Development of a portable electromyography IoT system for remote rehabilitation*

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***Abstract*— This paper describes the development of a portable system to measure surface electromyographical (EMG) signals based on the Internet of Things. The system comprises eight modules designed to allow the wireless transmission of the surface EMG signals through a self-designed board to a graphical user interface (GUI). The GUI has three main stages: the configuration that enables the online adjustment of acquisition parameters; the acquisition stage for the visualization and storage of the data, as well as the upload or download to the cloud, contemplating encryption for data security, and finally, a rehabilitation video game that can be programmed according to the users' needs. The system was tested on ten healthy participants, five men and five women, using a protocol for measuring signals during gait. The system showed a maximum data loss of 2.21% in a public network and 0.48% in a private network, a maximum stable frequency of 4700 Hz, and an autonomy of 128 minutes. Finally, it was compared with one commercial device and one clinical system.**

***Index Terms*— Portable system, Rehabilitation video game, Surface electromyography, Internet of Things**

I. INTRODUCTION

Surface electromyography (EMG) has gained significant attention due to its applications, including rehabilitation, prosthetic control, patient monitoring, and entertainment [1]. This non-invasive technique measures the electrical potentials generated in the muscles. These potentials are generated in most of a person's daily activities, such as eating, working, walking, and exercising. Hence, the evaluation of these signals is an important source of information [2]. Additionally, wearable sensors for EMG acquisition have been implemented recently because of their advantages, such as compact design, portability, and comfort.

In general, the development of wearable devices has shown remarkable advances, considering that this type of technology is expected to have an annual growth of 38% from 2017 to 2025 worldwide [3]. Based on the above, numerous devices have been developed to acquire EMG signals that combine precise circuits, methods for eliminating noise, and lightweight/compact designs that generate portable systems. For example, in [4], an EMG module with graphene-coated fabrics as textile electrodes was developed. This system was designed for dynamic applications such as those related to pedometers. In [5], a wireless surface EMG records the signals using Bluetooth and small acquisition modules attached with bands to the body's extremities. Likewise, in [6], a miniaturized wearable wristband-type surface EMG was developed, with a compact design for application in personal authentication systems. Although the devices presented above have a compact, portable design, they have limited applications to solve a specific need, which shortens the versatility of these devices. On the other hand, most of the developed devices do not have interfaces for user interaction, which hinders most people's use of this type of device and limits their use to specialized personnel.

For example, just a few surface EMG acquisition devices have integrated systems for rehabilitation applications. This is important considering that in 2020, the statistics reported in [7] indicated that around 190 million people with disabilities constantly require medical assistance services, which has created the need to develop new technologies that are accessible and adaptable to the patient's needs. The number of people who need assistance may increase due to population growth, demographic situations, and lack of medical personnel and equipment, among others [8].

One solution to mitigate this issue is to implement wearable systems based on the Internet of Things (IoT), thereby providing users at home with the comfort and accessibility of an integrated support system during rehabilitation [9]. This system also allows specialists to monitor patients, reduce the high demands of health services, and reduce therapy times. The use of portable technology can present a significant advantage compared to traditional rehabilitation since the use of sensors or the calculation of relevant parameters can help the physiotherapist to have a quantitative index to evaluate the process of each patient. In addition, the use of systems that integrate hardware and software, giving feedback to the patient, can be helpful for the correct execution of the movements necessary for their therapy, and also create interactive systems that motivate the patient to perform their rehabilitation sessions [10], [11]. In the case of surface EMG, which gives us a qualitative index of muscle activity, it can be of great benefit to create devices that adapt to the patient's needs and also support the recovery from home, with the advantage that specialized personnel can continuously monitor the process and make adjustments to the therapy if necessary [12].

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Based on the above, this work presents the development of a portable and wireless surface EMG acquisition system that integrates the IoT by implementing a graphical user interface (GUI). This interface allows the acquisition of up to eight surface EMG signals, the adjustment of parameters such as gain and digital filter applications, and finally, the development of a video game to support rehabilitation therapies with visual feedback. This paper is organized as follows: Section II provides the system requirements. Section III describes the developed acquisition system, comprising hardware and software. The application corresponding to the rehabilitation video game is discussed in Section IV. Section V presents the system validation and comparison with other devices. The obtained results are evidenced in Section VI. Some final remarks are provided in Section VII.

II. System requirements

The surface EMG signal acquisition system is mainly composed of two elements: the hardware, which comprises the development of the sensors, and the software, which includes the GUI that focuses on the possibility of performing complete studies of muscle groups, and an interface that supports the patients' remote rehabilitation. The following points contemplate the design requirements for the modules:

- A portable device, i.e., it should have a battery capable of generating the EMG study required by the user and, in addition, a fast and wireless communication protocol for sending the information.
- An easy-on and off device that can be adjusted to different anatomical body segments.
- Compact and lightweight, ensuring it does not interfere with the natural movement of human body joints.
- A simple GUI for the subject that provides visual feedback to indicate to the user that the rehabilitation process or execution of the movements is correct.
- Reproducible and easy to manufacture. 3D printing was considered for fabricating the structural elements.
- Adjustable parameters such as gain and application of digital filters in the acquisition sensor to obtain a product that meets the user's needs.
- Capable of acquiring up to eight surface EMG signals simultaneously, enabling comprehensive analysis of different human body sections.

III. Surface EMG sensors

This section provides a detailed description of the components that comprise the system.

A. Electronic instrumentation

For the design of the modules, the primary energy of the EMG was considered for the frequencies between 10 and 500 Hz [13]. From the above and based on the Nyquist Theorem, the minimum frequency of the system was set at 1000 Hz. Additionally, to eliminate the extra noise, a low-pass filter and two notch circuits were implemented, one to eliminate the noise at low frequencies and the other to reduce the noise caused by the electric power, which in our case has a frequency of 60 Hz. A Printed Circuit Board (PCB) was designed and fabricated with the acquisition circuit that considered the following four main stages:

1) Pre-amplification: The maximum gain was considered 1100 times the input amplitude. For this purpose, a fixed amplification of 150 times the input amplitude was established in the pre-amplification stage. In the post-amplification stage, the system amplifies between 150 and 1100.

For this stage, the INA333 was considered as the instrumentation amplifier since its internal circuit has radio-frequency-interfering circuits that decrease the recording of radio frequency emissions. On the other hand, it has a Common-Mode Rejection Ratio (CMRR) value of 110 to 115 dB for amplifications above 100 times the input amplitude. The above is important since a CMRR value above 100 dB is recommended for EMG circuits, considering that a high CMRR value reduces the acquisition of extra noise [14]. Additionally, the preamplifier circuit has a right-leg circuit to set the reference point of the acquisition circuit.

2) Filtering: The filtering stage considered a second-order Butterworth low-pass filter with a cutoff frequency of 500 Hz. This filter maintains the predominant frequency range. Then, a Twin-T notch filter with a center frequency of 6 Hz, a bandwidth of 8 Hz, and a quality factor of 0.75 was added. The function of this filter is to eliminate low-frequency noise caused by motion artifacts. A high-pass filter was not used to avoid the elimination of the baseline voltage. This parameter is one of the adjustable features of the system, taking into account that, as the gain is variable, the adjustment of this parameter will avoid signal saturation when the system gain increases. Finally, there is a notch Twin-T filter with a center frequency of 60 Hz and a bandwidth of 10 Hz to attenuate the noise caused by the power line.

3) Post-amplification: The post-amplification stage represents the innovative part of the designed circuit. As previously indicated, a primary objective is to generate a system that is adjustable to the needs of the study. To achieve the above, two digital potentiometers were added to the circuit. The first one varies the system's gain between 150 and 1100 input amplitudes. The second one allows the baseline's voltage value to be modified. The digital potentiometers were attached to the PCB, and their values were modified using the communication protocol proposed for the GUI. Specifically, the implemented digital potentiometers have 257 steps and a value of 10 kΩ. The potentiometers' adjustment is described in detail in Section IV.

4) Analog-to-digital conversion: The final stage of the instrumentation was an analog-to-digital converter (ADC). For this purpose and to reduce the size of the modules, a FireBeetle 2 ESP32-E microcontroller with a 12-bit ADC was used. The choice of a 12-bit ADC allows us to record minimal changes in the signal, which is important in EMG, considering that variations in the signal can represent relevant information in the signal analysis.

Another advantage of the FireBeetle 2 ESP32-E is its integrated Bluetooth and WiFi modules, which facilitate the wireless communication contemplated in the project's development. In addition, it has a battery charging circuit, which is activated by connecting the module and the battery to a power source through a USB Type-C port. Finally, and according to the characteristics of the microcontroller and the acquisition circuits, a 3.7 V Li-Po battery was used as a power supply, so the modules have an operating range of 0 to 3.3 V. This is important because the design of a system capable of acquiring positive and negative values requires more elements such as a second battery, thus increasing the size of the proposed system. The previous steps were summarized in the diagram presented in Figure 1.

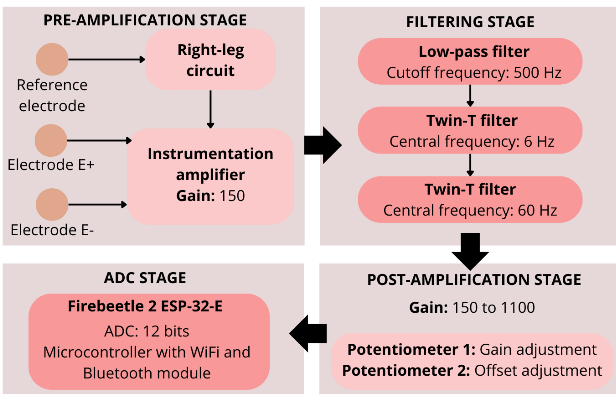

Fig. 1. Stages in the circuit design.

B. Structure design

The design of the structural elements was considered to be as compact and light as possible, guaranteeing no interference with the person's natural movement and placement in different anatomical segments. Wet electrodes were also chosen since their adherent surface facilitates their placement, and they do not require extra accessories to place the modules. On the other hand, their conductive gel with silver chloride improves the conduction of the electrical potential. It reduces the possibility of noise recording due to poor electrode contact with the skin [15].

On the other hand, the 3D printing method was used to guarantee the repeatability of the manufacturing process, using Polylactic Acid (PLA) as the printing material. This material was chosen for its advantages, such as ease of printing, biocompatibility, strength, and hardness [16].

The system has three structural components: a main case, an electrode holder, and a cover for the acquisition circuit. These elements were obtained considering as printing parameters a speed of 100 mm/s, a temperature of 200 °C, and a filling percentage of 30%. Figure 2 shows all the elements that compose the EMG module, where (1) represents the electrodes in bipolar arrangement for EMG recording, (2) represents the main structure where all the elements are condensed, (3) is the system cover, (4) is the battery, (5) is the electrode holder, (6) the PCB containing the analog circuit, and (7) is the microcontroller.

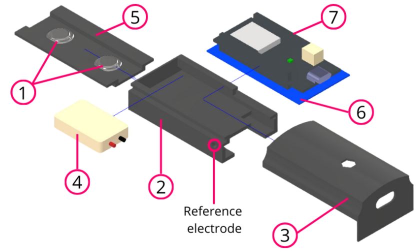

Fig. 2. Main elements of the surface EMG sensor.

IV. Rehabilitation software

The present section describes the design and functionality of the system software. Subsections include the communication protocol, software stages, and rehabilitation video game.

A. Communication protocol

The system must guarantee a minimum acquisition frequency of 1000 Hz to ensure that the recorded data generates a valid signal reconstruction and that the online processing and visualization of at least eight modules in the GUI can be performed. Sending the information via Bluetooth and WiFi protocols was a possible option. In the case of Bluetooth, it was observed that receiving the necessary data from the sensors for higher sample rates was not achievable. For this reason, WiFi was defined as the acquisition protocol.

On the other hand, the user is expected to be able to establish higher frequencies if the study requires them. The User Datagram Protocol (UDP) was chosen instead of protocols such as Message Queuing Telemetry Transport since the latter uses multiple confirmation messages to send data. In contrast, by establishing a communication port, UDP sends the data of interest continuously without needing confirmation messages, thus allowing higher sampling rates.

On the other hand, for the WiFi module connection, the microcontroller needs the network information and a UDP port. A serial protocol was used to send the information previously mentioned to the modules. With this protocol, from the GUI and using vectors with characters, the Service Set Identifier (SSID), the respective network password, and the UDP port of the module were sent in an orderly manner. It is important to note that a different UDP port was set from the GUI for each module. This way, once the module is loaded and connected to the WiFi network, the GUI uses only UDP-WiFi as a communication protocol. The UDP-WiFi connection was established in a bidirectional way since, during the adjustment of the modules, the user can send the value of gain, offset, or filter activation from the interface to modify these parameters directly in the sensor. Then, during the acquisition or use of the rehabilitation interface, the communication worked the opposite way, sending the surface EMG signals from the module to the GUI.

B. Software stages

The software consists of three sections: the device configuration section, the surface EMG signal acquisition or recording stage, and the rehabilitation video game. Each of the stages is described below.

1) Configuration: As mentioned above, one of the system's advantages is its wireless communication and adjustable parameters for the surface EMG signals. First, the GUI prompts the user to enter the SSID and password of the WiFi connection, and finally, the user enters the number of modules to be connected. Then, each module is connected to the computer through serial communication, and the microcontroller of each module receives the network information and the assigned UDP port. If the module connection is successful, a Light Emitting Diode (LED) on the interface indicates to the person that the process was completed. The GUI receives the Internet Protocol (IP) address assigned for UDP-WiFi communication through serial communication. Then, there is a calibration stage; here, the user can preview each signal online and adjust the offset and gain parameters by sliders, as shown in Figure 3. Additionally, each module contains a switch allowing the user to apply a digital high-pass filter with a cut-off frequency of 10 Hz. The signal displays are observed in voltage, considering that the system's operating range is from 0 to 3.3 V.

Fig. 3. Acquisition GUI.

Figure 3 shows that stage (1) is responsible for varying the amplification of the signals from 150 to 1000 Hz. On the other hand, stages (2) and (3) show the recording of two EMG signals with amplification and variation of the offset value using the sliders, while stages (4), (5), and (6) display the signals of modules with the implementation of the digital filter activated with the switch.

2) Acquisition: This stage executes complete surface EMG studies. In this section of the GUI, the user can see the adjusted signals online, and each signal has a text box for the user to indicate the area or muscle group evaluated. In addition, there is a local storage system with two text boxes, one for entering the file's name and the other for entering the computer's address where the comma-separated values (CSV) file is saved. This file contains both the signals and the values of gain, offset, or application of filters established in the configuration stage. On the other hand, for the IoT implementation, the interface has a Quick Response (QR) code that runs the interface on mobile devices; with that, it is possible to monitor and record studies remotely in case the specialist or working group is not in the same place. In addition, the interface has cloud storage. The user enters a password and the previously entered file name, as shown in Figure 4.(1). Then, the GUI creates a new file name with these two character strings and encrypts the information using the Advanced Encryption Standard algorithm with a 128-bit hidden key. The above is crucial since, to preserve the information's security, the users can only extract the file later using the name and the key they established for their file, as shown in Figure 4.(2). If the key and name match, the interface downloads the file from the cloud and decrypts it to store it in the local address entered by the user.

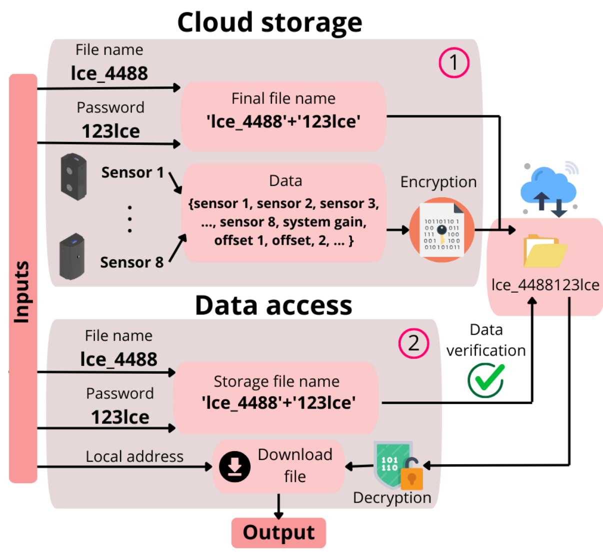

Fig. 4. Schematic representation of data access and storage in the software.

C. Rehabilitation video game

The design requirements considered for the rehabilitation game were the adaptability to different subjects and their muscular capacity, ease of use in case the patient decided to implement it at home, and adjustment according to the number of repetitions needed during therapy, the effort or power generated by the patient to achieve the objective, and the time of each session. Considering the above, the diagram in Figure 5 shows how the game operates.

To start the rehabilitation game, the user must input the number of repetitions, the maximum power percentage at which the video game will be executed, and finally, which connected module will be used. The above will be the input data for the video game configuration, as shown in Figure 5-(1). To connect the sensors to the interface, the user must carry out the process specified in Section IV-B.1.

Subsequently, the next stage is the calibration of the game, as shown in Figure 5-(2). For this, the user is asked to leave the muscle group where the module is located at rest and not to make any contraction, and then the signal power is calculated. Subsequently, the users need to perform their maximum voluntary contraction, and again, the GUI calculates the signal power during the contraction period. These two recorded power values indicate the operating range of the video game for the participant. From this, the levels and difficulty of the game are established. From the range of operations obtained, a power of 20% of the value entered by the user in the previous stage and 20% of the total number of repetitions is used to complete the first level. For Level 2, the participant must complete 40% of the repetitions with a power of 40% and similarly, as shown in Figure 5-(3).

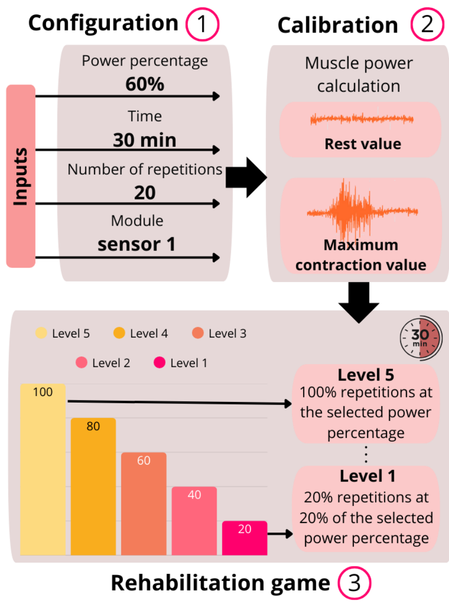

Fig. 5. Operation of the video game.

Finally, for Level 5, the participant must complete 100% of the repetitions with the maximum power value set in step (1). If all five levels are completed before the set time, an animation will indicate to the users that their therapy session was successful. Otherwise, the GUI will indicate to the participants that the process was unsatisfactory, and if necessary, they can start the game again. All the information generated, including the EMG signals, is stored in a CSV file so that specialized personnel can track the user's rehabilitation processes if necessary.

V. Validations

For the device's validation, three extra devices were used to acquire EMG signals, and different parameters were compared. A commercial sensor, a Myoware sensor, and a clinical device, Neuropack S1, were used. The subjects were asked to generate three contractions in a 3-second interval of the wrist extension movement. The sensors' electrodes were placed in the Extensor Carpi Ulnaris and Extensor Digitorum muscles. Then, the parameters evaluated were power, mean absolute value, root mean square value, signal-to-noise ratio, waveform length, and common-mode rejection ratio [17]. The results of the comparison are shown in Section VI.

VI. Results

To validate the video game and demonstrate its versatility, signals were collected from 10 participants, five men and five women, during a one-minute walk at 2 miles per hour. Signals were collected from each leg's: (1) Vastus Lateralis, (2) Biceps Femoris, (3) Tibialis Anterior, and (4) Gastrocnemius Lateralis muscles, as seen in Figure 6. The participation of all subjects was voluntary, and the protocol with number SIP-20250253 was approved by the Secretaría de Investigación y Posgrado del Instituto Politécnico Nacional (IPN).

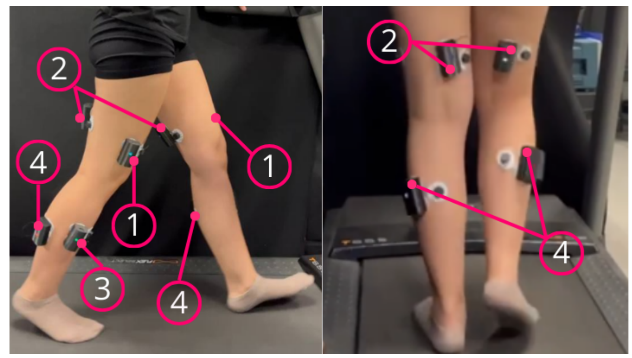

Fig. 6. Sensor placement.

The tests performed showed the generated system's versatility. It could be implemented to collect up to 8 muscle groups during human walking, verifying the correct design of both the circuit and the structural elements of each module. Data loss, system autonomy, module synchronization, and system acquisition frequency were also evaluated.

For data loss, it was validated that for the time of each test, the amount of data from the sensors corresponds to the sampling frequency considered. The average data loss was 1.81% for the tests performed with the 10 subjects. This is due to the tests being performed with two WiFi networks: one using a public network, where a maximum data loss of 2.21% was recorded, and a single network for the system connection, where the maximum data loss was 0.48%.

Subsequently, the eight modules were activated and verified when any of them were discharged to evaluate the system's autonomy. In this test, the autonomy time achieved with the eight modules was 2 hours and 8 minutes. This value shows the system's versatility to use it in prolonged tests. Then, for the validation of the synchronization of the modules, the 1-minute tests were collected for each user, and it was verified that the size of the vectors generated by the eight modules was equal. A difference of 0.06% in the size of the vectors was obtained. The difference in the size of the vectors, as well as the loss of information, was directly related to the WiFi network used, since, in the case of the network where only the surface EMG system was connected, the vectors generated had the same value.

Then, the maximum acquisition frequency was evaluated, achieving a maximum acquisition value of 4700 Hz. This can be very useful in specific studies where recording a frequency range is relevant to analyzing the information.

Figure 7 shows the rehabilitation game operation interface, where the system's acquisition and use parameters are guaranteed from the tests mentioned above. In the figure, when the user performs a voluntary contraction appropriate for the current level, an animation of a chicken is activated and jumps, generating visual feedback to the user to indicate whether the movement was appropriate.

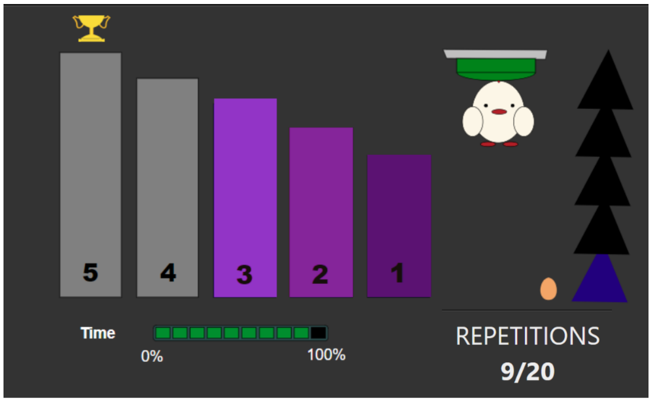

Fig. 7. Rehabilitation video game GUI.

The implementation of the video game with the participants shows its use in multiple applications, considering that the information used by the video game is stored in case the specialized personnel need it. Based on this, it is expected to perform, as future work, the video game evaluation during the rehabilitation process of a group of people, and thus quantitatively verify the percentage of improvement or recovery of patients, as well as the times and use of different therapies.

Finally, EMG signals were obtained with the three different devices. The signals were normalized from 0 to 1 to evaluate the characteristics presented in Table I. In this table, we can observe similarity in the parameters obtained, which shows, to a certain extent, the correct operation of the developed module. In addition, it is observed that our design presents a higher value of signal-to-noise ratio, which indicates that the proposed filters perform a considerable noise attenuation while maintaining the relevant information of the signal.

TABLE I
EMG SENSORS COMPARISON

Feature	Developed system	Neuropack S1	Myoware
Energy	358	413	399
Mean absolute value	1407	1503	1432
Root mean square	0.1962	0.2188	0.2017
Signal-to-noise ratio	0.5343	0.5649	0.6921
Waveform length	621	304	268
CMRR (dB)	115	112	140

VII. CONCLUSION

This work presented the development of a system for acquiring surface EMG signals based on the design of portable acquisition modules with adjustable circuit parameters and WiFi communication for wireless and wearable use. This system can connect up to 8 modules, which allows its application in different studies of the neuromusculoskeletal system. Additionally, the system uses IoT for remote control and storage in the cloud to generate greater accessibility to information. Finally, as a potential application, the system has an adjustable video game that allows the patient to carry out, in a didactic and remote way, the rehabilitation process, as well as to generate metrics that will enable the specialist personnel to evaluate the performance of the patient quantitatively during their therapy.

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