycle of the program loop.

Based on this information, a simple kinematics problem is solved to determine the position of the effector. The proposed effector shift is introduced to the determined position of the effector based on information from the joystick (in the forearm coordinate system, respectively). Having information about the new location of the effector, we solve the opposite problem for the mechanism with two rotational degrees of freedom and send information to the drives about the new target positions of the drives.

3. RESEARCH METHODOLOGY

Two methods of exoskeleton control were tested in order to evaluate and compare them. The control methods were implemented in the functional model of the upper limb support exoskeleton being development. The research was carried out in three people of up to 35 years of age and two people over 60 years of age, declaring no stereoscopic vision impairment.

The actual examination consisted in guiding the exoskeleton effector marked with a marker along a specific path between three points using the two developed control methods. It was a move that simulated picking up an item from a lower level and putting it down on a higher level, e.g. on a shelf (inverted letter L).

The hand movement was carried out with the manipulator loaded with a weight of 3 kg and without any load after about 15 repetitions of a specific movement. During the research, objective information was recorded regarding the accuracy of the effector guidance and the time of task execution. The accuracy of the guided effector was checked on the basis of the position record from the Qualisys motion tracking system with a calibration accuracy of less than 1mm. Effector marker movement was recorded at 60 Hz. The subjective assessment of the exoskeleton relates to its usability and the assessment of its comfort.

3.1. Research procedure and research tools

The research was carried out according to the sequence shown below:

- providing information about the conducted study, about voluntary participation in this study, about the possibility of withdrawing from the study at any stage, about ailments that may occur during the study with the use of the simulator,
- filling in the necessary forms, a personal information sheet and a questionnaire for assessing fatigue and mood using Grandjean's scale (10 min),
- adaptation of the exoskeleton to the study participant (arrangement of servos, forearm grips, joystick) (20 min),
- setting up the controller of the exoskeleton control method using information about the muscular activity of the upper limb and system calibration (10 min),
- break (10 min),
- training – 'joystick' control method (10 min),
- training – 'emg' control method (10 min),
- break (30 min),
- proper tests - the 'joystick' method of exoskeleton control (20 min),
- filling in the SUS questionnaire (2 min),
- filling in the QUEAD questionnaire (2 min),
- filling in the comfort questionnaire (1 min).
- fatigue and mood assessment questionnaire using the Grandjean scale
- break (30 min),
- proper tests – 'emg' method of exoskeleton control (20 min),
- filling in the SUS questionnaire (2 min),
- filling in the QUEAD questionnaire (2 min),
- filling in the comfort questionnaire (1 min).

Before starting the study and after its completion, the participants were asked to perform a subjective assessment of fatigue and mood using the Grandjean Scale.

Whereas, the following questionnaires were used to directly evaluate the developed solutions:

- System Usability Scale, SUS [6],
- Questionnaire for the Evaluation of Physical Assistive Devices (QUEAD) [7],
- Comfort assessment questionnaire based on the tool presented in Knight & Baber [8].

Figure 4 shows a marker placed on the effector and three places to which the effector marker should be guided as precisely and as quickly as possible. In the photos we can see two bars - the lower one and the upper one. The lower one has a marker that is used to measure only the accuracy of the vertical position of the effector, while the upper one has two markers. The marker closer to the exoskeleton operator is used to measure the accuracy of vertical and horizontal alignment, and the last marker is only used to assess the accuracy of the effector horizontal alignment.

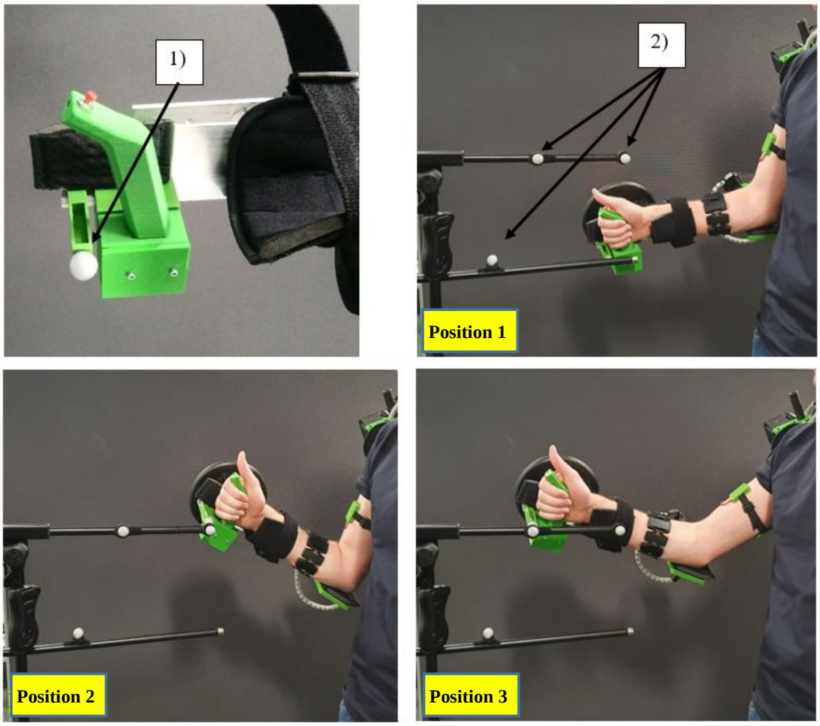

Fig. 4. Main points of guiding the exoskeleton effector. 1) a marker placed on the manipulator's effector, 2) markers placed on the bars

During the tests, each time the participant accepted the position, i.e. they did not want to make any corrections of the effector position, they informed the researcher. The latter then activated the recording of the position of all markers and the current time. The effector movement took place in order to establish the following positions: 1, 2, 3 then position 2 and 1.

4. RESULTS

A common tool for assessing the usefulness of a system or tool is the SUS survey. The highest utility value of 77.5 on the SUS scale was achieved by the joystick control method. The study participants assessed the control method using EMG signals at 39.5 points (0-100 scale).

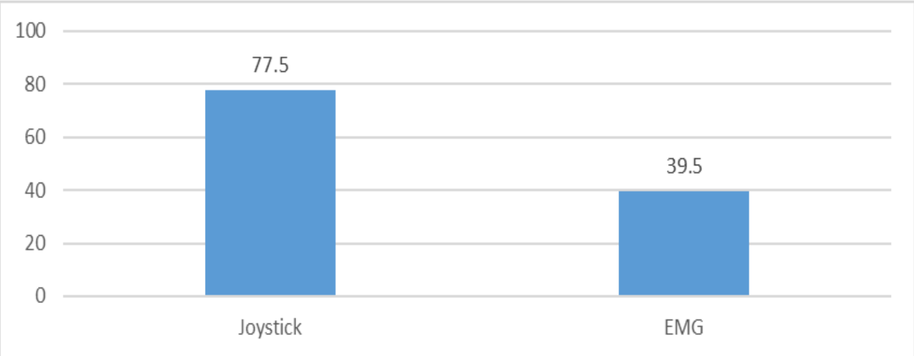

Fig. 5. Average utility values for the developed methods of controlling the upper limb manipulator

The questionnaire was designed and validated to evaluate new physically cooperating robots, exoskeletons, braces, prostheses or other physical assistive devices. QUEAD is used for comparison between at least two control modes or two assistive devices. It can be divided into subscales: perception of usability and usefulness, perception of ease of use, emotions during interaction, attitude and perception of experience and comfort.

The average values for the control method using signals of muscle activity are definitely lower and do not exceed the value of 4 on the point scale (1-7). We noticed the similarity of the values on the perceived usability/usefulness subscale with the mean values obtained for the SUS.

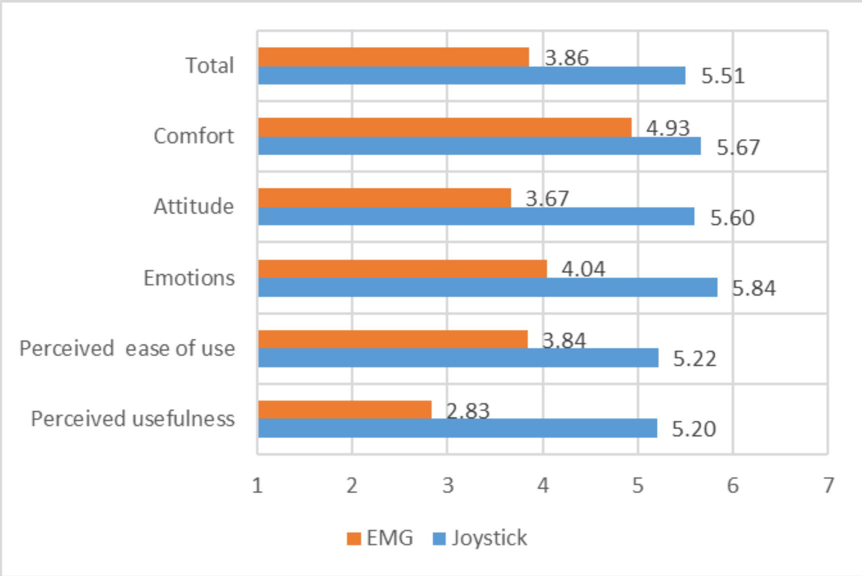

Fig. 6. The average of the values for the individual components of the QUEAD questionnaire

The analysis of the received responses regarding comfort indicates slight differences between the mean values for the tested methods and is approximately 6 on a scale of 1-21, where the lower the value, the fewer remarks on comfort.

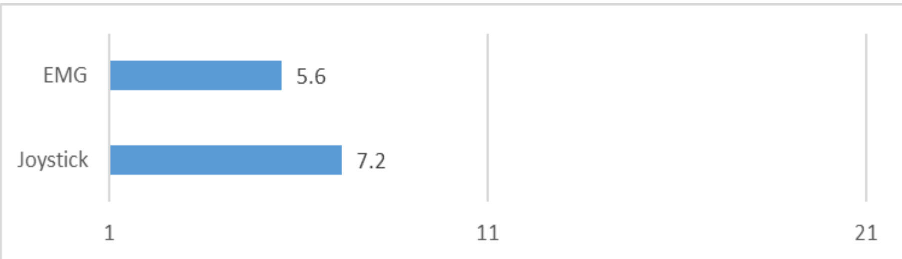

Fig. 7. Average comfort values for the tested methods

In addition to subjective indicators, the execution time of the last 10 repetitions of the tested trajectory was analysed showing that the load does not extend the time of task execution.

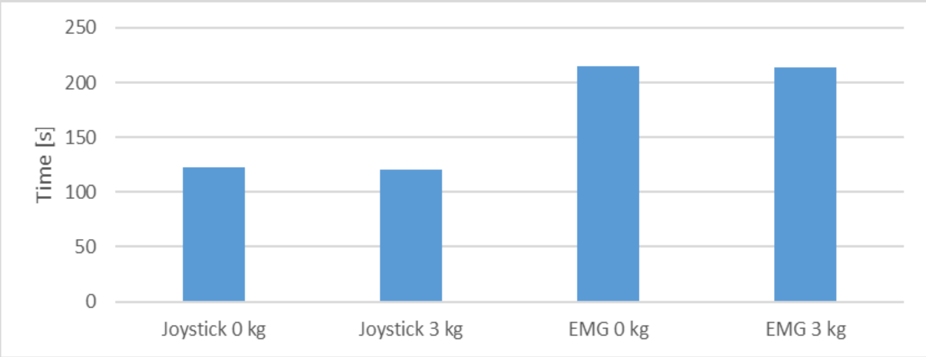

Fig. 8. Average values for individual control methods depending on the load

Another objective indicator is the measurement of positioning accuracy. The chart below shows the average values of the obtained accuracies depending on the tested method, load and direction. It is noticeable that the overall positioning of the manipulator's effector is highly accurate in the vertical and horizontal axis, not exceeding an average of 25 mm.

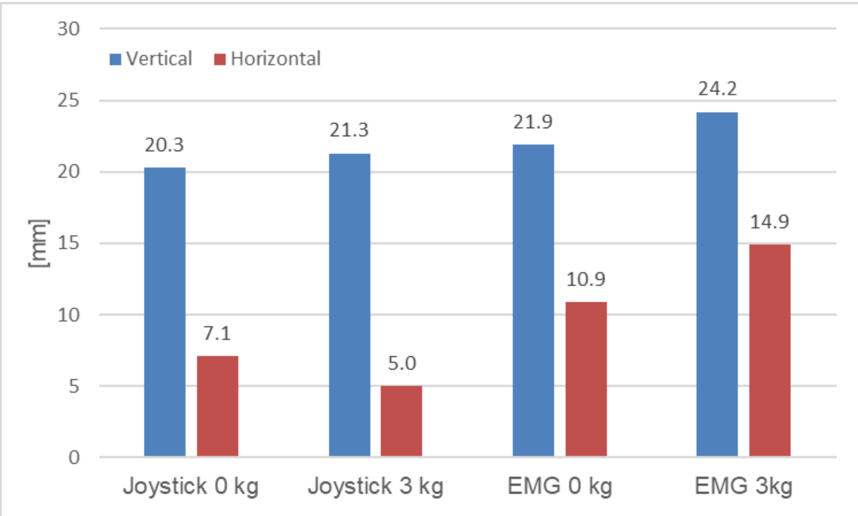

Fig. 9. Average values of manipulator accuracy

5. CONCLUSIONS

The analysis of the recorded data shows the high accuracy of vertical and horizontal positioning of the upper limb manipulator effector, not exceeding 25 mm on average. The time required to complete the task when using the method based on muscle activity was almost twice as long as the method using the joystick, which resulted from many attempts by the participants to obtain the best possible accuracy.

The tested exoskeleton with the joystick-based method achieved the best usefulness values (according to the SUS survey) of about 77 on a (0-100) scale, and below 50 points in the method based on EMG signals.

According to QUEAD, the values of individual indicators: perceived usability/usefulness, perceived ease of use, emotions during interaction, attitude and opinion on experience, comfort for the joystick manipulator were nearly twice as high as for the EMG controlled manipulator. This may be due to the fact that in general the people participating in the study had experience in using various types of joysticks, but had no experience in control using the EMG signal. The results could prove more favourable for the EMG signal if users were given the option of long-term training using this control method.

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Porównanie metod sterowania ruchem modelu egzoszkieletu wspomagającego ruchy kończyny górnej wykorzystujących sygnały o aktywności mięśni i manualne urządzenia sterownicze

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Streszczenie: W pracy przedstawiono metodykę badawczą oraz analizę wyników testu porównania dwóch metod sterowania egzoszkieletem kończyny górnej wykorzystującą sygnały o aktywności mięśni i manualne urządzenia sterownicze. Wyniki pokazują przewagę metody wykorzystującej joystick nad EMG w aspekcie użyteczności, czasu wykonywania zadania, łatwości użytkowania oraz komfortu.

Słowa kluczowe: egzoszkielet, metoda sterowania, EMG, joystick