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Development of a single actuator exoskeleton for wrist and forearm rehabilitation

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***Abstract*— Recent estimations state that the absolute number of strokes will increase in the future. For this reason, novel rehabilitation therapies, such as robot-assisted therapy, are essential to speed up patient recovery. This paper describes the design, development, and control aspects of a light-exoskeleton addressing forearm and wrist motions using one actuator. Besides, usability pilot study results are presented.**

I. INTRODUCTION

Stroke is the leading cause of adult disability in Europe. It affects roughly 1 million Europeans every year. The absolute number of strokes will increase by around 36% in 2025 [1]. People who have survived will have to overcome a wide range of consequences related to language and cognitive disorders, paralysis, pain, and emotional disorders [2].

Public healthcare system capacity seems to be inadequate according to the future expectations. Nowadays, novel therapies involving exoskeletons and other robotic devices in post-stroke physical therapy could be the break to avoid collapse.

Among these novel therapies, mostly robotic devices are active exoskeletons and address upper-limb occupational therapies combined with robot-oriented rehabilitation interfaces and environments [3].

Robotics applied in rehabilitation aims to raise the intensity of the therapy and the motivation of the patient [4]. Besides, it offers a safe environment, especially needed at the beginning of the recovery [5]. However, rigid exoskeletons with more than 2 degrees of freedom are usually heavy and bulky because of the actuators used in each joint. In [6], [7], [8] we can find some examples of heavy robotic devices used in rehabilitation therapies. Hence, the user's comfort would be lower than in traditional therapies where a voluminous device is not used. The development of an upper-limb comfortable treatment would positively affect the patient and the rehabilitation outcomes.

The objective of this work is to propose an upper-limb exoskeleton designed to increase the comfort of patients. The developed exoskeleton is lighter than other robotic devices with the same characteristics since it offers three degrees of freedom using one actuator. The experimentation aims to test if the exoskeleton can interact with a human arm with precision and safety while conducting a simple occupational therapy. Besides, the comfort of the device will be measured using a usability test.

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II. METHODS

A. Arm wrist exoskeleton

The robotic system presented in this paper is based on the registered patent number WO2020183049A1. It is composed of an upper-limb exoskeleton fixed to a height regulable table. Besides, it is adapted to people with reduced mobility. The rigid exoskeleton weights 2.25 kg.

The robotic device consists of a 3 degrees of freedom exoskeleton (Figure 1) optimized for rehabilitation therapies where the patient has limited mobility in the right wrist and arm. A computer performs Real-time control. The graphical user interface consists of a monitor that displays activities synchronized with the movements of the exoskeleton. The device has been named "AWEXOS" (arm and wrist exoskeleton).

1) Requirements: We aimed to design an upper-limb exoskeleton for forearm and wrist movements using one actuator. This configuration would make it possible to develop a lightweight robotic device that would increase the user's comfort. Thus, the positive impact on patient's rehabilitation therapies will increase. Furthermore, using one actuator, the cost and energy consumption will be much lower.

The maximum range of motion for forearm movement and wrist movements [9] can be seen in Table I. However, a smaller range of motion is used for activities of daily living [10]. As sometimes the morphology of the exoskeleton does not allow us to reach the maximum range of motion, we targeted the range of motion used in daily living for our design. The range of motion in daily living and the range of motion of the AWEXOS exoskeleton are shown in Table I.

Furthermore, the exoskeleton actuator should provide sufficient torque to actuate the forearm and wrist joints while the user holds a 2kg load in its hand. In [11], the necessary torque to manipulate a 2-litre water bottle is close to 1,4 Nm.

TABLE I
HUMAN BODY AND EXOSKELETON RANGE OF MOTION

Movement	Human body	Daily living	3 DoF exoskeleton
Pronation (FA)	90º	40º	70º
Supination (FA)	80º	35º	70º
Extension (W)	60º	40º	24º
Flexion (W)	90º	35º	90º
Radial (W)	20º	13º	10º
Ulnar (W)	35º	30º	26º

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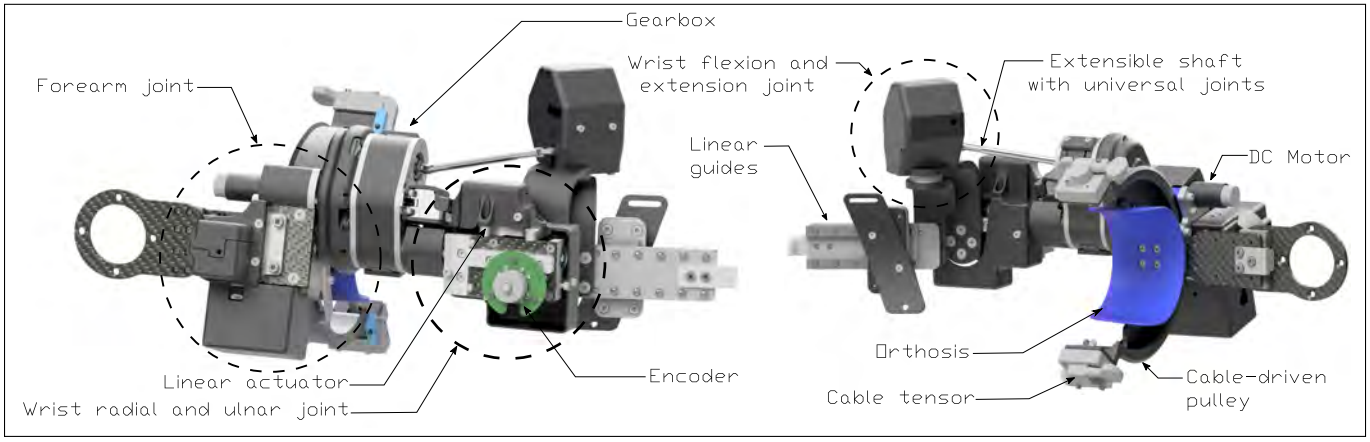

Fig. 1. Arm and wrist exoskeleton overview. The wrist radial and ulnar joint case has been removed to see the inner components.

2) Actuation and transmission: The core of the exoskeleton consists of a small gearbox that permits the movement of three joint motions using one actuator. The different parts of the gearbox can be seen in Fig. 2. The main pieces of the gearbox are a primary shaft and three secondary shafts, each connected to a mechanical joint.

The primary shaft is driven by a DC motor (MAXON DCX 19 S, 17 Watt) incorporating a gearhead with a reduction ratio of 62:1. The primary shaft of the gearbox mounts a three-wheel gear train in which only one wheel can be active at a time. Then, the activated wheel can transmit torque to one of the secondary shafts permitting the joint to move. The ratio of the gear drive is 1:1.

As shown in Fig. 2, the primary shaft is a hollow shaft with three sets of transverse holes. An inner shaft holds three sets of balls inside the aforementioned transverse holes. The inner axle is moved longitudinally along three positions by a small linear positioner (purple arrow in Figure 2 shows shaft translation). Fig. 2 shows the inner shaft at position number 2 pushing a set of balls into the middle wheel. In this way, the primary axle is engaged radially with the wheel in the middle and can transmit the torque (red arrow) into the secondary shaft 2. This process allows us to choose which joint is enabled each time.

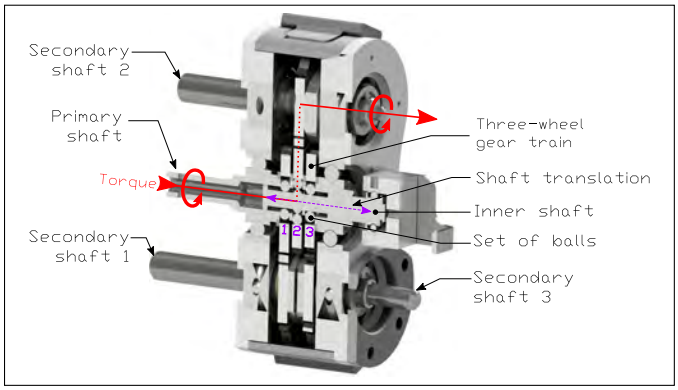

Fig. 2. Gearbox overview. Transverse sectional view. The magenta arrow represents the inner shaft longitudinal translation done by the linear actuator. The red arrow represents the torque transmission.

A low friction worm drive actuates the wrist flexion and extension joint. The ratio of the worm drive is 10:1. Combined reductions (DC motor + worm drive) gives a continuous torque output at the joint of 6.82 N·m. The articulation is coupled with the secondary shaft two through a universal joint. The wrist radial and ulnar joint has the same configuration as the previously described joint. A rigid coupling is used to couple the secondary axle three and the joint. The forearm joint is cable-driven and uses a set of pulleys that give rise to the movement. The ratio of the cable-driven pulleys is 9:1 and provides an output torque of 6.1 N·m. An electromagnetic brake is connected with the shaft of the joint to ensure that the forearm joint does not move when wrist joints are being actuated.

All in all, worm drives and cable-driven pulleys will lead to uncertainties in the position of the joints caused by the backlash. Furthermore, due to the morphology of the wrist flexion and extension joint, the angular velocity of the universal joint will not be constant.

3) Sensors and electronics: The central computer unit serves to execute the control algorithm of the exoskeleton. A real-time microcontroller controls the linear positioner and its driver. A dedicated motor driver (EPOS4 COMPACT 50/5) is used to control the DC motor. The devices are powered from a 150 W power source at 24 V, 12 V, and 5 V depending on voltage needs.

To overcome the uncertainties provoked by mechanical transmissions, we read joint positions using magnetic absolute rotary encoders (Orbis RLS) mounted in every joint. To overcome the variation in the velocity of the universal joint, we mounted an additional encoder in the secondary shaft 2 (Fig. 2) coupled to the universal joint.

4) Software and control: An interface has been developed to manage the rehabilitation therapies using the exoskeleton AWEXOS. In this way, motion data is collected for each patient involved. Windows .NET technology WinForms was used along with C# programming language for the development.

The motion parameters can be configured in the user's graphical interface for each user following rehabilitation therapy with the robotic device. Besides, it creates a database storing the user's data. In this way, the mobility status of the patient's arm can be evaluated to see its evolution through the sessions.

A loop control has been designed to control the DC motor and the linear positioner. Firstly, the robot connects to the computer, where the user's graphical interface is executed. The type, range of motion, and repetitions are sent from this interface using a communication module with user datagram protocol to the computational unit. The remitted data is analyzed to check if another gear in the gearbox should be active.

If the system detects that another gear should be active, the linear positioner moves the inner shaft into the desired position. Meanwhile, the DC motor turns step by step until the primary axle is engaged with the desired gear. The gear change is finished when the absolute encoder registers a variation of the rotational value.

Then, the DC motor rotates into the desired position controlled by the EPOS 4 PID controller. When reaching the desired position, the motor has to come back to its initial state. After completing the ordered repetitions, the system is set in standby mode until new data is sent to the computational unit or it is disconnected.

B. Protocol

We performed the usability test in seven sessions of 40 minutes, one per patient. Before the beginning of the session, a general evaluation of the mobility range of the patient has been carried out by a therapy specialist using manual methods to assure that no harm could be done. After the system initialization, we placed the subject on the left side of the robotic device in a comfortable position, and we attached the exoskeleton to his/her arm. The monitor displaying visual feedback was located in front of the patient and the robotic device at 1 metre of distance. The visual feedback consisted of a human arm imitating the movements done by the exoskeleton synchronously. In Fig. 3, a subject using the robotic device is shown.

Each session was structured in three blocks with a rest of 2 minutes between blocks. Each block would take up to 10 minutes. In each block, a joint motion is done.

After finishing the three blocks activity, each patient had to answer a short survey that would allow us to check if the requirements of the robotic devices were fulfilled.

The usability test was done to evaluate the satisfaction level of the subject after the session, the compliance level after the user's expectations, and the performance of the robotic system. A system usability scale (SUS) survey has been used [12]. The survey had ten questions asking about subjective assessments of usability. Answers measured the agree or disagree level of the users using a Likert scale (from 1, "strongly disagree" to 5, "strongly agree") [13] towards the robotic system.

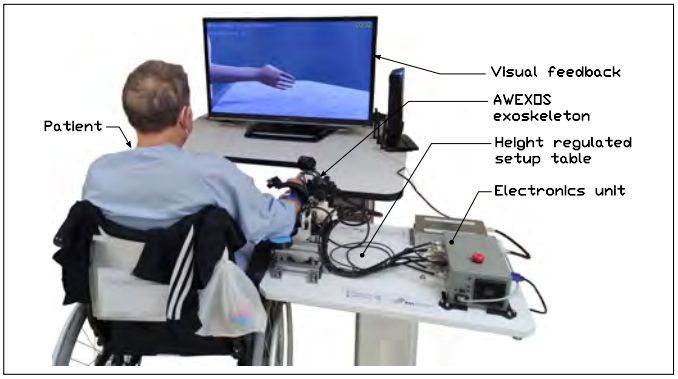

Fig. 3. Setup of the usability pilot study

C. Patients

The experimentation's protocol was approved by the medical ethics committee of the "Hospital La Pedrera". The participating subjects read and understood the purpose and requirements of the study and signed the informed consent before the validation tests began.

Our inclusion criteria included mainly post-stroke patients with reduced mobility in the right forearm and wrist. Besides, they should have the capacity to communicate and understand the tasks instructions.

After the selection process, seven post-stroke male patients aged between 40 and 70 have taken part in the experimentation (see Table II.) These patients had not previous experience with other exoskeletons or robotic devices.

III. RESULTS

On the one hand, the average answers to the system usability scale survey are shown in Fig. 4 in the left picture. The orange graph represents the optimal answers. The blue graph represents the medium answers of the subjects. The item's Likert scale values obtained through the surveys are translated into a specific scoring system determined in [12]. This scoring system range from 0 to 100%. The interpreted scores of the survey items are displayed in Fig. 4 in the right picture.

The mean value of the items scores is equal to 82% and represents the SUS score of the robotic device presented in this paper.

On the other hand, during the seven sessions, we registered the range of motion reached by the patients, and all of them reached the maximum motion degree span the arm wrist exoskeleton can offer.

IV. DISCUSSION

An arm wrist exoskeleton has been designed incorporating a patented novelty with which it is possible to actuate three joints with one DC motor. This invention draws the following advantages for rehabilitation therapies and medicine:

- Lighter and less voluminous robotic devices
- Reduced energy consumption, reducing costs
- More affordable robotic devices

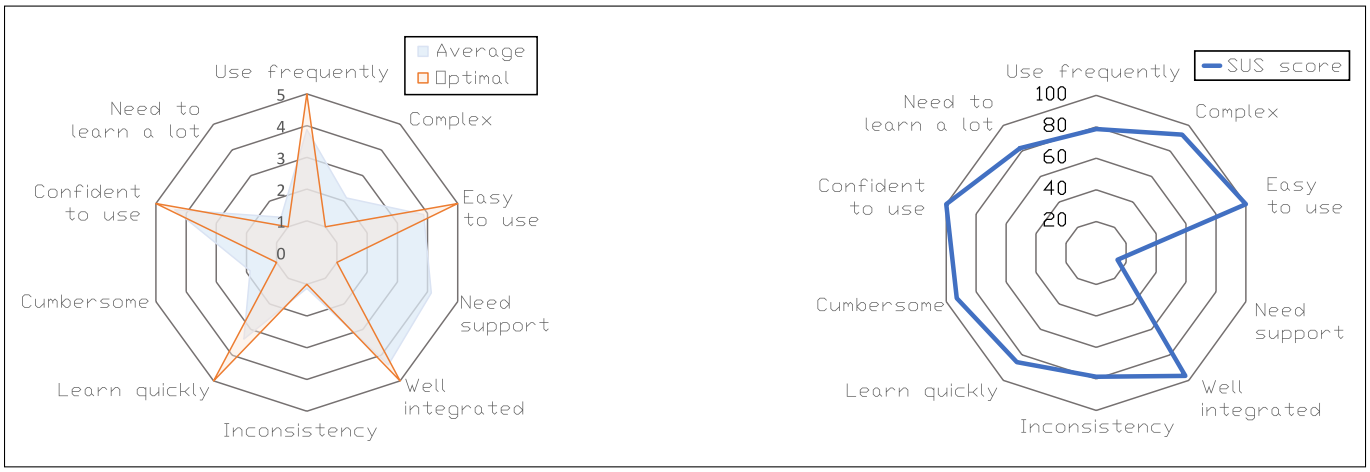

Fig. 4. Survey answers and SUS scoring graphs

TABLE II
SUBJECT'S DATA

ID	Barthel Index	STREAM	Gender	Pathology
1	25	3	M	Guillain Barré syndrome
2	40	7	M	Hemorrhagic stroke
3	30	**	M	Ischemic stroke
4	65	0	M	Ischemic stroke post-COVID-19
5	5	5	M	Ischemic stroke
7	45	14	M	Post-COVID-19
8	75	9	M	Ischemic stroke

As shown in Fig. 4, average answers are close to optimal answers. We must highlight that the answers we got differ from optimal answers in the "need of support" statement since our subjects were mainly post-stroke patients with reduced mobility. Accordingly, they needed support to install the robotic device on their arm.

The calculated SUS score equal to 82% means that the usability of the robotic device is between "GOOD" and "EXCELLENT", proving that the requirements have been met and the user's comfort has been proven. Additional experimentation could prove the positive impact in patients of such rehabilitation therapies with light-exoskeletons.

V. CONCLUSION

The arm wrist exoskeleton with three degrees of freedom and one actuator has been proven to be a suitable robotic device for rehabilitation therapies in post-stroke patients. The usability of the robotic system is suitable according to the SUS scale and offers several advantages.

Further experimentation will be done to validate the possible advantages it has towards the patient's rehabilitation.

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