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Design of a Cable-Driven Soft Elbow Exoskeleton for Rehabilitation and Movement Assistance

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Abstract **-** In recent years, soft robotic rehabilitation and assistive exoskeletons have gained significant attention due to their potential to enhance human mobility and improve rehabilitation outcomes. This paper focuses on the design of a Cable-Driven Soft Elbow Exoskeleton, specifically developed to provide a lightweight, comfortable, and user-friendly solution for rehabilitation and movement assistance. The exoskeleton integrates a Myoelectric Model Reference Adaptive Controller, enabling two operational modes: passive mode, where the system assists movement without requiring user effort, and myoelectric active mode, which allows voluntary user control with adaptive torque assistance. The proposed design prioritizes ergonomics, ease of use, and adaptability to different rehabilitation needs, making it a promising tool for enhancing physical therapy interventions.

Keywords**:** Soft robotic exoskeleton, Rehabilitation technology, Myoelectric control, Cable-driven actuation

1. Introduction

Nowadays, rehabilitation and assistance exoskeletons have gained a lot of popularity and research interest because they allow to enhance human physical capabilities, whether it's for augmenting the physical capacities to prevent musculoskeletal diseases caused by repetitive movements [1, 2] or assisting in movements when the user has lost its motor skills due to illnesses or an accident [3, 4]. In addition to that, exoskeletons can also be applied in the rehabilitation setting, allowing to provide more comfortable, adaptable, repetitive, intense and efficient rehabilitation therapies [5-7].

With the aim of improving such devices, the design trend of soft robotics has gained special interest among exoskeletons researchers. Soft robotics is a design strategy that aims to develop robotic systems with soft and deformable structures, allowing a better and safer interaction with the environment and other systems, for example, human beings [8]. In the specific case of exoskeletons, a soft design allows for a greater adaptability to body contours, which translates into greater comfort and efficiency when the user is wearing the exoskeleton [9-11].

With this in mind, multiple exoskeletons based on soft actuation mechanism have been proposed, among these developments it's possible to highlight cable driven exoskeletons, which use a series of cables and pulleys to generate movement in the limb [12-14]; pneumatic exoskeletons, which make use of artificial pneumatic muscles [15-17]; and, shape memory alloy exoskeletons, which use materials that respond to temperature or electricity to generate movement [18, 19].

Despite the advantages of using soft robotics for the design of rehabilitation and assistance exoskeletons, the use of this design strategy creates some challenges. One of the main challenges in the design of soft robotics exoskeletons, is the design of control schemes that allow an intuitive and voluntary control of the device. This challenge becomes harder when dealing with soft exoskeletons because the deformable nature of soft structures makes it difficult to use model-based control design strategies, in addition, soft systems are also prone to many parameter uncertainties [20, 21]. To solve this challenge myoelectric (EMG) control has been widely studied because it allows an intuitive human-machine interface [22, 23].Myoelectric control allows to use the muscles electrical activity as a feedback signal to predict the motion intention or some physiological variable like the joint stiffness, this variable is the used as parameter or input to a controller, for example, a proportional controller [24, 25] or an adaptive impedance controller [26].

This work presents the development of a Myoelectric Cable Driven Soft Elbow Exoskeleton with potential application in rehabilitation and movement assistance tasks. The exoskeleton is controlled by a novel Myoelectric Reference Model Adaptive Controller (MRAC) that allows voluntary control of the exoskeleton and can reduce the required torque when performing a movement. This paper is structured as follows: Section II presents the design of the exoskeleton, its hardware architecture and the implemented controller; Section III presents the performance of the exoskeleton when performing a series of flexion - extension movements; and finally, Section IV presents the conclusions of this work and the proposed future work.

2. METHODOLOGY

2.1. Exoskeleton Design

The designed exoskeleton is based on a cable mechanism that allows the user to perform passive and assisted flexion - extension movements. The Cable Driven Soft Elbow Exoskeleton is composed by a chest vest that is used as the main supporting element; in the back of this vest, a small compartment is attached, this compartment, contains the system's electronics and actuation elements, specifically the actuation motor. The exoskeleton is also composed by to arm straps, one that is attached to the vest and is placed in the arm of the user, this first strap is used to guide the cable through the arm and to hold the cable sheet. The second strap is placed on the forearm of the user and works as the attachment point for the cable, this strap is the one that hold the forearm and allows the cable to perform the traction necessary for the flexion - extension movement. Both straps have a pocket used to place an Inertial Measurement Unit (IMU) used to estimate the joint angle. Different views of the device are shown in Figure 1.

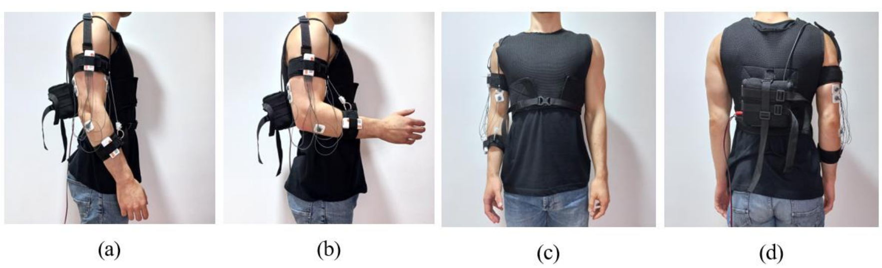

Fig. 1: Different views of the Cable Driven Soft Elbow Exoskeleton. (a) Lateral view in resting position. (b) Lateral view during flexion movement. (c) Front view. (d) Back view.

The Cable Driven Soft Elbow Exoskeleton's vest and straps are made with a light fabric breathable fabric reinforced with webbing on the borders of the vest and straps, in addition, the straps are reinforced on the bottom part with an stronger fabric so they can withstand the traction of the cable; the IMU pockets in the straps are made with an elastic band and the attachment point in the forearm strap consist in a metal ring. To secure the exoskeleton, the vest has a double Velcro closure mechanism on the front and a side release buckle for extra support, similarly, the straps have also a Velcro mechanism for adjusting them. The actuation and electronics compartment consisted in a small fabric bag that holds the box that contain the actuation and electronic elements, from this box, the Bowden cable comes out, passes on top of the shoulder and then the sheet attaches to the arm strap, then, the unsheathed part of the cable attaches to the forearm strap. The Cable Driven Soft Elbow Exoskeleton has a total weight of approximately 1.5 kg and it's modular, meaning that the actuation compartment and cable system can be dismounted easily, making the system easy to transport or repair. The device has an effective actuation range of 0◦ to 100◦.

2.2. Exoskeleton Hardware Architecture

To perform the actuation, the Cable Driven Soft Elbow Exoskeleton integrates different actuation and electronic components. The initial hardware component are two Shimmer3 EMG units, each one of these units integrates two electromyography (EMG) channels and a 10-DOF Inertial Measurement Unit (IMU). As mentioned earlier, each of these Shimmer3 devices is placed on the exoskeleton's straps located on the arm and forearm. The arm's Shimmer3 device acquires EMG signals from the Biceps Brachii and Triceps Brachii, these signals are used for the active myoelectric control described in Section 2.3.; also, both devices' IMUs are used to estimate the current joint angle by calculating the relative orientation between the two IMUs. Figure 2 shows the architecture that compose the soft exoskeleton.

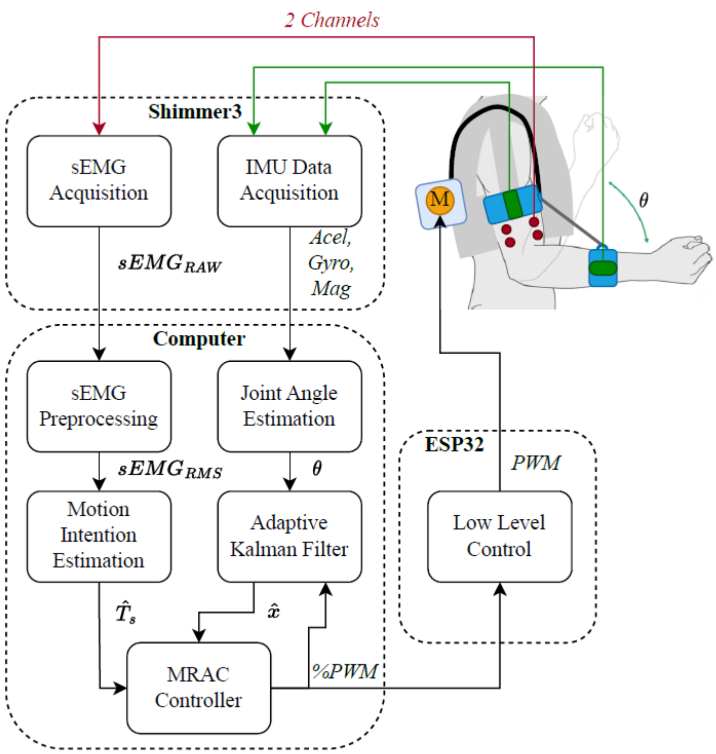

Fig. 2: Cable Driven Soft Robotic Exoskeleton architecture.

To perform the control of the exoskeleton and the joint angle estimation, the EMG data of the arm's Shimmer3 and the IMU data (accelerometer, gyroscope and magnetometer) are sent to a personal computer (PC) in which the main control algorithm is running. This computer also works as a user interface in where the user can configure different parameters of the controller and can also evaluate the behaviour of the exoskeleton. This PC then sends the percentage of PWM calculated by the main control algorithm to a ESP32 Devkit v1 board in which the low-level control is carried out. The ESP32 board then sends the PWM signal to a BTS7960 high power motor driver that is connected to the Pololu 37D DC brushed metal Gearmotor (34 kg cm stall torque and no-load speed of 100 RPM) used to pull the cable; this motor has a 3.5 cm aluminium pulley used to roll up the cable, which is a 1.4 mm Nylon cable.

The ESP32 board, the BTS7960 high power motor driver, the Pololu 37D DC brushed metal Gearmotor and the aluminium pulley are all contained inside the container at the back of the exoskeleton's vest. In addition, a regulation circuit used to power the ESP32 board is also contained in there. The regulation circuit, the motor driver and the motor are all connected to a 12 V DC power supply.

2.3. Model Reference Adaptive Controller

To control the exoskeleton, a Model Reference Adaptive Control (MRAC) was proposed. This type of controller allows to define a reference model that generates the desired state trajectory x_m, that the system's state x must follow. This type of controller is extremely useful because it doesn't require the model of the system and can adapt to the system's uncertainties; to do that, the controller adjusts its control gains online based on the outputs of the system.

The proposed controller includes an adaptive observer, this observer is required because the MRAC design requires the complete system's state, in this case, the joint angle and the joint speed. Nevertheless, as mentioned earlier, only the joint angle is available for measurement.

This adaptive observer is based on a linear parameterization of the system that uses online parameter estimation for finding its parameters. The exoskeleton was parameterized as a second order linear system of the form $\ddot{y} + a_1\dot{y} + a_2 y = bu$; where the parameters a_1, a_2 and b were estimated using the Recursive Least Squares with Covariance Resetting algorithm. This parameterization was then used to implement a Kalman Filter for performing the sate estimation. It's important to note, that the time varying parameters a_1, a_2 and b allow the linear parameterization of the system to capture its nonlinear dynamics.

The control law of the proposed MRAC is given by the following equation,

$$u = \theta_c^T \tag{1}$$

where $\theta_c = [k_r, k_1, k_2]^T$is the control law parameter vector and $\omega = [r, x_1, x_2]^T$ is the signal vector that contains the reference r, the joint angle x_1 and the joint speed x_2. The adaptation law for determining the parameter vector θ_c is given by the following equation,

$$\dot{\theta}_c = -\bar{\Gamma} e^T P B_I \omega \tag{2}$$

where $\bar{\Gamma}$ is the adaptation weights matrix, $e = x - x_m$ is the error between the system's state and the reference model state, P is a positive definite matrix, $B_I = [0, 1]^T$ is an auxiliary vector and ω is the signal vector.

The proposed MRAC controller allows two modes of operation, a passive control mode, and an active-assistive control mode, the following sections will explain in further detail these two operation modes.

1) *Passive Mode:* The passive control mode allows the user to perform passive guided therapies, in which the device oversees performing the totality of the movement; this type of exercise is ideal for the initial stages of the rehabilitation process, because it prevents muscle atrophy and allows the gradual recovery of the joint's range of motion. This mode uses as reference r the desired joint angle trajectory. For this mode, a second order reference model was defined.

2) Active Mode: The active control mode allows the user to perform active-assistive exercises, in which the devices are controlled voluntarily by the user based in its motion intention, in this mode, the device only provides some assistance to the user when the movement is being performed. This type of exercise is ideal for an intermediate phase of the rehabilitation process in which the goal is to recover the full joint's range of motion. The active mode of the proposed controller integrates an electromyography (EMG) motion intention estimation loop into the main control loop. In this mode, the reference r of the MRAC controller is the estimated joint torque $\widehat{T_s}$. For estimating this torque, the EMG signals from the Biceps and Triceps are acquired; after that, the signals are pre-processed to extract the RMS value of different segments of the signal, and the, the joint torque $\widehat{T_s}$ is estimated using a multi-layer perceptron neural network. The active mode reference model is based on the idea of a "*gravity compensated virtual arm*", the purpose of this model is to define a "*virtual arm*" that has a different dynamic than the user's arm. By changing the parameters of the reference model, it's possible to define a "*lighter virtual arm*" that requires less torque for performing a flexion-extension movement; thereby, when user tries to perform the movement, the exoskeleton will assist the movement while requiring less torque from the user.

2.4. Exoskeleton Evaluation

To evaluate the Cable Driven Soft Elbow Exoskeleton, it was tested with a subject of 80kg and 1.80m of height. Both control modes of the exoskeleton were tested by performing an unloaded flexion - extension exercise for five sets of ten repetitions each. Before each of the trials, an initial set of ten repetitions was performed for the purpose of calibrating the controller's and observer's adaptive parameters.

It's important to note, that in the case of the myoelectric active mode, the test included two sub-tests. The first sub-test had the reference model parameters $mv = 2.2, kv = 0.7$ and $\beta v = 0.5$, while the second sub-test had the parameters set to $mv = 2, kv = 0.5$ and $\beta v = 0.4$. The purpose of this was to define a *"lighter virtual arm"* in the sub-test 2 when comparing it to sub-test 1, this, to determine the effect of the parameters on the level of assistance generated by the exoskeleton.

The tracking error of the controlled exoskeleton was evaluated using the Mean Absolute Error (MAE), in the case of the active mode, the assistance level supplied by the exoskeleton was evaluated by comparing the Root Mean Square (RMS) of the estimated user's joint torque $\widehat{T_s}$ and the actual required joint torque T_{Req} to perform the movement. The results of the five sets were averaged allowing to obtain the final metrics.

3. Results

3.1. Passive control

As mentioned in the last section, before doing the five sets for testing the passive mode, an initial calibration set was performed, this set was performed until the convergence of the controller's parameters. As it can be seen in Figure 3, were both the angle and speed trajectory during the calibration set are shown, the controller's parameters converged in approximately 40s which in this case was equivalent to 7 repetitions; after that time, it's possible to see how the trajectory tracking became near perfect showing a minimal error, both for the angle's and speed's trajectory.

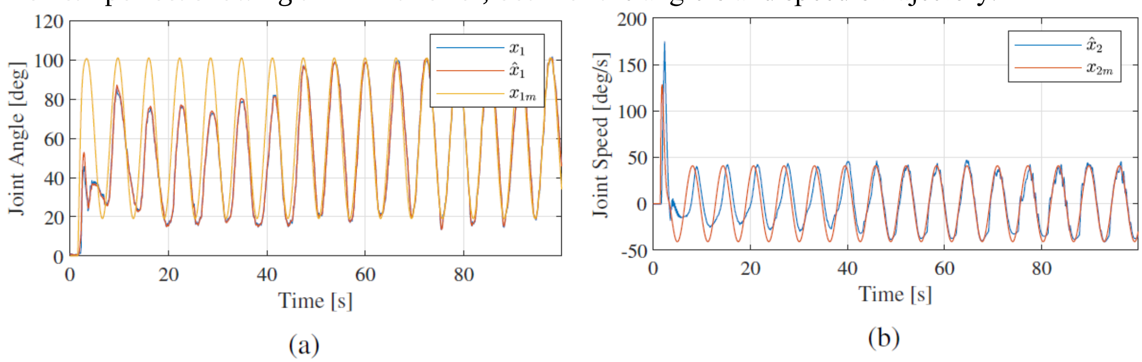

Fig. 3: Trajectory tracking during the controller's calibration procedure for the passive control mode test. (a) Joint Angle. (b) Joint Speed.

During the five sets of ten repetitions of the passive test, the device obtained an angle trajectory tracking MAE of 4.5273° and a speed trajectory tracking MAE of 5.3220°/s. As it can be seen, the MRAC controller can follow both the angle and speed trajectory during passive movements. In addition, it was observer, that the controller was able to effectively reject external perturbations caused by involuntary movements of the user during the trial, proving the robustness of the controller.

3.2. Active control

As established in Section 2.4. an initial calibration set was performed before conducting each one of the sub-tests; during this calibration procedure, similar results as the results obtained in the passive control mode calibration were obtained. The results obtained in one of the five sets of both sub-tests of the active control mode test are presented in Figure 4.

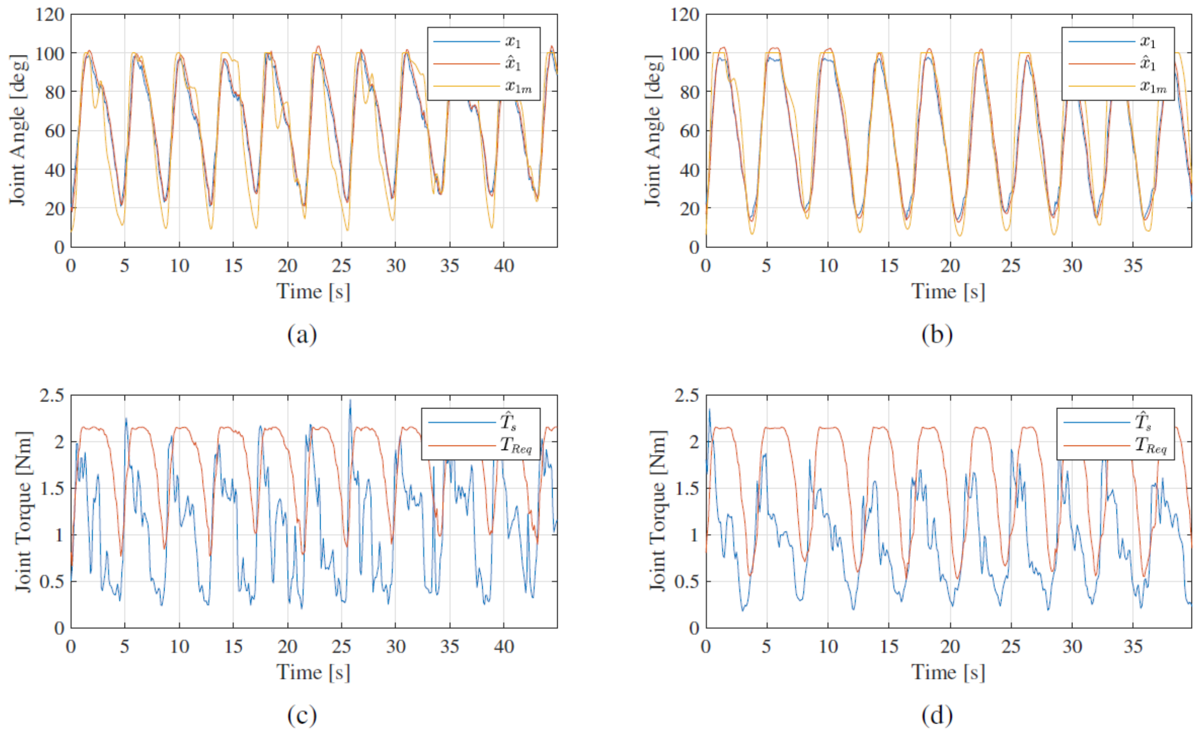

Fig. 4: Trajectory tracking, and comparison between estimated torque Tˆs and required torque TReq for the myoelectric active control mode during sub-test 1 and sub-test 2. (a) Joint Angle sub-test 1. (b) Joint Angle sub-test 2. (c) Estimated joint torque and required joint torque sub-test 1. (d) Estimated joint torque and required joint torque sub-test 2.

As it can be seen in Figure 4, during both sub-tests the controller behaved similarly during the angle trajectory, however, it's noticeable how the sub-test 2 has a more stable and smoother trajectory when comparing it to sub-test 1. In the Figure, it is also possible to observe how the estimated torque varies during both sub-tests, it's possible to see how during sub-test 1 the estimated torque during the movements is higher than the one in sub-test 2; nevertheless, it's important to note, that in both cases, the estimated joint torque $\widehat{T_s}$ was less than the actual required joint torque T_{Req} when performing the movements. The numerical results are shown in Table 1.

As it can be seen in Table 1, the numerical results are consistent with what was shown in Figure 4. As shown on the table, the average angle trajectory tracking MAE is similar for both sub-tests. Conversely, it's possible to note how the estimated torque, and the torque reduction percentage are different during the sub-tests; as expected, sub-test 2 had a higher torque reduction and thus, a lower estimated RMS torque than sub-test 1, this, because the parameters of the reference model in sub-test 2 were set to represent a *"lighter virtual arm"* that requires less torque from the user in order to perform the same flexion-extension movement. These results support the feasibility of the proposed reference model as a method for modifying the arm's dynamics to provide assistance with an exoskeleton.

Table 1: Myoelectric active control mode average results.

sub-test	**MAE Angle [deg]**	$\widehat{T_s}$ **-RMS [Nm]**	T_{Req}**-RMS [Nm]**	**Torque Reduction [%]**
1	10.6233	1.2000	1.8279	34
2	10.2310	0.9846	1.6667	40

4. Conclusion

The designed Cable Driven Soft Elbow Exoskeleton proved to be suitable for rehabilitation and assistance applications. The designed device is lightweight, comfortable, easy to transport and requires a minimum setup to operate. The developed exoskeleton allows two different operation modes, a passive mode and an active mode based on electromyography that allows the voluntary control of the device; these two operation modes give versatility to the device and the possibility to be used for different rehabilitation and assistance tasks.

The implemented Model Reference Adaptive control obtained an average trajectory tracking MAE of 4.5273◦ during the passive control mode test, and an average trajectory tracking MAE of around 10° during the active control mode tests. The myoelectric active control mode allowed a reduction between 34 % and 40 % in the required RMS joint torque for performing a movement, proving its feasibility for movement assistance tasks.

Future work includes the implementation of an additional cable on the posterior part of the arm that allows assisted extension; the implementation of a higher torque motor so the device can handle heavier loads, and to test the exoskeleton assistance capability while the user performs loaded movements with different objects.

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