CURE: A Cable-Driven Upper-Limb Rehabilitation Exoskeleton for Assisting ADLs in Home-Based Environment

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***Abstract*—Various upper limb wearable robots have been developed to promote rehabilitation effectiveness. Some are devoted to single-joint rehabilitation with simple structure, while others target multi-joint rehabilitation with bulky size and complex frameworks. A multi-joint wearable robot is desired to facilitate home-based upper-limb rehabilitation. In this paper, a lightweight and compact wrist-elbow exoskeleton is designed for home-based activity of daily life (ADL)-oriented upper-limb rehabilitation. This exoskeleton utilizes a cable-driven actuation system to locate the motors in the backpack part and reduces the physical burden on the user's arm. Three motors actuate the movement of three degrees of freedom (DoFs), elbow flexion/extension, pronation/supination, and wrist flexion/extension. Three IMUs are mounted on the exoskeleton's hand, forearm, and upper arm parts to capture the exoskeleton's movement. An experiment with healthy subjects was conducted to validate that this proposed upper limb rehabilitation exoskeleton can accurately assist the ADLs of patients by simultaneously helping the movement of three DoFs, and the root mean square error (RMSE) of the tracking error was less than 3° for all DoFs. The proposed upper limb exoskeleton can promote the effectiveness and convenience of ADL-oriented rehabilitation.**

***Index Terms*—Wrist-elbow exoskeleton, home-based rehabilitation, cable-driven actuation, activity of daily life.**

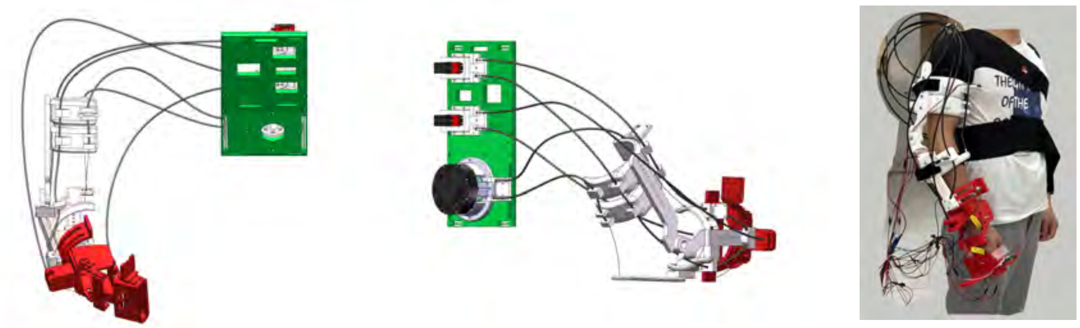
I. Introduction

Rehabilitation robotics is a promising and emerging research field in recent decades. Rehabilitation robots can provide repetitive and accurate assistance during patient rehabilitation and relieve the physical burden on physical therapists (PTs) [1]. Moreover, rehabilitation robots can record and quantify the progress made by the patients and provide an assessment for PTs so that they can adjust the rehabilitation plan accordingly.

Various kinds of wearable upper limb rehabilitation robots have been developed recently. Compared with end-effector rehabilitation robots [2], wearable robots [3], [5], or exoskeletons [6], [7], can assist with the movements of upper limb joints instead of helping with the moving trajectory of patients' hands. It allows the exoskeletons to target the movement of different joints and customize the assistance to patients suffering from neurological impairments.

The upper limb exoskeletons can be classified as single-joint and multi-joint rehabilitation exoskeletons. They are developed to provide rehabilitation to patients under different rehabilitation phases. The single-joint rehabilitation exoskeletons target the patients at an early rehabilitation stage, where patients require basic movement training of one joint. Liu et. al [4], [8] developed an elbow exoskeleton with variable stiffness for bilateral training. It is compact and lightweight, using aluminum alloy as the framework and a cable-driven actuation system. Pneumatic artificial muscles are also used in a wrist-joint rehabilitation robot, and surface electromyography (sEMG) is used to estimate the impedance of the wrist joint and motion intention of users [9]. A cooperative control strategy is developed to improve voluntary participation and training effectiveness. Besides, some soft exoskeletons are designed to assist joint movement without adding excessive physical load on patients [10]. However, soft wearable rehabilitation robots suffer from the complexity and precision challenges of control posed by their nature. Multi-joint upper limb robots are developed to train multiple joints and DoFs simultaneously [7], [11]. Although most of them utilize the bilateral training strategy, which is helpful for the simple movements of the upper limb, it is hard to implement for ADL-oriented training. A pulley set-based mechanism used in a wrist/elbow cable-driven exoskeleton is proposed to provide bilateral mirror training for hemiplegia patients with high effectiveness and safety [11]. ANYexo 2.0 is a wearable robot that covers all joints and DoFs of the upper limb, and it can assist complex movements such as throwing a tennis ball and washing dishes. However, it is bulky and heavy, making it suitable only for hospitals or care facilities [7].

Few upper limb rehabilitation exoskeletons can achieve both multi-joint/DoF assisting ability and lightweight simultaneously. These are two crucial factors that allow the rehabilitation exoskeleton to be implemented at home and provide patients with home-based and ADL-oriented rehabilitation. Patients who suffer from neuromuscular impairments find it



(a) Front view (b) Back view (c) CURE

Fig. 1: Structure of CURE

hard to move, which makes it expensive to transport and physically overload PTs, considering the requirements for high-frequency and high-repetition task-specific training. Home-based rehabilitation is promising for delivering high-dose rehabilitation sessions without the fatigue and expenses caused by regular visits to hospitals [12]. ADL-oriented training involves the movement of multiple joints and interaction with the physical world, directly targets skills needed for daily life, and bridges the gap between clinical therapy and practical application. Besides, it can enhance patient motivation and engagement [13]. And repetitive, task-oriented practice promotes cortical reorganization, strengthening neural pathways associated with functional movements [14]. ADLs require simultaneous cognitive planning (e.g., sequencing steps to pour water) and motor execution, fostering holistic recovery.

To address the above challenges and limitations, a wrist-elbow cable-driven upper limb rehabilitation exoskeleton (CURE) is proposed in this paper to assist ADL-oriented rehabilitation. CURE is designed with a compact, lightweight framework with three active DoFs and three passive DoFs. The plastic material is used for the main framework to reduce the weight of the arm part. Three motors are used with a cable-driven force transmission system to assist the movements of wrist flexion/extension, pronation/supination, and elbow flexion/extension separately. The motors are mounted on a backpack, relieving the physical load on users' arms. An experiment with healthy subjects validated the feasibility of using the proposed CURE to assist the ADLs with high trajectory tracking accuracy.

The contribution of this study can be summarized as follows:

1) A lightweight cable-driven home-based wrist-elbow rehabilitation exoskeleton for ADL-oriented training has been designed and developed.

2) Experiments with healthy subjects validated its effectiveness in assisting patients to perform ADLs accurately.

II. Method

A. Structure of the cable-driven upper limb rehabilitation exoskeleton (CURE)

The structure of the proposed CURE is shown in Fig. 1. It mainly consists of three parts: the back section (green part), which is used to mount motors, the controller, and batteries; the elbow section (white part) includes the arm cuffs and an elbow joint movement framework; and the wrist section (red part) consists of an arm rotation and a wrist flexion/extension mechanism. The total weight of CURE is 1.5 kg, making it considerably lightweight considering that it can assist the movements of three DoFs. Instead of using pulley sets to drive the joints, cables are attached to the cuffs or far ends of the structure. Hence, a longer arm length for joint rotation can be achieved, and a smaller force is required to provide the same assistance to patients, reducing the force/torque requirements for the motors, which can further reduce the weight of the motors and lead to a lightweight design of the system. For instance, the arm length of the elbow joint is 12 cm, much larger than a pulley that can be implemented on a wearable robot. The structures of elbow flexion/extension, pronation/supination, and wrist flexion/extension are presented in Fig. 2.

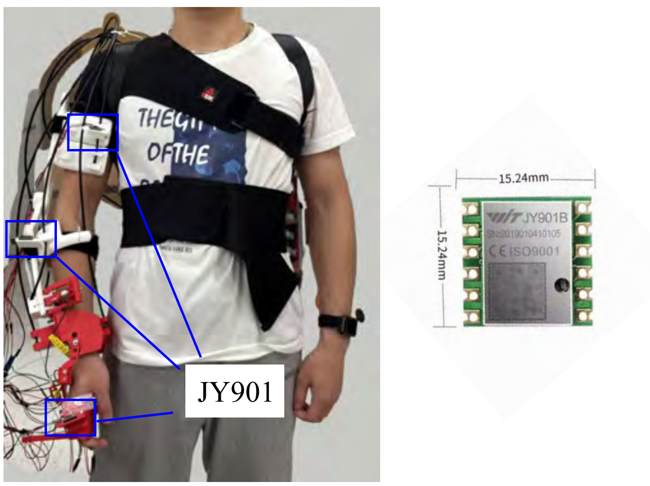
B. Sensing, actuation and control

1) Joint angles: Since CURE is a cable-driven exoskeleton, the joint angles cannot be obtained directly through the encoders of the motors. Therefore, the joint angles of CURE are calculated through the posture of each segment (upper arm, lower arm, and hand) monitored by three IMUs (JY901B, WitMotion Shenzhen Co., Ltd, Shenzhen, China) mounted on the framework of CURE as shown in Fig. 3.

To avoid the problem of "Gimbal lock", the pitch angle of IMUs is aligned with the movement of abduction/adduction of the wrist joint since it is much less than 90° as shown in Fig. 2. Moreover, the Euler angles of the different IMUs are transformed to quaternions, and the joint angle is calculated using the quaternions of the arm segments. And the calculation process can be represented as follows:

(a) Elbow flexion/extension (b) Pronation/supination (c) Wrist flexion/extension

Fig. 2: Parts of CURE for assisting different movements



(a) Mounting positions of IMUs (b) JY901

Fig. 3: The sensing system

Let us assume that the Euler angles are in the ZYX sequence, the roll, pitch, and yaw angles are represented as ϕ, θ, and ψ. Then, the quaternion representation of the individual segment:

$$q_z(\psi) = \begin{bmatrix} \cos\frac{\psi}{2} \\ 0 \\ 0 \\ \sin\frac{\psi}{2} \end{bmatrix}, \quad q_y(\theta) = \begin{bmatrix} \cos\frac{\theta}{2} \\ 0 \\ \sin\frac{\theta}{2} \\ 0 \end{bmatrix}, \quad q_x(\phi) = \begin{bmatrix} \cos\frac{\phi}{2} \\ \sin\frac{\phi}{2} \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

For each IMU, the combined rotation is:

$$q_{\text{imu}} = q_z(\psi) \otimes q_y(\theta) \otimes q_x(\phi) \tag{2}$$

For arbitrary quaternions $q_1 = [w_1, x_1, y_1, z_1]$ and $q_2 = [w_2, x_2, y_2, z_2]$:

$$q_1 \otimes q_2 = \begin{bmatrix} w_1w_2 - x_1x_2 - y_1y_2 - z_1z_2 \\ w_1x_2 + x_1w_2 + y_1z_2 - z_1y_2 \\ w_1y_2 - x_1z_2 + y_1w_2 + z_1x_2 \\ w_1z_2 + x_1y_2 - y_1x_2 + z_1w_2 \end{bmatrix} \tag{3}$$

The relative rotation quaternion of two segments can be represented as follows,

$$q_{\text{joint}} = q_{\text{imu2}} \otimes q_{\text{imu1}}^{-1} \tag{4}$$

where the inverse quaternion $q^{-1} = [w, -x, -y, -z]$

Then, transforming the quaternion to Euler angles (ZYX sequence) can be achieved by letting $q_{\text{joint}} = [w, x, y, z]$, then:

$$\phi_{\text{joint}} = \operatorname{atan2}\left(2(wx + yz),\ 1 - 2(x^2 + y^2)\right) \tag{5}$$

$$\theta_{\text{joint}} = \arcsin\left(2(wy - zx)\right) \tag{6}$$

$$\psi_{\text{joint}} = \operatorname{atan2}\left(2(wz + xy),\ 1 - 2(y^2 + z^2)\right) \tag{7}$$

2) Actuation: Two servo motors (DS32118MG, Dongguan City Dsservo Technology Co.Ltd, Dongguan, China) assist in arm rotation and wrist flexion/extension movements. A bionic robot joint motor(GO-M8010-6, HangZhou YuShu TECHNOLOGY CO., LTD, Hangzhou, China) assists elbow flexion/extension movement since it can provide a higher torque.

In each joint shown in Fig. 2, two cables assist the movements in opposite directions, similar to agonist-antagonist pairs, to achieve accurate control of the joint movements. Also, the two cables are connected to the two ends of a motor; the rotation of the motor leads to the pulling of one cable and the releasing of the other, as agonist-antagonist.

3) Control: The control of CURE is realized by using Robot Operation System 2 (ROS2) on a Laptop, which connects to the elbow joint motor directly and the servo motors, assisting the wrist joint movement, and IMUs through an Arduino Mega board. The cables cannot always be tightened, resulting in unreliable position information obtained from the encoders of the motors. Therefore, the closed-loop control of the system does not rely on the position information of motors; instead, the joint angles are calculated from the arm segments' postures and directly used as the feedback signal to adjust the output speed of the motors. The structure of the control system is presented in Fig. 4.

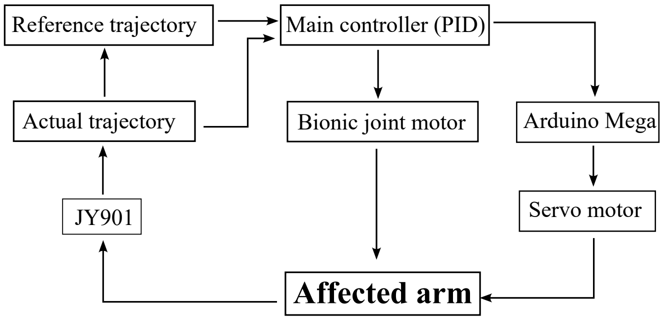


Fig. 4: The diagram of the control system

III. Experiment

A. Experiment protocol

Two healthy participants joined the experiment, and they were informed of the protocol and gave written informed consent before the experiment sessions. They did not suffer from any neuromuscular disorders or conditions. The experiment was approved by the ethics committee of the Southern University of Science and Technology (approval no. 20250066), and it was conducted following the principles stated in the Declaration of Helsinki. All experiments were performed at the College of Engineering, Southern University of Science and Technology, Shenzhen, China.

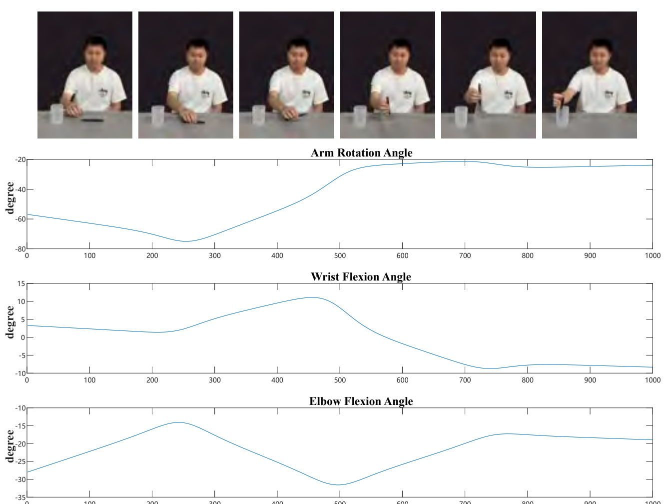


Fig. 5: The movement of pickup

The activity of daily life adopted in the experiment section is the pick and place movement, as shown in Fig. 5. The user picks up a pen placed on the table and puts it in a pen container, which simultaneously requires the movement of the wrist and elbow joints. Each participant's movement trajectory is recorded before the experiment by wearing three IMUs (HWT-9053, WitMotion Shenzhen Co., Ltd, Shenzhen, China) on their hand, forearm, and upper arm. Then, participants performed the pickup movement, and the joint angles during the movement were recorded as the reference trajectory. After obtaining the reference trajectory, a researcher helped the participant wear CURE and allowed them to acclimate to it for 10 minutes. During the experiment, the participants relaxed their arms and let CURE assist the pickup movement. For each participant, the pickup movement repeats 5 times. The actual trajectory (joint angles during the experiment) and the cable tension, which are recorded by force sensors, are used to evaluate the performance of assisting the ADL for patients.

B. Experimental results

TABLE I: TRACKING ERROR DURING THE PICKUP TASK

DoF	Elbow	Wrist	Arm rotation
Tracking error (RMSE)	2.65	0.49	2.42

RMSE: Root Mean Squared Error, unit is degree.

As shown in TABLE I, the tracking error of three DoFs is considerably small, the maximum tracking error in RMSE was 2.65°, and the minimum error was 0.49°. One example of a participant performing the pickup task with the help of CURE is presented in Fig. 6. The actual trajectories were almost identical to the reference trajectory, as shown in the first row of Fig. 6. The error increases when the movement of the joint changes, starting or stopping. For the elbow joint (Fig. 6 (a)), the tracking error is higher at the times of 20s, 25s, and 30s, all of which were the timing of the change of movements, coinciding with the time when the force generated by the motor changes rapidly as shown in the lower figure of Fig. 6 (a).

IV. Discussions

This study designed and developed an ADL-oriented home-based upper limb exoskeleton, and an experiment with a daily activity, a pickup task, was conducted to validate its effectiveness in assisting with ADL. In the experiment, participants were required to relax and not to move their arms voluntarily, and CURE passively assisted the arm of the participant in the predefined trajectory. The tracking error of the reference trajectories of three DoFs was considerably small, while the tracking error for the elbow joint and arm rotation (pronation/supination) was comparatively high. The reason could be that the movement of wrist flexion/extension requires less force, as the range of motion and the stiffness of the wrist joint are smaller as shown in Fig. 6(b), making it easier for the exoskeleton to assist the wrist joint to follow the movement of a predefined trajectory accurately.

Home-based rehabilitation has been a trend since it can avoid the time-consuming and tiring transportation from home to hospital, and improve the training effectiveness by extending the training time. The challenge lies in home-based rehabilitation, which involves remotely guiding or assisting rehabilitation training sessions [14]. Rehabilitation robots can provide repetitive and accurate assistance for patients at home, and they can record the performance of patients during training, which can be used to assess rehabilitation progress by PTs. However, few rehabilitation robots target home-based training and can meet the requirements, including being lightweight

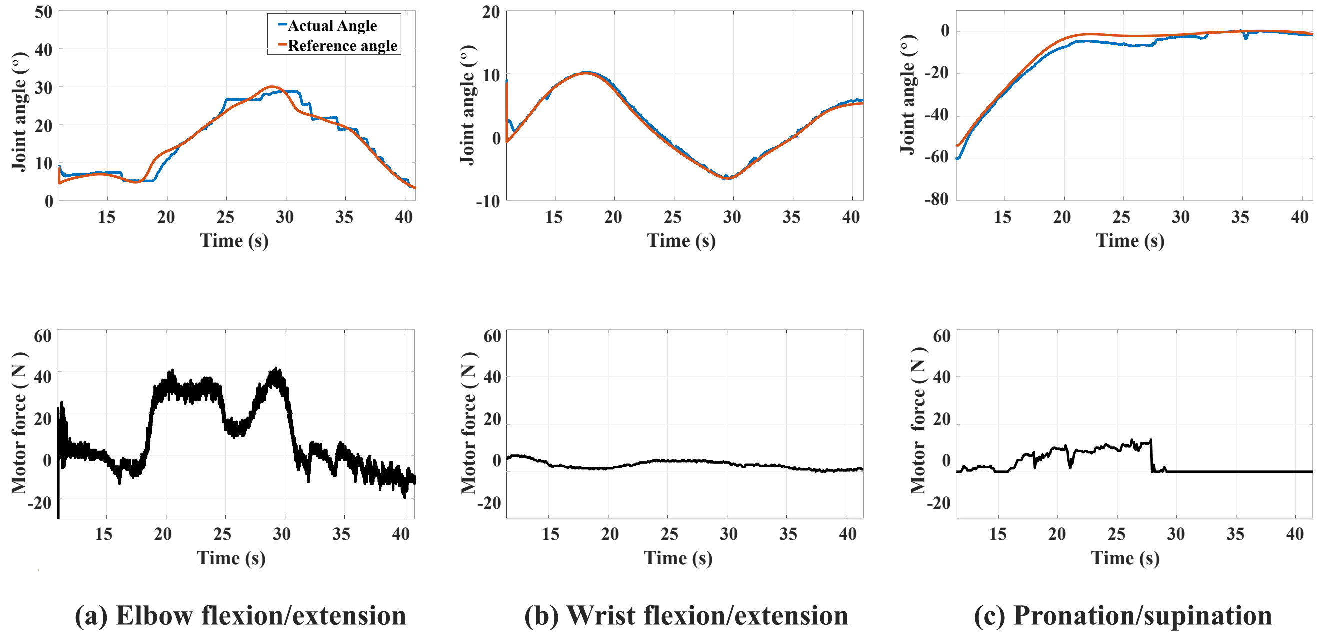


Fig. 6: Tracking performance during the pickup task

and compact. Moreover, a rehabilitation robot should assist the movement of multiple joints and help with the ADL-oriented training, which allows the patients to interact with the environment. The upper-limb rehabilitation exoskeleton proposed in this study can assist three DoFs simultaneously in following predefined trajectories for performing ADLs. Its lightweight and compact size make it suitable for patients to perform ADL-oriented training at home, where they can interact with a familiar environment. Training at home can boost voluntary participation, and it is task-specific to improve the skills and movements required by the daily tasks the patients need to complete at home. It can enhance the effectiveness of rehabilitation and promote the quality of life of patients with neuromuscular impairments.

This study focused on the design of the hardware and control system of a wrist-elbow joint exoskeleton, and the movement of the shoulder is not assisted by the exoskeleton. It is still challenging to design a portable exoskeleton to help users with the movement of the shoulders due to the complex nature of shoulder movements. Besides, it requires a large torque/force generated by motors or other actuators to effectively assist the movement of the shoulder because of the high inertia caused by the heavy weight of the whole arm part. The three large motors (each for assisting one DoF of the shoulder joint) and a complex framework make the exoskeleton too bulky and heavy for even healthy people, let alone patients recovering from neuromuscular impairments, such as stroke. Another limitation of the current exoskeleton is that the method to sense users' movement is only the IMUs to detect the joint angles, which can only provide passive training to users. As the next step, more human-robot interaction interfaces will be introduced to enhance the sensing ability of the exoskeleton, such as surface electromyography and brain-computer interface.

V. Conclusion

In this paper, a home-based cable-driven upper limb rehabilitation exoskeleton is designed and developed to assist daily life activities (ADL). The proposed exoskeleton assists the movement of elbow flexion/extension, pronation/supination, and wrist flexion/extension through a cable-driven system. It was designed as a lightweight, portable rehabilitation robot, weighing less than 3kg, and the wearable arm part weighs less than 1.5 kg. An experiment using a daily life task was conducted to evaluate its effectiveness in assisting the ADLs. The accuracy of the movements of 3 DoFs is substantially high; the root mean square error (RMSE) of the tracking error was less than 3° for all DoFs. As the next step of this study, surface electromyography (sEMG) will be integrated into the system to enhance its human-robot interface, and an updated framework, including active shoulder movement assistance, will be implemented to improve the effectiveness of the home-based ADL-oriented upper-limb rehabilitation exoskeleton.

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