Cable-Driven Exosuit to Assist Affected Upper-Limb Users with Hemiparesis

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Abstract— **Neurological impairments such as stroke cause muscular weakness in several joints in the human body. As a result, the development of activities of daily living (ADL) is affected. Particularly, upper limb movements executed with external loads are restricted for post-stroke patients who present extreme sensitivity to mechanical loading. In rehabilitation, upper limb gravity support and assistive torques improve post-stroke users' skills and support the elbow joint's flexors muscle during the therapy. In this sense, this work presents the design and a preliminary assessment for a portable upper limb exosuit to assist flexor muscles in the elbow joint. The robotic device comprises a wearable structure employing a cable-driven system that does not generate limitations in the elbow joint. An impedance controller was implemented based on the right elbow joint movements to generate estimated torques applied in the left elbow joint. The experimental findings with three healthy participants showcase the short-term effects of a notable reduction in muscle activity, ranging from 60% to 72%, when the exosuit was tested in lifting a 2.5 Kg load.**

I. INTRODUCTION

In 2015, the UK reported a prevalence of 950.000 to 1.3 million related to individuals that suffered a stroke [1]. Projections regarding stroke incidence in the UK indicate an increase from 117,600 cases in 2015 to 148,700 and 186,900 cases in 2025 and 2035, respectively [2]. The societal costs of stroke in social care witnessed a substantial increase, with estimates soaring from £26 billion in 2015 to a projected 194% increment for 2035 [2]. Residual impairments such as poor motor control, muscle weakness, spasticity limitations[3], and strength loss in the elbow flexors/extensors [4] can affect the motor ability of the post-stroke survivors. Particularly for people who suffer from hemiparesis [5]. In upper limb rehabilitation, several methods, such as weight-bearing, traction, and stimulation, based on repetitive motor practice movements, are implemented to generate neuroplasticity [6]. Robotic devices, such as exoskeletons, support the lower limb rehabilitation process for several ADL [7]. These robotic devices have also been presented in the literature for upper limb rehabilitation [8]. The exoskeletons can be categorized based on their mechanical structure. A rigid structure is implemented in the upper limb exoskeleton to transfer high torque levels generated by actuation systems such as DC motors and a gearbox ratio, pneumatic actuator, and Bowden cable actuator [9], [10]. These mechanical structures are developed with resistant materials that increase the exoskeleton weight. The rigid structures implement several DoFs similar to the human body to prevent the misalignment between the exoskeleton and the user [10]. Exoskeletons based on a textile material that lacks a rigid structure have been proposed in rehabilitation environments [10]. This structure is lightweight and allows the user to perform unrestricted joint movements. Several exoskeletons have been presented with this type of structure named exosuit [11].

Several exosuits with pneumatic actuator systems were developed due to the joint's low-cost, lightweight, flexible, and pressure distribution [11], [12], [13]. For instance, a soft exosuit based on a pneumatic actuator presented in [11] reports approximately a 43% reduction in muscle activity. An elbow exosuit proposed in [14] utilizes an elastomeric bending actuator to aid in elbow flexion/extension movements through an EMG-Driven Active Contropropsed. Exosuits based on a muscle fabric developed to assist the biceps muscle demonstrate a 60% reduction in muscle activity lifting loads [15]. Conversely, exosuits incorporating a cable-driven actuator offer numerous advantages, including a lightweight design that enables unrestricted user joint movements, with force transmission to the joint achieved through a cable [9], [16], [17]. For example in [18], a cable-driven exosuit is presented for rehabilitation of elbow and hand in flexion/extension and open/close movements.

In the presented literature, the development of exosuits is based on bilateral system actuation based on soft actuation systems. However, no proposed wearable exosuits have been developed for users with hemiparesis, motor limitations and strength loss in the elbow flexor muscles. For this reason, this work presents the design and a preliminary test of an exosuit for lifting assistance of the left upper limb (affected limb) based on the movements of the elbow joint (unaffected limb). This work is organized as follows: Section II involves

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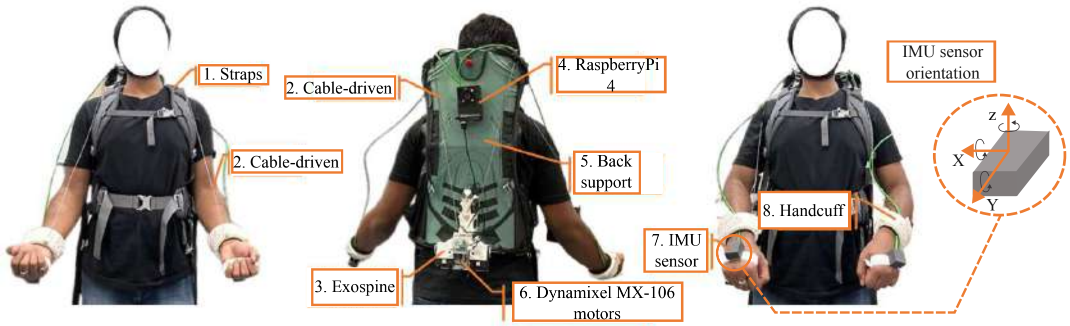

Fig. 1. Upper-limb exosuit for rehabilitation.

the upper limb exosuit for elbow joint hardware and software composition and testing protocol; Section III presents the results obtained from the tests performed on healthy users; Section IV discusses of the preliminary test, and Section V summarizes the outcomes presented, different considerations to improve the exosuit response, and future works for the upper limb exosuit.

II. Experiment Methodology

A. Upper-limb exosuit

Comprising four modules, the upper limb exosuit is designed to interface with the human body directly. It acquires kinematic parameters during tasks, filters and processes the user's kinematic data to derive torque values, and subsequently utilizes these calculated values to support the elbow joint. In this section, a wearable exosuit structure (see Fig. 1) is presented in the following modules: (1) exosuit structure module, (2) processing module, (3) sensory module, and (4) actuation system module. The total cost of the exosuit is close to US $1.909.55.

- ***Exosuit structure***: This device incorporates a modular structure located in the lumbar region, two electric motors, and a steel cable to establish an engagement with the forearms passing over the user's shoulders. For this work, only the motor on the left side is used to actuate the left elbow joint. The main objective of this configuration is to efficiently transfer external loads directly to the user's shoulders and lumbar region, thus minimizing the involvement of the biceps muscles during lifting activities.
  A mechanical structure was designed to adapt to the lumbar curvature of the spine to optimize the application of the portable device concept. This innovative design called exospine serves a dual function: i) it facilitates the mobility of the fundamental degrees of freedom of the spine by providing 8° of mobility for each segment in abduction to adduction and up to 51° in the sagittal plane. ii) it provides essential support to improve load transmission when the motors are activated, and the exoskeletal system operates. The design of the dorsal exospine consists of four distinct components seamlessly interconnected by a robust steel cable. This strategically placed cable ensures the transmission of loads along the user's spine while allowing the spine to flex. This bending capacity emulates the natural functionality of the individual segments of the spine, contributing to the user's comfort. (see Fig. 1).
  Various textile materials commonly used in sports backpacks were employed in the exosuit structure. These materials feature straps designed for comfort and to allow natural perspiration during prolonged walks. Additionally, rigid structures were incorporated to provide enhanced support to the spine.
- ***Processing/Control module***: A RaspberryPi4 (Raspberry Pi Foundation, UK) was used to process and control the signals of the exosuit. The elbow exosuit architecture software was developed using the Robot Operating System (ROS) Melodic version. The Dynamixel motors package was developed to control the actuation system in this architecture. Additionally, a sensor package was created to acquire and process the sensor module of the exosuit.
- ***Sensory module***: A kinematic sensor was employed to monitor the elbow joint movements. Non-invasive sensors are employed considering the lightweight, small size, easy instrumentation, and lack of a rigid structure for instrumentation. In this case, an IMU (Unit Measurement system) BNO055 (Adafruit, USA) with 9 DoF was implemented to estimate the elbow angle. The IMU sensor orientation for the application is indicated in Fig. 1.
- ***Actuation system***: A DC electric motor Dynamixel MX-106T (ROBOTIS, USA) with a pulley located in the user's lower back, was employed to assist the elbow joint. A cable-driven was coupled with the DC motor to address the assistive force to the elbow joint. The motor current, position, and velocity were calculated to generate estimated torque with the Dynamixel motor (Maximum torque equal to 5.6Nm). The actuation system composition was selected to transmit the estimated torque without restricting the natural movements of the elbow joints. The actuation system was powered with a DC power supply adapter with $12V$ and $6Ah$.

B. Control architecture

Physical Human-Robot Interaction (pHRI) was considered for implementing a control strategy for elbow rehabilitation. In this sense, estimated torques were generated to assist the flexion movement of the elbow joint. Therefore, a multilevel control architecture was proposed, composed of a low-level and a mid-level controller, where several user kinematics parameters were acquired. In this section, the control architecture of the upper limb exosuit is presented.

- ***Low-level:*** Torque mode was activated in the Dynamixel motor configuration to provide different torque values. A hall effect sensor was employed to monitor the motor current value during each task. Equation. 1 presents the relationship between the current and the torque.

$$T = 0.0523I^4 - 0.4696I^3 + 1.2055I^2 + 0.7472I - 0.0386, \quad (1)$$

  Where T is the torque value, and I is the current value estimated through the Hall effect sensor.

- ***Mid-level controller:*** An impedance controller was proposed to achieve a desirable pHRI during the test. This controller was proposed to simulate spring and damper elements using the DC electric motor using kinematic parameters such as elbow joint angular position, elbow joint angular velocity, and motor current values. Equation. 2 shows the estimated torque calculation.

$$T_m(q, \dot{q}) = K(q_{des} - q_j) + \beta(\dot{q_{des}} - \dot{q_j}), \quad (2)$$

  Where T_m is the motor torque, K is an elasticity constant, β is a damper constant, q_{des} is equal to desired elbow angular position $[rad]$, q_j is the elbow angular position, $\dot{q_{des}}$ is the desired elbow angular velocity equal to 0, and $\dot{q_j}$ is the elbow angular velocity $[rad/s]$. The second-order system of a mass-spring-damper system is used. The transfer function shown in equation 3 is used to obtain an approximate estimate of the elastic constant and the damping constant of the system.

$$G(s) = \frac{K}{MS^2 + \beta S + K}, \quad (3)$$

  Where M is the mass of the system. Subsequently, K and β are equal to $w_n^2 = \frac{K}{M}$, and $2\zeta w_n = \frac{\beta}{M}$. Where w_n is the undamped natural frequency and ζ is the damping ratio. The value of $K = 3.5$ and $\beta = 0.8$ for this work. The equations 4 and 5 present the steel cable length l_α that varies according to elbow joint value θ_{joint}.

$$l_\alpha = l_{arm}^2 + l_{farm}^2 - 2l_{arm}l_{farm}\cos\alpha \quad (4)$$

$$\alpha = 180 - \theta_{joint} - \theta_b - \theta_a \quad (5)$$

  Fig. 3 presents the controller schematic proposed for the upper limb exosuit. The IMU sensor is located in the distal part of the right upper limb to estimate the elbow angular position. This value is operated with the desired angular position equal to $0rad$ to obtain the position error. A similar process is applied using the angular velocity, where the elbow joint angular velocity is estimated to obtain the error with the desired angular velocity equal to $0rad/s$. The collected data generates estimated torque through an impedance controller simulating the mass-spring-damper system. Finally, the actuation system addressed the estimated torque to the left user's forearm. The test bench presented in Fig. 2 was employed to test the proposed controller for the upper limb exosuit.

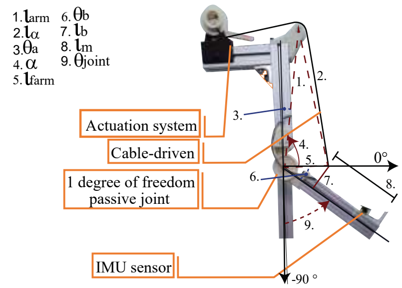

Fig. 2. Test bench setup equipped with a Dynamixel motor MX-106T, a pulley, a steel cable to address the estimated torques in the 1 DoF passive joint, and a 9 DoF IMU sensor located in the distal part of the passive joint.

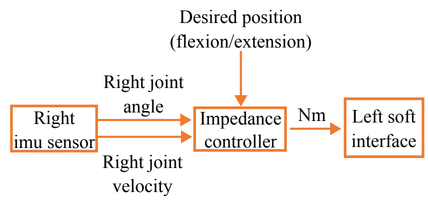

Fig. 3. Controller schematic for upper limb exosuit.

C. Experimental test

The initial version of the elbow joint exosuit was assessed in two phases: i) an impedance controller employed in the test bench was implemented; ii) the exosuit underwent adaptation for the creation of a preliminary test focusing on the flexor muscles of the upper limb. Consequently, healthy participants were recruited, considering various parameters for the test. This section details the protocol test and inclusion criteria employed for participant assessment.

1) Impedance controller test: Fig. 2 presents the test bench setup where the impedance controller was tested. In this case, the first chirp signal with $1.22rad$ (70°) with periods of 8s, 6s, and 4s was applied to the proposed impedance controller to obtain the RMSE comparing the desired angular position with the passive joint angular position. The second signal applied periods of 8 s, 6 s, 4s, 2s, 1s, and 0.5s with $1.22rad$ (70°) peak to peak was employed to obtain the system bode diagram. During the test, the 1 DoF passive joint was coupled in the distal part with a load equal to 1 kg.

2) Participants: Three healthy participants, aged between 20 and 40 years, were enlisted for the exosuit test. Before the test, a pre-questionnaire gauged each participant's physical

TABLE I
KINEMATIC PARAMETERS FOR EACH USER DURING NO EXOSUIT AND EXOSUIT TESTS (MEAN ± STD).

User	No exo				Exo			
	Maximum angle	Minimum angle	RoM	duration time	Maximum angle	Minimum angle	RoM	duration time
1	12 ± 19.77	-50.33 ± 6.43	62.54	2.67 ± 0.92	-0.31 ± 6.37 *	-55.55 ± 4.08 *	55.24*	8.45 ± 1.31 *
2	25.23 ± 4.49	-52.60 ± 5.91	77.83	2.08 ± 0.55	1.42 ± 13.85 *	-47.70 ± 7.88 *	49.13*	7.43 ± 3.73 *
3	11.75 ± 3.62	-54.93 ± 9.06	66.68	3.51 ± 0.78	24.10 ± 3.41 *	-52.62 ± 3.36	76.72*	9.40 ± 1.32 *

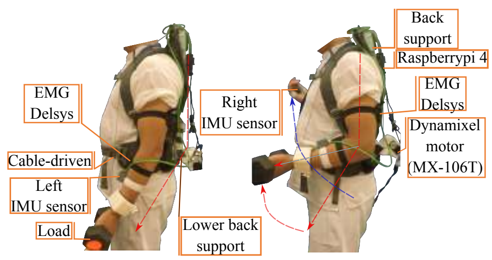

Fig. 4. Protocol test using the exosuit. The user uses another IMU sensor in the left forearm to monitor the joint angular position.

health, exercise routine, and any history or current presence of musculoskeletal discomfort in the left upper limb. Written informed consent was obtained from all participants, following approval by the University of the West of England Institutional Ethics Committee. Exclusion criteria for participants encompassed musculoskeletal and systemic disorders, impairments in postural control or motor function, acute pain or illness, and drug addiction.

3) Experimental tasks: For each participant, a static test was performed to record the muscle activity with the exosuit (”Exo” condition) and without the exosuit (”No Exo” condition). For this test, the participant must look forward at a stationary point in the environment with a straight posture and legs shoulder-width apart. First, the participant will execute the flexion/extension movement of the left elbow joint to lift a load of $2.5Kg$. The participant will perform 10 repetitions of this exercise. The participant will take a break of 30s at the end of this task. The participant will perform 3 cycles in the same way. Second, the participant fits the upper limb exosuit using belts and straps. The participant grabs a load equal to $2.5Kg$ with the left palm facing forward. The participant starts with the test with the arms fully extended. Full flexion movement is performed by the participant with the right forearm. This action activates the exosuit to generate the left elbow joint flexion movement. The participant holds this flexion position for a short period. Subsequently, the right arm is extended slowly to the initial position, generating the extension of the left elbow joint. The participant executes 10 repetitions of this exercise. The participant will take a break of 30s at the end of this task. The participant will perform 3 cycles in the same way. Fig. 4 shows an example of this test using the exosuit.

4) Data collection and analysis:

- ***Procedure:*** EMG signals of the biceps brachii were recorded to capture the muscle activity of each participant. The sampling frequency was 1KHz using the Delsys Trigno wireless EMG and IMU system (Delsys, USA). The information was processed using a bandpass filter of 20Hz to 450Hz to eliminate high-frequency noise and low-frequency drifts [19]. Muscle activity was normalized using the user's Maximum Voluntary Contraction (MVC). This was recorded at the beginning of the test, where the user generated the MVC during 5 seconds and 10 seconds to rest, this cycle was applied 3 times.
- ***Statistical analysis:*** MATLAB R2021B was used for statistical data analysis. Kolmogorov-Smirnov was applied for EMG data, elbow joint angular position, elbow joint maximum value, and elbow joint minimum value to check the normality, where non-parametric distribution data was obtained. The data was analyzed using a non-parametric test considering where p-value < 0.001. A Mann-Whitney U test was applied to estimate the exoskeleton effect in the upper limb joint, assessing the muscle activity, cycle time, maximum elbow joint value, and minimum joint value recorded for each user executing the test for ”Exo” and ”No Exo” conditions, this process was implemented using the. As a result, Fig7 presents the mean biceps brachii's muscle activity, mean elbow joint trajectory, and Table I indicates the maximum elbow joint angle, minimum elbow joint angle, RoM, and cycle time. Finally, the standard error was presented for each EMG signal acquired for ”Exo” and ”No Exo” conditions. Raw data can be found here [1]

III. RESULTS

Fig. 5 presents the impedance controller response tested in the test bench, where the system reaches the desired position ($0rad$) with an error close to 7%. This result was obtained by applying estimated torque (current) by the proposed impedance controller (See Fig. 5). In this sense, the desired and current positions present a RMSE close to $0.0758rad$. On the other hand, the bode diagram (See Fig. 6), was obtained by applying the second chirp signal. As a result, Fig. 6 shows that the system presents a maximum frequency equal to 0.38Hz.

Fig. 7(a) presents biceps brachii's muscle activity for ”No Exo” and ”Exo” conditions. The exosuit reduces the biceps brachii's muscle activity of 72%, 60.8%, and 60.4% for each user. The Mann-Whitney U test demonstrated significant influences (p-value$<$0.001) in muscle activity for all the

[1] Raw data is available here.

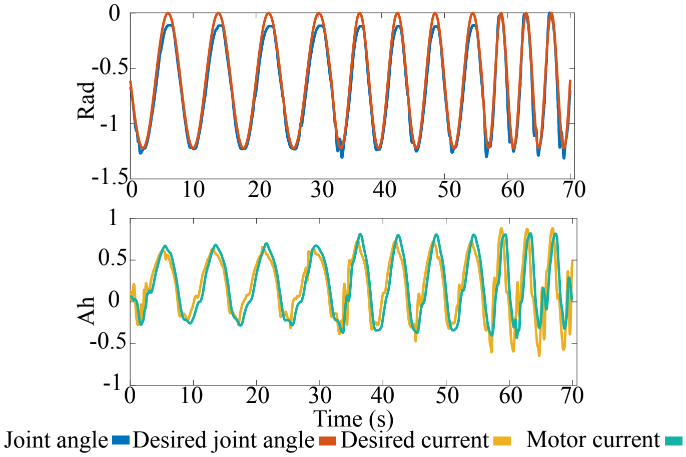

Fig. 5. Impedance controller test using a chirp signal with periods of 8s, 6s, and 4s.

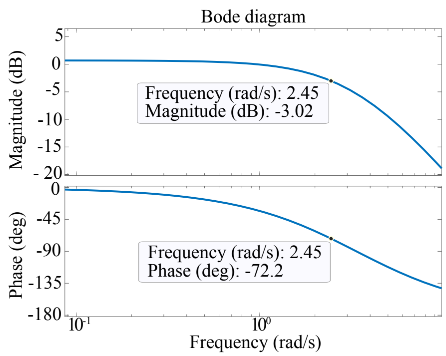

Fig. 6. Bode diagram of the impedance controller test.

users executing the test for "No Exo" and "Exo" conditions. Fig. 7(b) presents the mean trajectory generated for each user during the test. The Mann-Whitney U test was applied to demonstrate a significant influence in the angular position trajectory obtained during the test (p-value<0.001). Table I presents several kinematic parameters such as maximum/minimum left elbow angular position, Range of Motion (RoM), and cycle time per repetition for the flexion/extension movement. The first parameter observed in table I is the standard deviation for the maximum/minimum elbow angular position in users 1 and 3 decreased in the "Exo" condition. Subsequently, user 1 and user 2 demonstrated a decrease in the elbow joint RoM. Additionally, the maximum elbow joint angle reports a significant influence (p-value<0.001) where this parameter decreased using the exosuit. The minimum angle value obtained during the test shows significant influences in user 1 and user 2 (p-value=0.0040 and p-value=0.0019, respectively). On the other hand, user 3 does not present a significant influence on this parameter (p-value=0.8561). Finally, flexion/extension cycle time for each user demonstrated an increase comparing the data obtained during the test for "No Exo" and "Exo" conditions (p-value<0.001).

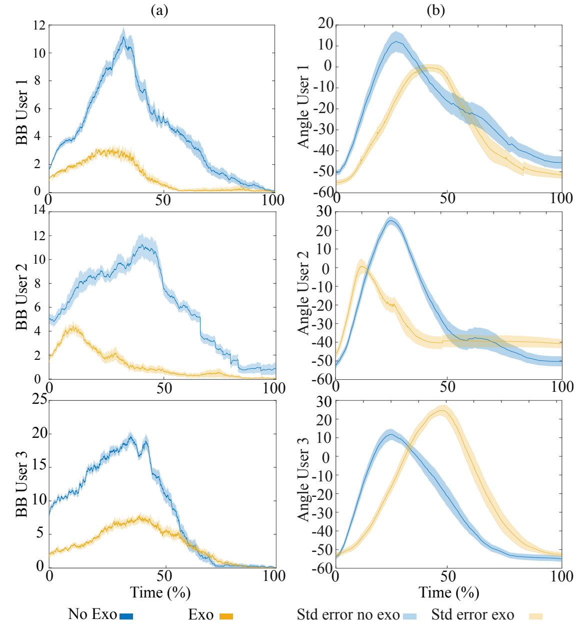

Fig. 7. (a). The mean value of Biceps-brachii's Muscle activity during the test for each user; (b). The mean value of left elbow joint trajectory obtained during the test for each user

IV. Discussion

Using the exosuit for elbow assistance showed significant changes in all the users. The elbow angle shown in Fig. 7(b) demonstrates that the user can generate additional torque without limitations related to the exosuit structure. This can be evidenced by the elbow angle data from users 1 and 2, where the maximum angle recorded during the "Exo" condition is close to 0°, the setpoint configured for impedance control. However, user 3 reached a maximum angle greater than 0° during the "Exo" condition. Regarding the increase in time per repetition and the reduction of RoM shown in users 1 and 2, it is not feasible to conclude a correlation between the two variables due to user 3 presenting an increase in these parameters. A significant population sample assessment will show if a correlation exists between a reduced elbow RoM and increased duration time per repetition.

The cycle time for each repetition demonstrated an increase in the mean obtained for each user performing the tests in these two conditions. The test outcomes depend on the technical characteristics of the actuation system. The exosuit presented in this work showed a maximum frequency of 0.38Hz (see Fig. 6). This value is higher than other devices in the literature, such as [12], which reports a maximum frequency of 0.03Hz for no load elbow actuation. Likewise, in [17], a cycle time for elbow flexion/extension using a 7Kg load of the 40s is presented. However, the actuation system based on an electric motor has higher characteristics than the Dynamixel Motors used for this exosuit. In [18] presents a higher maximum frequency than presented in this work of 1Hz of the system for elbow movement without load. On the other hand, the exosuit construction cost is high compared to [18]. However, it may be decreased by evaluating the implementation of a low-cost electric DC motor with similar torque values and housing properties. Likewise, low-cost, non-invasive sensors that could provide the elbow joint angle could be implemented instead of IMU sensors, which would decrease the construction cost of the device. Nevertheless, it could increase device fitting time in the user's body.

The user's RoM was limited to flexing to a value of 0° of the left elbow using the exosuit. Therefore, the values shown in Table I indicate that the RoM during testing is in the range of the elbow joint values presented in [14], [16] with an approximately 60° to 70°. Finally, the muscle activity is in the range of exosuits with soft actuation systems. In [20] showed a 63 $\%$ reduction of muscle activity using a load of 2.5kg, and the exosuit based on a textile material [15] presented 54.8$\%$ reduction of muscle activity using a load of 5kg. The RMSE is in the range of that reported by the methods applied to decrease the error between the desired and joint current positions, as shown in [18].

Finally, The exosuit tests showed a relevant decrease in muscle activity with longer cycles for each repetition. Considering the device response time, the upper limb exosuit can be used in users who demonstrate minimal muscle activity of the flexor muscles for unloaded/loaded forearm flexion. According to [21], it suggests that the user presents long failure task times only in the execution of exercises for the elbow flexors (biceps brachii) with a low load level, i.e., the requirement of a low $\%$ MVC during the activity. Likewise. Applying long-duration isometric contractions can increase the muscle volume of the affected limb [22].

V. Conclusion

An upper limb exosuit designed for users with hemiparesis was presented in this work. The short-term effects of a preliminary test with 3 healthy users were assessed. The users performed this task for "No Exo" and "Exo" conditions. As a result, the user's muscle activity reported a reduction in the range of 60$\%$ up to 72$\%$. The maximum value/minimum value of the elbow joint and RoM, presented significant changes in the tests, where the maximum value of the elbow joint decreased for two users when using the exosuit. Nevertheless, Section II mentions that impedance control has predefined the desired position of $0rad$. Where the maximum value of the elbow decrease does not correlate with the exosuit structure limitations. Various parameters obtained during the test with the exosuit were compared with other exoskeletons in the literature. As a result, this proposal has not been explored for flexor elbow joint rehabilitation using an impedance controller based on the unaffected elbow joint movements. The actuation system requires some adjustments to improve the torque transmission to the forearm. Finally, a long-term effects study with a larger sample of post-stroke survivors must confirm the device's effectiveness in assisting elbow flexion movement.

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