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Design and Development of an Elbow Exoskeleton for Home Therapy.

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***Abstract*— Medical robotic systems might play an important role by assisting the healthcare personal by allowing patients to continue their therapy at home and protecting the healthcare personal and patients from COVID-19 with social distancing [1]. This article describes the design and development of an elbow exoskeleton. The design follows a methodology based on the ISO 9241, that deals with problems of anatomical design of the device, types of control, and user-centered design (UCD), to develop a medical robotic rehabilitation device that supports the healthcare professional and suits the needs of the rehabilitation user.**

***Keywords*— Exoskeleton, User-Oriented Design, Stroke patients.**

I. INTRODUCTION

Worldwide most of the healthcare systems capacity has been focused on fighting the COVID-19 pandemic, pausing less urgent care such as physical neurorehabilitation. Medical robotic systems might play an important role by assisting the healthcare personal by allowing patients to continue their therapy at home and protecting the healthcare personal and patients from COVID-19 with social distancing [1].

According to [2], over 120 medical devices based on robotics systems are announced, where only four are FDA certified. The reason for reporting many robotic devices is because this type of system has advantages over traditional therapies, such as providing more intensive and controlled therapy and measuring the progress of the individual. In the case of the economic aspect, it is reported that this type of system might reduce the assistance of a physiotherapist. In the case that this system is supervised by a physiotherapist, this type of system will allow attending a greater Number of patients [2–4], since it will prevent the physiotherapist of getting tired.

Most of the reported exoskeletons focus on treating subjects who suffer from stroke [5–14]. Also, most of the developed or research exoskeletons have a weight that ranges from 16 - 204 Kg [8, 11–14], occupying large work areas, making difficult to take this system for home therapy. Current portable upper limb exoskeletons weight 2 Kg or more [7, 10], which can still be considered high for subjects who do not have high muscular strength.

According to the above, it is observed that there are many robotic rehabilitation devices, where its advantages in the economic field and therapy are great, however, its use is not common. This can be due to two main reasons. The first reason is that this type of system still cannot demonstrate all its benefits. The second reason and as pointed out [15], is that the design of this type of exoskeletons focus on stroke patients but do not focus on their needs.

This article describes the design and development of an elbow exoskeleton with one degree of freedom (DOF) to assist the rehabilitation process of persons who suffer from a stroke or spinal cord injury. For the exoskeleton design of this project, the guide is followed as indicated in [15], which is based on the process design of ISO 9241 standard, although it does not describe the processes that will be used, it can be applied to robotic rehabilitation devices, which focuses on knowing the characteristics and objectives of the users, the activity and the usability measures. The proposed exoskeleton weighs 1.5 kg, is portable, and focuses on end-user needs; these features might result in an exoskeleton whose uses might become common.

II. METHODOLOGY OF DESIGN.

As a basis for this UCD, the use of the ISO 9241 standard on ergonomics of human-system interaction is being used (see Fig. 1). Although the standard does not describe the processes used, it generally describes the products to be obtained.

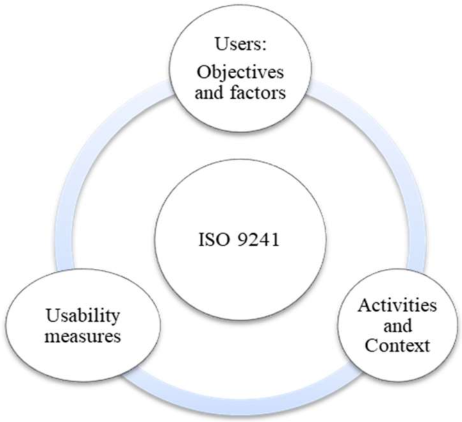

Fig. 1. ISO 9241 processes diagram.

In the case of rehabilitation, there are two types of users: the patient and the medical personnel [14]. In the case of a robotic rehabilitation device, the objective should be to support the movement of the person during the therapy. In the case of medical personnel, the aim of using this robotic orthosis can be identified as the ease of use, and the ease of follow-up of the patient's rehabilitation. For the design of this elbow exoskeleton, it identified as patients those suffering from a stroke.

In order to know the activities and contexts of the patients as well as in [14], a functional evaluation battery methodology is followed to collect relevant information for the design of the elbow exoskeleton.

On the other hand, to comply with the functional evaluation battery methodology, six items [14][16][17][18][19][20] were selected after a search in PubMed (years: 20005-2018, key words: CP, MS, Stroke, TBI, SCI).

From the review of these articles, five rehabilitation scales are identified (the rehabilitation scales allow medical professionals to evaluate the functionality of a patient), which, together with the help of medical professionals, five priority activities in the use of daily life are determined. The importance of the identification of the activities is since during the rehabilitation, and the subjects must relearn motor tasks to overcome their limitations and perform their activities of daily life.

Some classification scales for performance measurement in upper extremity rehabilitation therapies are Van Lieshout Test (VLT), Fugl Meyer (FMA), shoulder and arm disabilities (DASH)

The third block of ISO 9241 corresponds to the measures of usability, which are understood as those elements that allow us to measure the success of the device. This can be achieved through the user identified as clinical staff through their feedback and interaction with the exoskeleton, and through the implementation of a rehabilitation scale in the system that allows us to measure the rehabilitation progress of the subject.

Once defined, the elements that belong to the ISO 9241, the proposed conceptual design diagram is shown in Fig. 2. in

TABLE I. DAILY LIFE PRIORITY ACTIVITIES OF A PERSON SUFFERING FROM STROKE OR SPINAL CORD INJURY.

Priority activities found on people suffering from stroke and spinal cord injury.			
Functions	***Structures***	***Activities***	***Environmental factors***
Mobility of joint functions	Structure of upper extremity	Transferring oneself	Technology for personal use in daily living
Muscle tone functions	lower extremity	Toileting	Technology for personal indoor and outdoor mobility
Muscle power functions	Structure of trunk	Changing body position	Immediate family
Voluntary movement functions	Shoulder region	Hand and arm use	Health services, systems, and policies
Proprioceptive function	Spinal cord	Moving around using equipment	Products and technology for communication

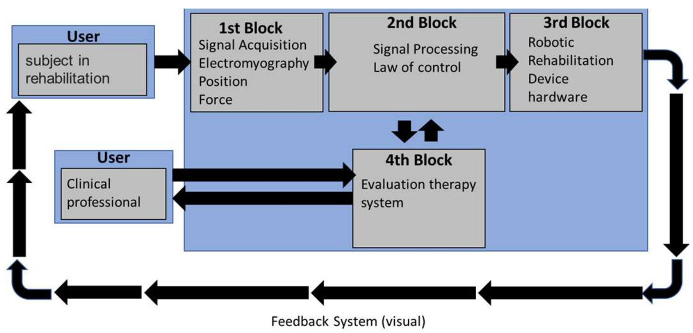

Fig. 2. Robotic rehabilitation device conceptual design diagram.

the conceptual diagram, there are two main elements. The first element corresponds to the users, while the second element relates to the robotic rehabilitation device. In the case of the second element, four sub-blocks are described as follow:

The first block relates to the acquisition of physiological signals. This block allows the acquisition of signals that are used as input to the processing system, which in turn is used as input to the control system.

The second block corresponds to the processing system and control system. This block processes the signals of the different sensors and activates the actuators based on the control law. This block has communication with the therapy evaluation system.

The therapy evaluation system has two functions. The therapy system's first function is to help the clinical professional determine the type of therapy given to the user in rehabilitation. The second function of the therapy evaluation system corresponds to keep track of the progress of rehabilitation therapy.

Finally, the third block of the robotic rehabilitation device belongs to the mechanical part of the system.

III. Development of an elbow exoskeleton.

A. *Signal processing.*

This section relates to the first block of the robotic rehabilitation device's conceptual design. Sensing is an important feature to consider in the design of a robotic rehabilitation device. The sensors are used to estimate the state/physical properties such as: joint position, velocity, acceleration, and motor torque. The integration of sensor data in the robotic rehabilitation device allows to plan for a control system and add security for the end-user. To get the joint position, encoders from the electric motors are used. To add protection to the system, a load cell placed on the elbow motor to the forearm interface is placed. This load cell allows measuring the resulting force between the end-user and the actuators when performing a movement

Surface Electromyography (sEMG) signal from the biceps is obtained with a proposed sensor previously defined in [21]. sEMG signals measure the activity of the muscles and might contribute with information on how the user is progressing in therapy [22]. Some features of the sensor are: Bluetooth wireless, 1000 Hz frequency sampling.

These signals are currently being processed to indicate muscle activation. The signals had the following processing (see Fig. **3**):

•Pass – band filter of 40 - 450 Hz.

• Rectification of the signal.

• Low-pass filter at 10 Hz to obtain the signal envelope.

Once these signals have been processed, the maximum value of the signal is obtained and normalized to one. The activation threshold is defined as 30% of the normalized signal value for the system to work.

Electromyography signal processing is performed in the therapy evaluation system program. The therapy evaluation system is run on a computer with a windows operating system. Once the electromyography signal is processed, it is sent to the embedded system as input to the system's control.

B. *Exoskeleton Implementation.*

This section focuses on the second and third blocks of the robotic rehabilitation device's conceptual design. When designing a robotic rehabilitation device, it is important to consider the anatomical structure of the human upper limb. The incorrect alignment between the exoskeleton and the human upper limb makes patients uncomfortable when they are given therapy [3, 23, 24]. To deal with this feature in the case of the elbow, the developed exoskeleton proposes to attach the mechanical structure of the robotic rehabilitation device to an orthosis allowing the exoskeleton to adapt perfectly to each anatomical extremity.

According to [25, 26], the actuators that will be used in the exoskeleton must be light, have high operating bandwidth, be able to produce a precise movement, and deliver a large amount of torque.

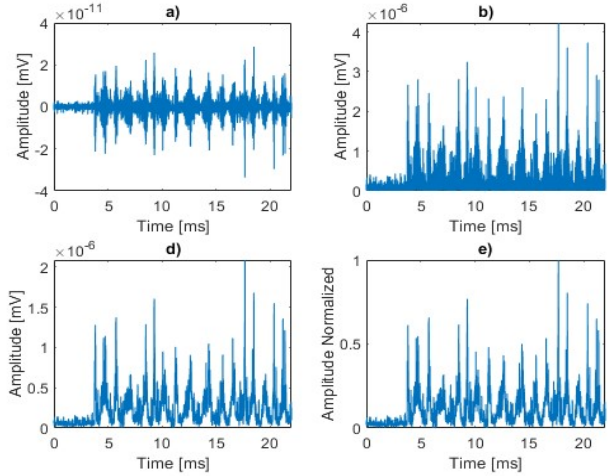

Fig. 3. sEMG signal processing. A) Raw sEMG. B) Rectified sEMG. C) The envelope of the sEMG signal. D) Normalized to one sEMG signal.

In the literature, three means to actuate an exoskeleton are available: electric motors, hydraulic/pneumatic actuators, and linear actuators. The proposed exoskeleton actuators such as hydraulic/pneumatic and linear were dismissed because they lack precision and accuracy or have a big weight, respectively. Therefore, electric motors were adopted because they can provide greater controllability using motion control, are lighter than other actuators, and have a lower power-to-volume and power-to-weight ratios. In the joint of the elbow, a servomotor MX-106 (Robotics S.A., Barcelona, Sabadell, España) is used. The MX-106 has a recommended operating voltage of 12 V, which allows it to generate a

torque of up to 10 N m (Torque considered sufficient to raise a forearm whose average weight is 2.5Kg). Other relevant features of the MX-106 is the torque control via current sensing, or the possibility of getting the feedback of the position, temperature, load, input voltage, current, allowing the designer to implement any custom law of control.

The range of motion of the elbow flexion and extension of the functional elbow described in the literature [14,15] of the elbow ranges from 30 ° –130 °. Outside of this range, the exoskeleton has mechanical stops that limit movement.

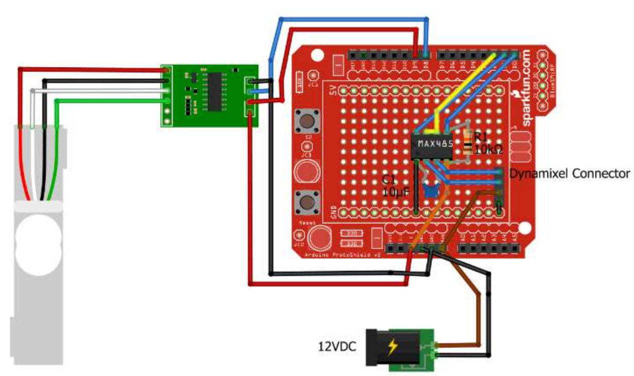

Fig. 4. Elbow exoskeleton circuit diagram.

To integrate all the actuators and sensors, an Arduino is used. The load cell data was collected with an HX711 (Avia Semiconductor, Xiamen) signal amplifier. To communicate with the MX-106 actuator UART two bias to one bias arrangement is done with the Max485 (Maxim Integrated, San Jose CA, USA) is done. To feed all the system, a Lipo battery with an output of 12 V with 5 Amp delivery is used. To communicate the system via Bluetooth, an HC-05 device is used (see Fig. 4.). The sensor and the mechanical design the system are depicted in Fig. 5

The developed exoskeleton attached to fiber carbon orthosis covered with antibacterial foam is shown in Fig. 6.

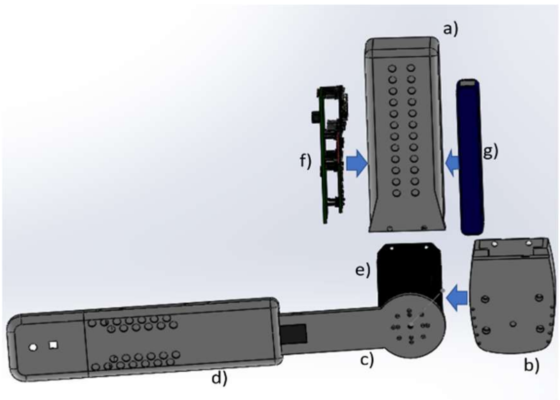

Fig. 5. Elbow section exoskeleton. a) Electric circuit cover. b) Servo motor cover. c) Motor interface piece to the forearm. e) Cover of the motor interface piece to the forearm. f) electronic circuit. g) System battery

Fig. 6. Developed elbow exoskeleton.

The law of control that is implemented on the proposed exoskeleton is a Proportional Derivative control (PD). In the PD controller, the variable, τ was the joint actuator torque, q and $\dot{q}$ were the position and velocity obtained by integrating the dynamics of the musculoskeletal model, qd, $\dot{q}d$ were desired joint position, and desired velocity, respectively. The PD controller output is presented in equation (1).

$$\tau = k_p(qd - q) - k_d(\dot{q}d - \dot{q}) \quad (1)$$

The gains k_p and k_d were set to 2, and 5, respectively. The PD controller was tuned manually.

The purpose of the exoskeleton is to allow the user to participate in rehabilitation. For this, the system identifies muscle activation. This muscular activity is used as a switch. When muscle activity is found, the PD control law moves the robotic arm into a flexed position in 10 ° increments and stops at 130 °. When there is no muscle activity, the system decrements its position by 10 ° and stops at a 30 ° position.

The Proportional Integral Derivative control is not used because it is considered that this control law is pure error-driven, which might generate a large amount of torque if the exoskeleton is stuck somewhere because of the accumulation of the error.

This final section deals with the fourth block of the robotic rehabilitation device's conceptual design. The therapy system is an interface developed in the C# programming language, compatible with windows operating systems. The robotic arm connects via Bluetooth to a pc, and it communicates with the program through a serial port.

The interface must be controlled by the medical professional. The developed interface has four options (see Fig. 7). In the goniometry option, the robotic arm does not offer resistance, and through it, the user can move his arm while the exoskeleton encoder sends this data to be plotted in real-time. This function is useful to see the ranges of movement of the user. The second option, "Set Position," allows us to define a trajectory by the medical professional, and this is reproduced for the user in therapy. The third option of "game" displays a game of pong where through the goniometer of the robotic arm, a bar is controlled in which all the color blocks must be eliminated, and the ball must not fall (see Fig. 8). The fourth option, which is an assistance mode, uses the load cell to drive the exoskeleton.

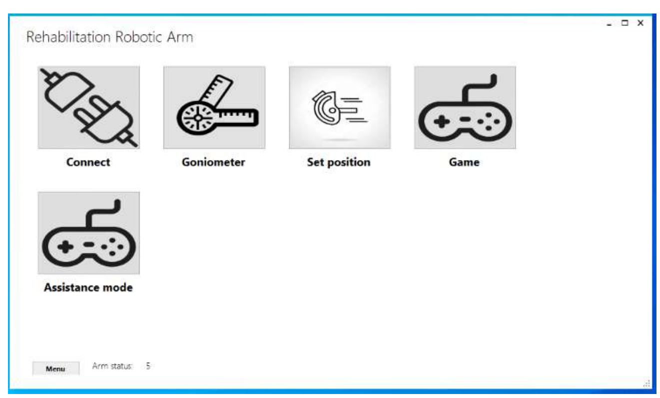

Fig. 7. Therapy system, main user interface.

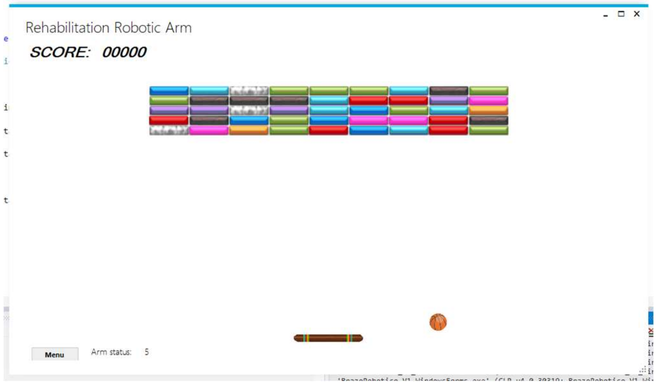

Fig. 8. Therapy system, game interface.

IV. CONCLUSIONS

This article presents the development of an elbow exoskeleton that was designed through a UCD approach. Applications like the goniometry system and games will allow users and medical staff to reread motor tasks to overcome their limitations and perform their activities of daily life. Elements on the sensors such as assessment of a range of motion, muscle signal activity, and the force applied to the exoskeleton allow objective data from the therapy. These data can be transported to the evaluation scales and thus obtain a better follow-up of the user in the therapy treatment.

As noted in the UCD assessment, rehabilitation should focus on training users in activities of daily living. For this, the exoskeleton must have a greater number of joints that allow movements of the elbow and wrist that will be added in the future. Also, the selection of control laws to be used on therapy where the user is involved is still a challenge since when patients start regaining their lost motor function over time, the robotic rehabilitation devices must allow patients to move their limb on their attempt.

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