A Bamboo-inspired Exoskeleton (BiEXO) Based on Carbon Fiber for Shoulder and Elbow Joints

Ahmad Zahedi, Yansong Wang, Nathan Lau, Wei Tech Ang, and Dingguo Zhang *

***Abstract*—This paper presents a novel cable-driven exoskeleton (BiEXO) for the upper limb including shoulder and elbow joints. BiEXO is made of carbon fiber that is inspired by the Bamboo structure. The key components of BiEXO are carbon fiber tubes that mimic bamboo tubes. A combined driver is developed for BiEXO with two cable-driven mechanisms (CDMs) and a power transmission belt (PTB). The CDMs are used for shoulder and elbow flexion/extension movement utilizing cables to mimic the skeletal muscle's function, while the PTB system drives a shoulder link to mimic the scapula joint for shoulder abduction/adduction movement. Simulation studies and evaluation experiments were performed to demonstrate the efficacy of the overall system. To determine the strength-to-weight of the bamboo-inspired links and guarantee high buckling strength in the face of loads imposed from the user side to the structure, finite element analysis (FEA) was performed. The results show that the carbon fiber link inspired by bamboo has more strength in comparison to the common long carbon fiber tube. The kinematic configuration was modeled by the modified Denavit-Hartenberg (D-H) notation. The mean absolute error (MAE) was 5.9 mm, and the root-mean-square error (RMSE) was 6 mm. In addition, verification experiments by tracking the trajectory in Cartesian space and the wear trials on a subject were carried out on the BiEXO prototype. The satisfactory results indicate BiEXO to be a promising system for rehabilitation or assistance in the future.**

***Index Terms*— exoskeleton, bamboo, carbon fiber, cable-driven mechanism, upper limb, rehabilitation robots.**

I. Introduction

Motor impairment of upper limbs caused by neurological disorders or factors like aging and accidents have significantly diminished physical ability leading to a variety of challenges for normal activities of daily living (ADLs). Previous studies show that patients who suffered from motor or sensory deficits of the upper limb also had to bear a subsequent economic burden and face severe psychological problems. Rehabilitation programs utilizing wearable exoskeletons not only eliminate the physical load of motion therapy for the physiotherapist but also minimize treatment-related costs [1-3]. Robotic exoskeletons enhance accuracy and reliability and improve the efficiency of rehabilitation training and the effectiveness of physiotherapy sessions. Robotic exoskeletons are also very helpful in assisting disabled people to regain independence in daily life, and portability is a key issue in this case [2]. At present, there are two main streams for exoskeletons, i.e., soft exoskeletons and rigid exoskeletons.

Soft exoskeletons, or exosuits, typically employ soft mechanisms to transfer functional forces to the wearer. They also focus on textile-embeddable sensors, and soft human-device interaction [4-6]. Although much attention has been given to soft wearable exoskeletons due to advantages in adaptability, comfort, portability, compliance, weight, energy consumption, etc. The major drawback of the soft exosuits is the structure. Exosuits have no rigid frame that can transfer power to the environment, so this issue may cause a decline in power transmission efficiency. In addition, the actuation mechanism in the soft exosuits requires fixed points on the upper limb to support its activities. It is very challenging to design proper mechanisms in consideration of the location and number of fixed points [4, 5, 7-10]. Other challenges that may restrict the application of the exosuits include sensors and actuators positioning, textile slipperiness, and ill-fitting to the wearer's anatomy that can lead to discomfort in long-term usage [11, 12].

Rigid exoskeletons in comparison with soft exosuits are generally fabricated by rigid links employing rotating joints in parallel to the human arm to imitate the movement of the upper extremity. Various rehabilitation and assistance devices with rigid actuators on human joints have been examined to gain a more precise positioning of motion, a faster response in frequency, and an easier trajectory tracking control [12-15]. However, while interacting with the user, bulky wearable devices face serious problems, such as low portability and lack of patient acceptance. Moreover, this configuration increases the inertia of the device and the size of the actuator [16, 17]. Furthermore, rigid exoskeletons generally employ a series of coupled rigid actuators on the mechanical structure to actuate rotational joints which may cause misalignment of the robot axes and the arm joint axes in a position [15, 18]. The misalignment generates parasitic forces that induce pain and discomfort to the user and may result in fracture or dislocation. The problem of misalignment has been addressed by adding degrees of freedom (DoFs) to the exoskeleton in the following work [19]. However, this solution tremendously increases the complexity of the exoskeleton. Today rigid exoskeletons are eliminating heavy and bulky mechanisms and seeking lighter structures that are more comfortable to wear [20, 21]. Even

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though the solutions of soft and rigid exoskeletons for rehabilitation and assistance programs lack consensus, it seems that a combination of cable-driven approaches and creative exoskeleton structures can be more attractive to researchers. It can supply many benefits including a high payload-to-weight ratio, low inertia, large workspace, good modularity, and reconfiguration [4, 17, 22].

According to the points mentioned above, a cable-driven mechanism (CDM) and power transmission belt systems (PTB) are used widely for exoskeletons. Cable-driven systems employ a similar structure to provide movement to the limb. They deliver the required torque or forces for limb movement while the actuators can be located away from the rotational joints. The cable-driven exoskeletons can minimize the risk of additional injuries during operation for patients due to low inertia and lightweight. [1, 2, 6]. It should be noted that the workspace and performance of the cable-driven systems are limited due to the inherent properties of the cable which must only be pulled to generate force. This may bring challenges for shoulder joint design because four to six cables are generally needed for shoulder joint movement [26]. At present, the available devices have been designed and developed with two or three cables to provide shoulder joint movement [21, 27, 28]. Most cable-driven systems proposed in the previous studies commonly used Bowden cable for exoskeletons to assist limb motions.[2, 16, 20, 26, 29-33] It seems that the Bowden cable system may not be a proper choice for power transmission in an exoskeleton system, because it imposes friction on the system due to close contact of the cable with its cover or container. Large actuators are required to overcome the big friction force. Moreover, the presence of Bowden cables around the user's body when wearing the system may cause safety issues, and this is not aesthetic which may lead to limitations of user acceptance [1, 32-34].

Based on a cable-driven mechanism, we aim to develop a kind of upper limb exoskeleton that has the merits of smart and friendly configuration, modular and personalized structure. This novel exoskeleton is made of carbon fiber and inspired by a bamboo structure. This bamboo-inspired exoskeleton is named BiEXO. The important components of BiEXO are carbon fiber tubes that mimic bamboo tubes. The BiEXO from a design point of view is summarized below.

1) *Cosmetic design*: All the cables and wires can be hidden in the carbon fiber tubes. Therefore, the system looks neat and has an elegant appearance in comparison to the other cable-driven exoskeletons, in which the Bowden cables and wires are uncovered [1, 32-34].

2) *Modular design:* We adopt a modular design inspired by carbon fiber tubes. Different carbon fiber tubes can be combined for a required structure via nodes. A single carbon fiber tube can be replaced easily if necessary.

3) *Personalized design*: The number of carbon fiber tubes and the size of carbon fiber tubes can be adjusted according to the situation of the upper arm and forearm of different individuals.

BiEXO has innovative features of the transmission mechanism. The BiEXO from a technical point of view is summarized as follows.

1) BiEXO uses two customized actuated systems named CDMs and a PTB system equipped with a torque sensor, capstan, and gear. CDMs are used for shoulder and elbow flexion/extension movement and PTB is employed for shoulder abduction/ adduction movement. Embedded torque sensors in actuation systems as physical human-robot interfaces are key features in this study that allow more accurate and better examinations of the exoskeleton system [28].

2) The exoskeleton system utilizes cables to mimic the tendons and employs actuation systems to mimic muscle function. To minimize the burden on the user's arm, the actuator is placed far away from the user's arm and mounted remotely over the user's back.

3) The cable friction created inside the BiEXO structure may be less than the cable friction created inside a conventional Bowden cable. Based on previous studies [28, 33], an association between the transmission efficiency, the friction, and the lengths (or curve angles) of Bowden cable on the human body has been well investigated. In BiEXO, a lot of Bowden cables around the wearer are removed, and the wire (rope) contacts the links of the upper limb exoskeleton at only a few points (aluminum nodes), which may reduce friction.

The rest of the paper is arranged as follows. Section II describes the design objectives and the proposed mechanical structure of the BiEXO system. Section III describes the modeling studies and experiment results of BiEXO. Section VI provides the discussion including comparison analysis and future work. Section V is the conclusion.

II. Method

A. General Requirements

We have provided some general requirements for designing BiEXO. We expect the following requirements can be met.

- Providing a natural range of motion

Physiological constraints cause limitations in human arm orientation in the 3D workspace. Hence, the parameters of the exoskeleton design are only expected to consider providing a natural range of motion (ROM) for human arm orientations. The ROM degree and the range of the shoulder and elbow joint are obtained as shown in Table I. ROM in the exoskeleton system should be realized regarding the accurate alignment and

TABLE I
ROM OF SHOULDER AND ELBOW ANGLES FOR ADLS TASKS PERFORMED BY UNIMPAIRED PARTICIPANTS

Type of motion	Anatomical range	BiEXO range
Glenohumeral joint		
Shoulder Flexion	180°	145°
Shoulder Extension	50°	45°
Shoulder Abduction	180°	127°
Shoulder adduction	50°-180°	4-116°
Internal rotation	110°	---
External rotation	90°	---
Scapulothoracic joint		
Horizontal motion	12 cm	7 cm
Vertical motion	12 cm	3 cm
External rotation	60°	---
Elbow joint		
Elbow Flexion,	150°	152°
Elbow Extension	150°	152°

adjustable link lengths between human joints and exoskeletal. This is a key point to keep in mind when the exoskeleton is designed [35]. An ideal ROM assists the user to well perform tasks such as eating, moving, and holding objects.

- Mass and volume minimization

Since the purpose of the exoskeleton design is to reach to portable exoskeleton for assistance and rehabilitation, the design shall be such that it minimizes mass and volume. for this purpose, Finite element analysis (FEA) or the Taguchi method must be studied and examined to deliver the best possible state for choosing the size and weight of the components of the exoskeleton. Moreover, the exoskeleton must be capable of tolerating maximum weight and buckling strength that may be imposed by patients' bodies. Our proposed exoskeleton meets such expectations well with the carbon-fiber structure inspired by bamboo. FEA will be performed. The total weight of the arm of BiEXO is expected to be about 800 g.

- Power transmission system

Bowden Cable Transmission (BCT) system as a power transmission system has already been presented in previous studies [6, 21, 29]. However, the main drawback of the BCT system is the high friction and backlash hysteresis which impacts their control efficiency[30]. In this study, a novel design of the exoskeleton equipped with CDMs is proposed to overcome the drawbacks of the BCT system. In addition, a PTB system is also employed for shoulder movement in abduction/ adduction movement. CDMs and PTB systems are explained in detail in the next sections.

B. Design and Development of BiEXO

Since a proper design must provide the desired functionality for the exoskeleton systems, it is necessary to pay attention to these points: the configuration of links and joints, the number of degrees of freedom (DoFs), sensors, actuators, and control system. Although one of the major targets of exoskeleton design was to mimic the human arm motions as closely as possible, however, there were restrictions in covering all movement of the shoulder in all directions. The hardware of the proposed exoskeleton is shown in Fig.1.

Overall, BiEXO is a wearable exoskeleton to allow shoulder abduction/ adduction, shoulder flexion/extension, and elbow flexion/extension. The BiEXO system is a cable-driven system that is developed and fabricated based on the carbon fiber material. The backrest compactly houses the actuator module including a cable-driven mechanism (CDMs) and power transmission system (PTB), embedded controller, I/O board, and battery. Fig. 1(c) shows the arrangement of the actuation system in the suggested exoskeleton as a sample. The phantom view in the two actuator modules out of three actuators displays the driving system of the elbow joint and shoulder (Ab/Ad) joint, where the blue piece is the cable-driven pulley (winch capstan) to fix the cable, the red piece is the torque sensor, and the purple piece is the gear for driving PTB system.

1) *Configuration of links and joints*

The structure of the arm and forearm links of the BiEXO system is inspired by the bamboo structure, which is the key feature of the system. Bamboo has inherent properties and many advantages such as lightness in weight, high bending resistance, excellent tensile properties, and high strength [36].

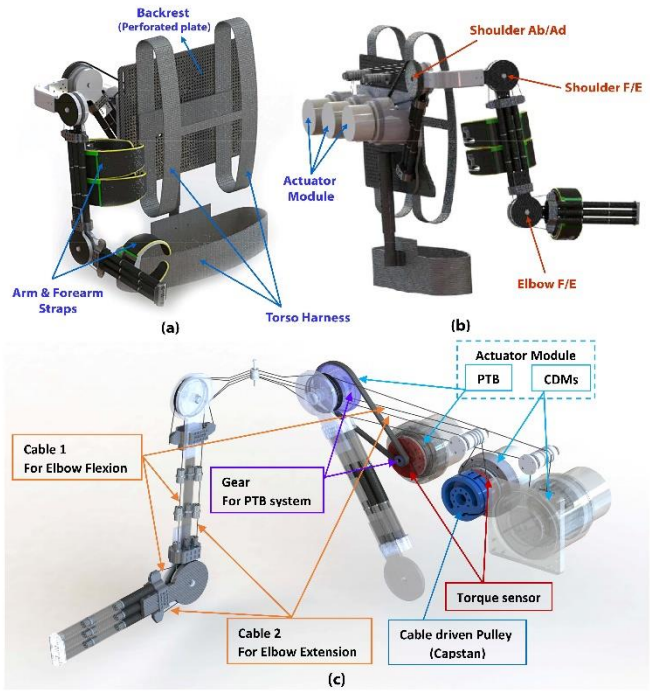

Fig. 1. Structure of the BiEXO system: (a) Front view, (b) Back view, (c) Schematic of the compound actuation system. The blue piece is the cable driven pulley (winch capstan), the red piece is the torque sensor, and the purple piece is the gear for driving PTB system.

The carbon fiber tube and aluminum parts are used to play the role of tubes and nodes of bamboo respectively. The arm and forearm links of the proposed device are fabricated by assembling carbon fiber tubes and aluminum parts next to each other based on the bamboo structure, see Fig. 2. The cables need to be routed from the shoulder and elbow joints to the actuator system on the Backrest through the guide holes which are

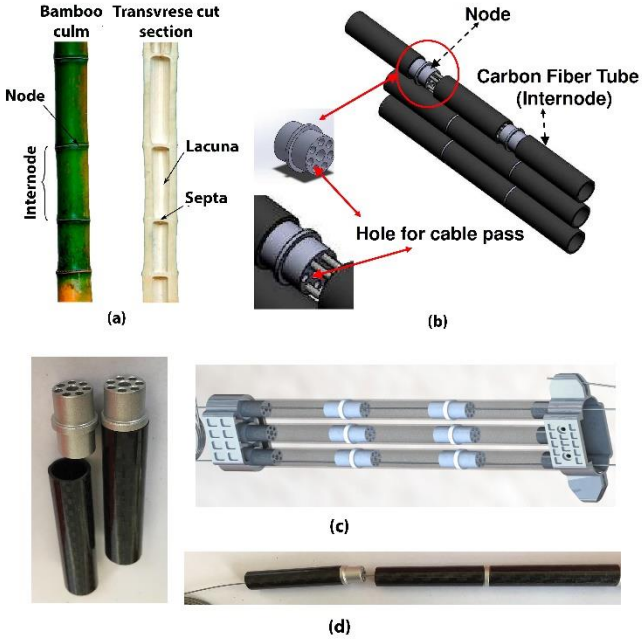

Fig. 2. (a) Anatomy of a bamboo. (b) Carbon fiber tube inspired by bamboo tube. (c) Design of carbon-fiber link. (d) Actual photo of a link of BiEXO.

embedded in the aluminum node to obtain a cable-driven system, see Fig. 2(c). According to our previous experience, the cable diameter is considered to be 1.2 mm, which is composed of seven twisted strands shaped by seven individual wires of stainless steel. As shown in Fig. 2(b) and Fig. 2(c), the aluminum node is embedded between two carbon fiber tubes. This is another strength of the BiEXO system that allows users to move the arm with smaller motors, as a result, it reduces energy consumption and increases the portability of the device.

2) *Mechanical design of elbow joint*

The human elbow joint has 1 major DoF (flexion/extension), while the forearm has 1 DoF (supination/pronation) that was not considered in this study. The elbow joint of BiEXO is designed as an incomplete hinge joint. During the elbow flexion, like lifting a cup, the biceps muscle is the prime mover, and the elbow extension is performed by a triceps muscle with an opposite operation of the prime mover, which is named an antagonist. It should be noted that the triceps (as an antagonist) muscle plays two significant roles: maintaining limb position and rapid movement control. Therefore, the elbow joint of BiEXO can be proposed based on human muscles biceps, and triceps [37], as shown in Fig. 3. A set of bidirectional cable-

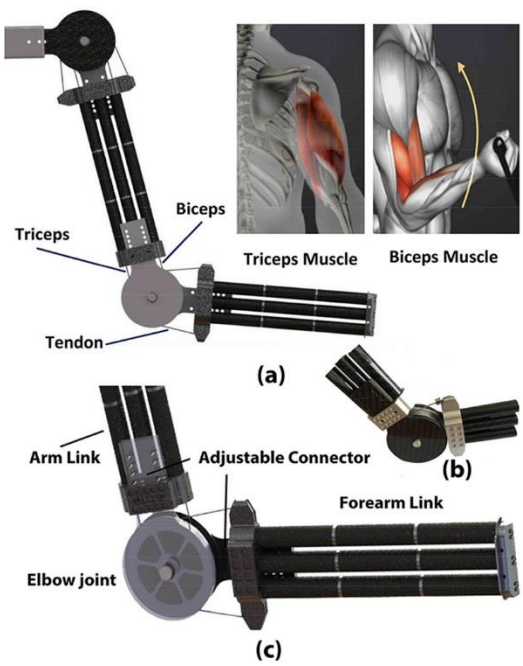

Fig. 3. (a) Concept design of structure of the arm exoskeleton. (b) Porotype of the elbow joint. (c) 3D design of the bionic elbow joint.

driven systems is used to assist elbow joint movements, which is attached to the forearm link from one side and to the cable-driven pulley on the other side (cable-driven pulley is the same winch capstan connected to the torque sensor that torque analysis is completely investigated in our previous paper [28]). The cables mimic the functions of the tendons of the biceps and triceps. The cables are attached to both sides of the forearm link, after being wrapped around the rotational pulley in the elbow joint, and can be routed to the winch capstan through the cable-fiber link and guide holes in the aluminum node to provide the forearm movement. In this manner, the linear motion of the cable when in pulling mode will be converted to the rotation motion of the forearm around the axis of the elbow joint. In fact, the two cables act as a pair of antagonistic muscles. The mechanisms and the cable routing systems are designed based on the biomechanics of the elbow joint, which can completely provide elbow flexion/ extension for BiEXO during ADLs.

3) *Mechanical design of shoulder joint*

The human shoulder joint is very complex and has a wide range of motions. It requires the cooperation of many muscles to work together. Hence, the design of the shoulder joint is the most complex and challenging. The glenohumeral joint supports three DOFs including flexion/extension, abduction/adduction, and internal rotation/external rotation, and the Scapulothoracic joint supports two DOFs including horizontal motion and external rotation. The complex movement of the shoulder is performed by the glenohumeral joint which is a spherical joint.[24] In this study, the presented mechanism, see Fig. 4, aims to ease the shoulder joint action of the user in rehabilitation or assistance. To meet the requirements of rehabilitation exercise effectively, and meet proper engineering structure, we simplify the movement of the biomechanical joint of the shoulder to decrease the intricacy of the mechanical structure. Regarding the safety of the exoskeleton system and providing useful rehabilitation therapy as well as assisting in achieving essential ADLs, such as eating, drinking, and grasping, preliminary investigations on the anatomical range of the upper limb movement, see Table I, have been performed to choose the appropriate movable ROM for the presented mechanism. The ROM degree and the range of

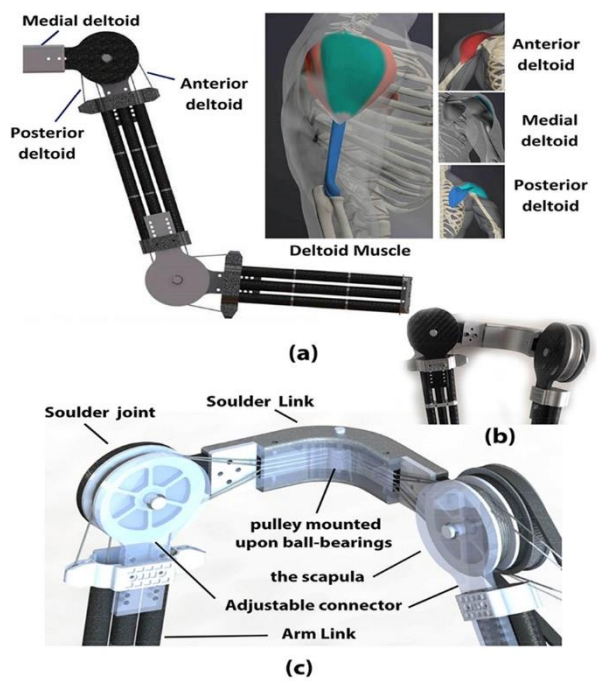

Fig. 4. (a) Conceptual design of the biomechanical structure of the arm exoskeleton. (b) Porotype of the shoulder complex (c) 3D design of the bionic shoulder complex.

the mechanism of the shoulder and elbow joint are obtained as shown in Table I. To achieve shoulder movements, the deltoid muscle is one of the most important muscles. The deltoid muscle has the largest physiological cross-sectional area in the shoulder joint girdle and is significant in the abduction of the

shoulder. It is a triangular large muscle, which lies over the glenohumeral joint and covers the complex of the rotator cuff and the humeral head [23, 24]. Moreover, the corporation between the deltoid muscle and the rotator cuff muscles creates a force couple to facilitate smooth shoulder joint movements.

Deltoid muscle includes three anatomical portions, named the anterior, the medial, and the posterior portion, respectively. Each muscle portion work for a specific movement, which is the arm flexion, abduction, and extension respectively [23, 24], see Fig. 4(a). The anterior deltoid located in the front serves for shoulder flexion, horizontal adduction, internal rotation, and the motion of the arm raising overhead. The medial (lateral) deltoid between the anterior and posterior is principally responsible for shoulder abduction. The posterior deltoid is responsible for shoulder extension, external rotation, and horizontal abduction. For shoulder flexion/extension, the cable attached to the forearm link is wrapped around the rotational joint, which is placed in the shoulder joint, then it is transferred to the CDMs (actuator) through the arm link which has been explained in one of the previous sections. The proposed mechanism taken from the anterior deltoid and the posterior deltoid completely provides shoulder flexion/extension during ADLs.

4) *Mechatronic and transmission system*

The control system relies on the RT-Linux operating system that realizes the communication with motor servo drives via the EtherCAT bus, see Fig. 5(e). A Beckhoff terminal with extensibility is employed for toque sensors signal sampling. The sampling rate and control frequencies are both 1000 Hz and the maximum delay is approximately 2 us. The control system and extracting data from the torque sensor have been proposed in our recent paper [28]. Because of the natural features of the cable (unidirectional nature), the workspace and the performance of the cable-driven system are restricted. To overcome this problem, two actuation systems (CDMs and PTB system) are used, as shown in Fig. 1(c) and Fig. 5(a). CDMs are used for elbow and shoulder movement in flexion and extension movement while PTB is carried out for shoulder abduction/adduction. The BiEXO system is designed based on compliant human-robot interaction which can assist the wearer to move the arm during the ADLs. These non-localized CDMs allow the use of a more powerful actuator permitting greater lifting power for the wearer. The CDMs will help in decreasing the overall weight of the BiEXO which is located over the perforated carbon fiber sheet (Backrest) on the back of the body. The lightweight Backrest will be well-fastened on the back of the body by Torso Harness which is shown in Fig. 5(a). The Backrest is designed such that other necessary equipment can be easily mounted over it which will cause user convenience and acceptance. The experience setup is evaluated in the next sections in detail. The CDMs consist of the actuator (geared Maxon motor), a speed reducer with a gear ratio of 100, a torque sensor (M2210A, Sunrise Instrument Company, China), coupling, a cable-driven pulley (winch capstan), an aluminum plate, and shield of CDM, see Fig. 6. The torque sensor is placed between of the output of the harmonic reducer and cable driven pulley. The CDMs shown in Fig. 6. are another key feature of BiEXO. Among our indicators for choosing the motor was the capability to modify the output torque and lightweight. One of the drawbacks of the CDMs is

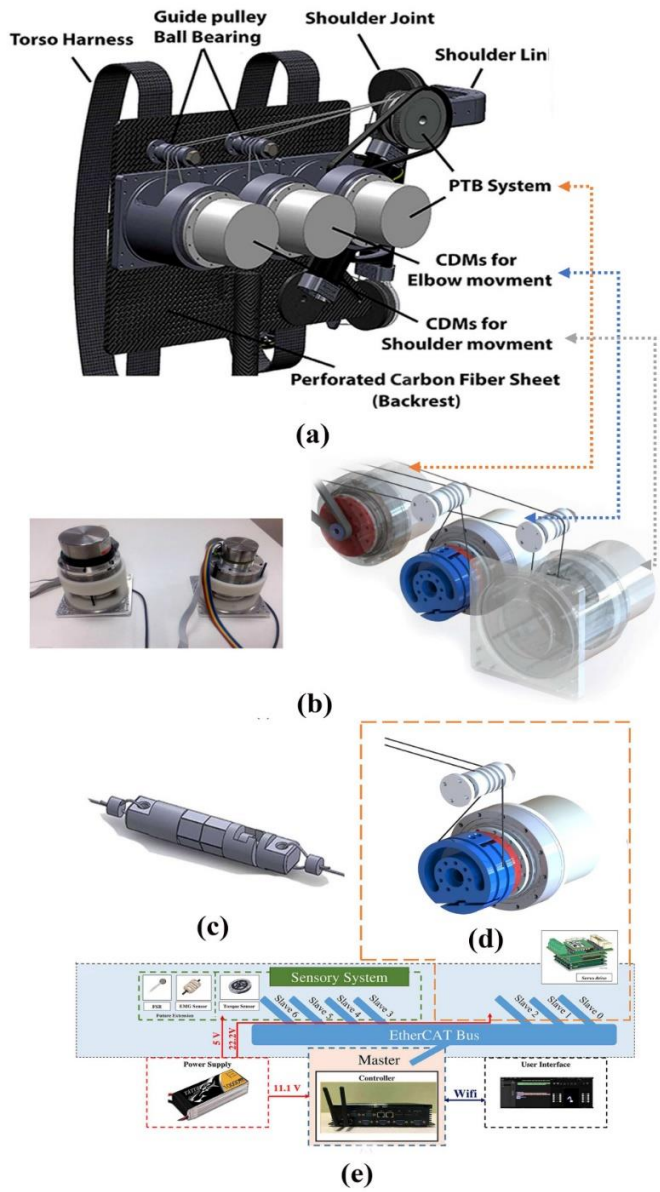

Fig. 5. Mechatronic system and actuation module: (a) Equipment mounted on the backrest. (b) Actuator modules including CDMs and PTB system. (c) Cable pre-tensioning mechanism. (d) 3D design of the CDMs. (e) Control system.

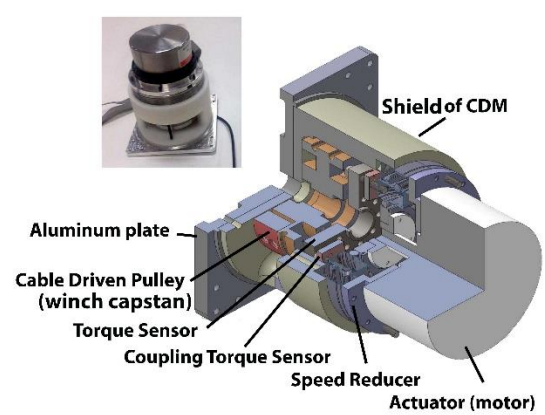

Fig. 6. 3D design of the CDMs (Actuation module).

the motion-decoupling for a cable-driven system which leads to a change in the length or tension of the cable. To overcome this drawback, samples of various mechanical mechanisms have been proposed [25]. Although the proposed solutions are presented as a precise solution [38], here, the motion-decoupling is compensated by the control system.

To decrease the friction between the cable and other parts, several models of the guide pulleys (see Fig.1, Fig. 5) equipped with ball bearings have been used, especially in the corners like the shoulder link (L-shaped link) that provides two DoFs of the shoulder joint as shown in Fig. 4(c). The guide pulley equipped with ball bearings reduces dry sliding friction. Furthermore, to obtain cable pre-tensioning, a pair of cable end connectors are utilized to join the cable segments, see Fig. 5(c). As mentioned above, the workspace and performance of the cable-driven system are limited due to the natural properties of the cable, because it must be pulled to generate force. Therefore, the PTB system is proposed to increase the workspace of the BiEXO system in some direction. The PTB system generates shoulder abduction/adduction movements. In this system, the mechanical power of the actuator is conveyed through the belt and pulley to the shoulder link which is demonstrated in Fig. 5(a). The key advantages of using the PTB system are its lightweight, protection against overload and high efficiency. In addition, the PTB systems are the best idea for transmitting torque between shafts that have not axially aligned. The actuator mechanism of the PTB system is similar to CDMs in our study, see Fig. 5(b), with a different item that a toothed pulley is used instead of the capstan, see Fig. 1(c) and Fig. 5(b).

III. Modeling and Experiment Results

The arm exoskeleton is remotely driven by cables, and its total mass is 800 g. Under the current architecture, the total weight of the BiEXO system is 7.4 kg in this study, and the maximum weight (about 5 kg) is for the motor and reducer of the CDMs. The total weights can decrease to lower than 4 kg, by selecting the proper motors and reducers. We are going to decrease the total weight of the CDMs in future work by choosing smaller motors and reducers and improving the system. Based on our experimental evaluation, the power created by the actuator systems is high for the proposed arm of the BiEXO system, hence, the selection of the smaller motor and reducer is possible for the movement of the arm exoskeleton with 800g. To show the performance of the system, some simulation, and experimental tests have been performed as follows:

A. SimMechanics Model

Human movements are defined in three dimensions based on a series of axis and anatomical planes which are the sagittal, frontal, and transverse planes. The upper limb movements include elbow and shoulder movements, as shown in Fig. 7 (III). In this section, the movements of the upper limb are simulated by the SimMechanics toolbox of MATLAB software. The block diagram of the SimMechanics has depicted in Fig. 7 I, and the result is shown in Fig. 7 II. For this purpose, in a virtual environment, the mechanical structure of the BiEXO is modeled with the SimMechanics Toolbox, which is a block

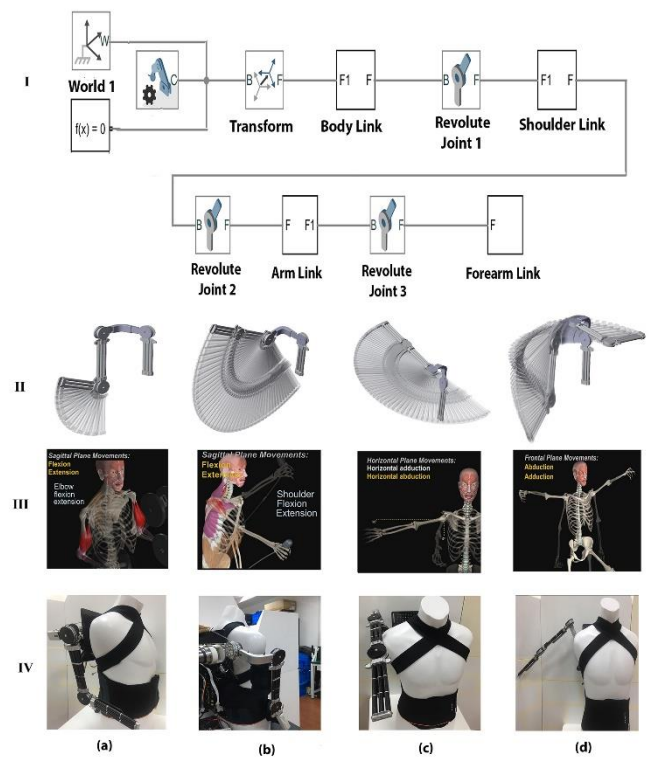

Fig. 7. (Row I): SimMechanics Block Diagram, (Row II): simulation of the BiEXO system by SimMechanics, (Row III): Upper limb movement in anatomical planes (https://app.strength.muscleandmotion.com), (Row IV): evaluation of the movement of the prototype of BiEXO system based on SimMechanics, Column (a) shows the elbow movement directions in flexion and extension; Column (b) shows the shoulder movement directions in flexion and extension; Column (c) shows the shoulder movement directions in horizontal abduction/adduction; Column (d) shows the shoulder movement directions in abduction/adduction.

diagram technique for the analysis of human movement and mechanical systems formed of rigid multi-body structures [39].

B. Kinematic Model

The kinematic configuration of the exoskeleton was modeled by the Denavit-Hartenberg method. To achieve D-H parameters, firstly, the position of the coordinate axis is determined based on the D-H model as shown in Fig. 8, then the D-H parameters are placed in the transformation matrix. Consequently, the transmitted matrices are obtained and exoskeleton kinematics analyses are carried out. The transformation matrix of the Denavit-Hartenberg is given as follows:

$$T_i^{i-1} = \begin{bmatrix} R_{i,i+1} & P_{i,i+1} \\ [0] & 1 \end{bmatrix} \tag{1}$$

$$T_i^{i-1} = \begin{bmatrix} Cos\theta_i & -Sin\theta_i Cos\alpha_i & Sin\theta_i Sin\alpha_i & r_i Cos\alpha_i \\ Sos\theta_i & Cos\theta_i Cos\alpha_i & -Cos\theta_i Cos\alpha_i & r_i Sin\alpha_i \\ 0 & Sin\alpha_i & Cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$T_4^0 = T_1^0 T_2^1 T_3^2 T_4^3 \tag{3}$$

The four parameters of the D-H convention are demonstrated in Fig. 8(a) in red font, which are $\theta_i, d_i, a_i, \alpha_i$. four transformation parameters are known as D–H parameters given the following:

θ_i is the angle from X_{i-1} to X_i around Z_{i-1}.

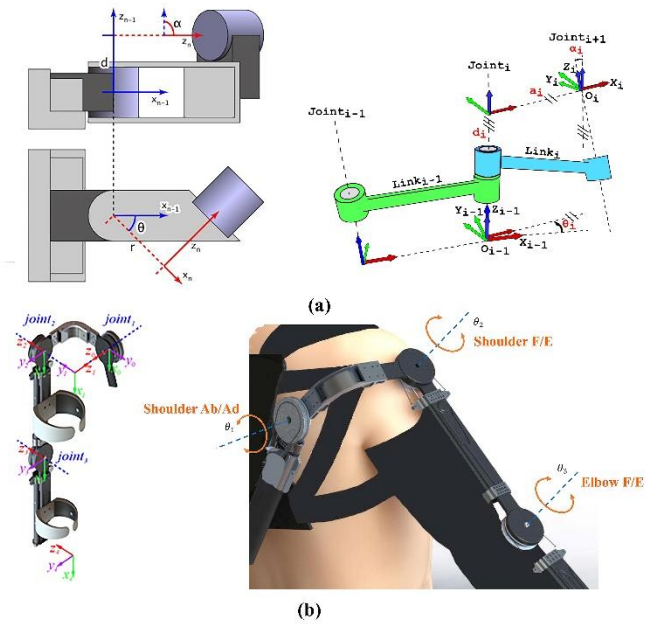

Fig. 8. CAD model with modified Denavit–Hartenberg coordinate frame annotation. Subscripts 0 and 4 represent the base coordinate frame and the tool coordinate frame, respectively. These two coordinate frames are fixed while the other 3 are revolving, representing three active DOFs.

α_i is the angle from Z_{i-1}.to Z_i. around X_i.
d_i is the distance from X_{i-1} to X_i along the Z_{i-1} direction.
a_i is the distance between the origin of the $i-1$ frame and the origin of the i frame along the X_n direction.

With these parameters, the coordinate is translated from $O_{i-1}X_{i-1}Y_{i-1}Z_{i-1}$ to $O_iX_iY_iZ_i$. As shown in Fig. 8, the coordinate frame notated as 1 to 3 corresponded to three rotational movements with a positive direction on the z-axis.

TABLE II
MODIFIED DENAVIT–HARTENBERG PARAMETERS.

Joint(i)	α_{i-1}	l_{i-1}	d_i	θ_i (current value, range)
1	180°	*0*	$-d_1$	θ_1 (0°, 0°~120°)
2	-90°	*0*	d_2	θ_2 (0°, -30°~120°)
3	0°	L_2	0	θ_3 (0°, 0°~100°)
4	0°	L_3	$-d_2$	*0*

Coordinate frames 0 and 4 were fixed, representing the base and end coordinate systems respectively. The end coordinate system represented the position of the upper extremities, which was the major concern of trajectory planning in Cartesian space. According to the kinematic model, the corresponding D-H parameters were listed in Table II.

Inverse kinematics is also analyzed to determine the joint angle of the robot to reach the target position in Cartesian space. For instance, an exoskeleton arm requires precise movement from an initial point to the desired position to pick up the bottle. The grasping end of the exoskeleton is considered the end-effector. The exoskeleton configuration is a list of the shoulder, elbow, and wrist joint positions which are within the position boundaries of the exoskeleton model. Given the desired end-effector positions of the exoskeleton, inverse kinematics can determine a proper joint configuration to conduct the movement of the end-effector to the target pose. If the inverse kinematics

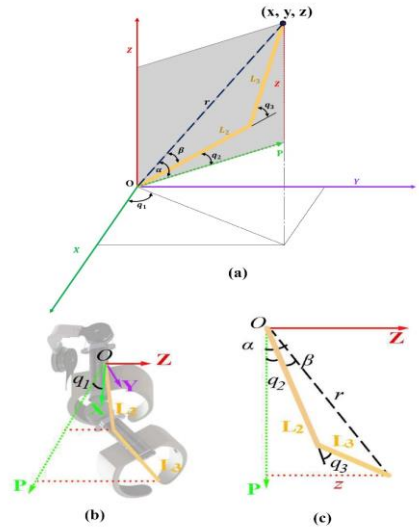

Fig. 9. Structure diagram for inverse kinematics derivation. (a) 3D view of coordinate system. (b) 3D view exoskeleton system. (c) 2D view in POZ plan. The yellow links represent the human arm. The coordinate system is represented by coloured arrows, where P-axis is the projection of human arm in XOY plane.

formula was deduced based on the kinematics model of the exoskeleton, it will be very complicated due to the existence of various parameters such as the l_{i-1} and d_i. Exoskeleton joints should be aligned to the human joint, which means that the joint angle of the exoskeleton is consistent with that of the human arm. Therefore, the analytical solution of exoskeleton inverse kinematics can be obtained through the human arm model in this study. As illustrated in Fig. 9, the human arm is represented by two linkages in yellow.

The three joint angles are represented by q1, q2, and q3 respectively. The target point (x, y, z) is given in the coordinate frame, and the value of the joint angle (q1, q2, q3) is deduced as follows. The angle q1 does not affect the position of the human hand in the z-axis direction and can be easily obtained by:

$$q1 = \arctan(\frac{y}{x}) \tag{2}$$

The joint angles q2 and q3 are derived from the POZ plane, as shown in Fig. 9(a) and Fig. 9(c). According to cosine law, i.e.

$$\cos(\gamma) = \frac{{L_2}^2+{L_3}^2-r^2}{2L_2L_3} \tag{3}$$

$$\cos(\beta) = \frac{{L_2}^2+r^2-{L_3}^2}{2L_2r} \tag{4}$$

where $r = \sqrt{x^2+y^2+z^2}$ is the distance between the target point and the origin of the coordinate system. We have:

$$\alpha = arcsin\left(\frac{z}{r}\right) \tag{5}$$

$$q3 = \pi - \gamma \tag{6}$$

$$q2 = \alpha - \beta \tag{7}$$

The angle of the exoskeleton joint is the same as that of the human so the corresponding solution of exoskeleton inverse kinematics is given here:

$$\begin{cases} q1 = \arctan(\frac{y}{x}) \\ q2 = arcsin\left(\frac{z}{r}\right) - arccos\left(\frac{{L_2}^2+r^2-{L_3}^2}{2L_2r}\right) \\ q3 = \pi - arccos\left(\frac{{L_2}^2+{L_3}^2-r^2}{2L_2L_3}\right) \end{cases} \tag{8}$$

C. FEA Study

For achieving optimum mass and volume of the carbon-fiber links to increase the strength-to-weight of the structure of the bamboo-inspired links and to possess high buckling strength in the face of loads imposed from the user side to the structure, FEA analysis is carried out. For this purpose, using FEA analysis in COMSOL software, various parameters of the carbon-fiber tube and aluminum nodes are simulated and examined to find a better geometric model. Based on the FEA, the inner diameter, outer diameter, and length of the carbon fiber are considered 10 mm, 12 mm, and 50 mm respectively. Also, the aluminum node is designed and fabricated that can be embedded in the carbon fiber tube. To compare the common long carbon-fiber tube and the arm link of the BiEXO system inspired by the bamboo structure, an FEA analysis is carried out.

The result is shown in Fig. 10. In this analysis, three important parameters are examined including displacement magnitude, stress, and strain. The result shows that the carbon fiber link inspired by the bamboo can tolerate more force than the long carbon fiber tube. It may be recommended for different applications that require high payloads with low mass, especially for upper limb exoskeletons, which can easily bear

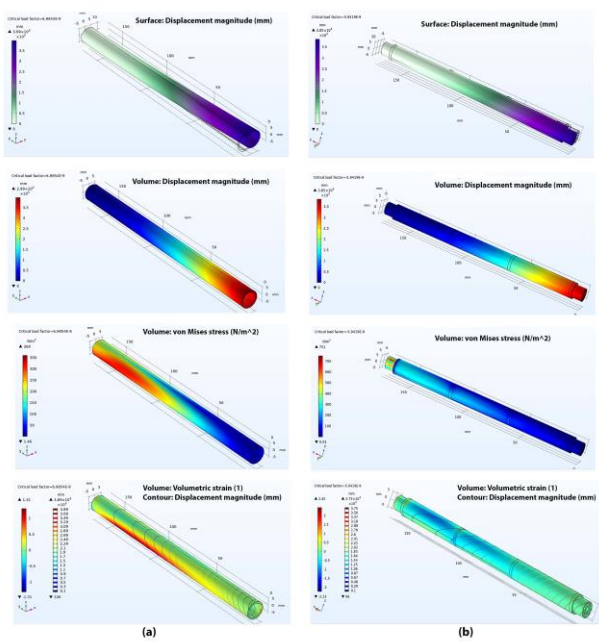

Fig. 10. FEA analysis of the links by COMSOL Software for comparison in three parameters includes displacement magnitude, stress, and strain. (a) FEA analysis of the cable fibre tube. (b) FEA analysis of the carbon-fibre link inspired by bamboo.

the weight of the human load during tasks in active daily living. According to the von Mises theory, the tolerable stress for the proposed link of the arm exoskeleton that is inspired by the bamboo structure is $751 N/m^2$ in comparison with the long carbon fiber tube that can bear 360 N/m^2.

D. Experiments and Results

The position of the virtual hand, represented as the origin of the 4th coordinate in the kinematics model, was taken as the focus point, and its reachable range of motion (ROM) simulated by the Monte Carlo method is shown in Fig. 11. The end

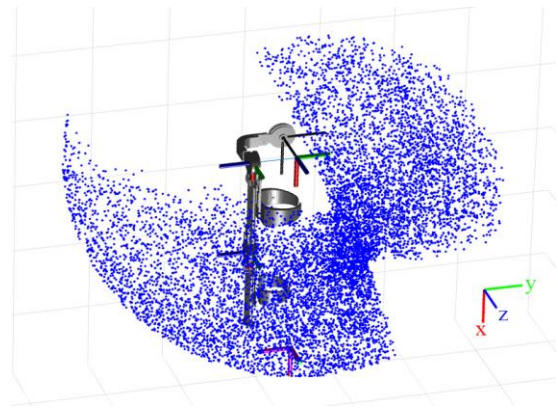

Fig. 11. The reachable range of motion (ROM) simulated by Monte Carlo method. The blue dots indicate where the end-effector or the human hand can be reached.

coordinate system is illustrated in purple, and the blue point is the possible position of the end. As a safety precaution, each range of joint angle of the exoskeleton was limited based on the range of human joint motion as listed in Table II.

Since the human shoulder joint was simplified and limited to two degrees of freedom (DoF), the ROM of the exoskeleton mainly covered the outer side of the arm and the front side of the head while excluding the position in front of the contralateral arm. Under this mechanical structure, some functional movements can still be achieved, such as reaching and grasping, reaching to the mouth, or lifting an object.

In addition, the verification experiment was carried out after the prototype was developed. The experimental scene is shown in Fig. 12. By tracking the trajectory in Cartesian space, the formula of inverse kinematics was verified, and the cable transmission mechanism was assessed. Because the BiEXO system only equipped an encoder at the motor side, the real angle of the joint was measured by the goniometers SG65 and

Fig. 12. Photo of the experimental scene. Three goniometers (the green parts) were used to measure the joint angle respectively. The two ends of the goniometer are separately fixed on the two connecting rods of the joint by double-sided tape.

DataLOG wireless data acquisition instrument (Biometrics Ltd. UK) in the experiments. Three single-axis goniometers were affixed to the target joints shown in Fig.12 through double-sided adhesive tape.

The reaching experiment with the desired trajectory in Cartesian space was conducted. The pre-defined trajectory is circular with a fixed value offset in Y-axis, which requires three joints moving simultaneously to accomplish the reaching task. The experimental results are compared and shown in Fig. 13. The end circular trajectory is synthesized based on forward dynamics using joint angles measured from the encoders on the motors and the goniometers on the joints. Due to the use of two acquisition systems (motor position by the embedded control system and joint angle by the external system), the time axis is

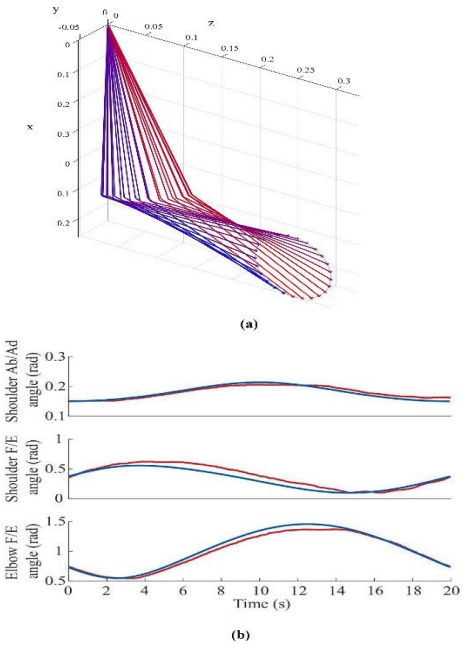

Fig. 13. (a) Experimental results for tracking the trajectory (circle, the unit is meter) in Cartesian space. (b) Results of joint angle.

manually aligned, and there may be some errors. Fig.13 b shows that there is an error in the tracking trajectory in joint space, which is mainly caused by the backlash in the bi-directional cable drive. Through experiments, it can be observed that the backlash is about 0.06 rad, or about 3°. Considering the diameter of the cable pulley, the backlash is about 1.5 mm. Comparing the distance between the trajectory and the center of the circle with the reference radius, the mean absolute error (MAE) is 5.9 mm, and the root-mean-square error (RMSE) is 6 mm. The desired trajectory radius is 100 mm, which means a relative error of about 6%. This experiment verified the accuracy of the kinematics model and the movement ability of BiEXO. In actual application, we will obtain the motion intention of the subject based on the joint space (e.g. torque sensors in CDMs) and control it from the joint space, so the Cartesian spatial error does not affect the practical use.

E. Wearing trials of BiEXO

The wearing trials of BiEXO were carried out on a healthy subject. The experiment was approved by the Ethics Committee of Shanghai Jiao Tong University, China (ID: ML2020036). The subject was fully informed and signed the written consent. The preliminary experimental demonstration is shown in Fig. 14. The photos in the left column show the wearing trials of BiEXO, and the photos in the right column show the wearing trials of BiEXO in a combination of brain-computer interface (BCI). BCI aims to realize the multi-dimensional control of the BiEXO system using the subject's own mind. Six classes can be generated using SSVEP-based BCI, which indicate elbow flexion, elbow extension, shoulder flexion, shoulder extension, shoulder abduction, and shoulder adduction of BiEXO, respectively. BiEXO operates in a speed loop control mode, obtains human motion intentions in an on-off form through the

Fig. 14. A subject wearing BiEXO performed basic motions of upper limb. (a) Elbow flexion/extension. (b) Shoulder flexion/ extension. (c) Shoulder abduction/adduction.

BCI, and treats the human arm as a load to move in a certain direction of motion. When the desired joint angle is reached, the subject stops the exoskeleton by gazing at the flicking block for resting. To ensure safety and allow sufficient reaction time, the maximum joint speed is set to 10 °/s.

The electroencephalography (EEG) signals of BCI were recorded using a BrainAmp amplifier (Brain Products GmbH, Germany) with a 32-channel electrode cap. The EEG signals were first down-sampled with 200 Hz and referenced to the left mastoid. During online decoding, we incorporated a C++ program with MATLAB engine for decoding the EEG signal in real-time. Finally, the decoded command was transmitted to the BiEXO via socket communication for motion execution. More details of the BCI algorithm are available in our previous work [47]. The subject carried out a functional task such as picking up or putting an object down. The object used is a bottle with water weighing 0.8 Kg. The motion of the shoulder and elbow was realized by BiEXO, and the subject controlled his own wrist and hand. The demonstration shows that the BiEXO system can assist the subject to achieve the desired motion of shoulder and elbow joints in a functional task. It should be noted that only the qualitative evaluation was performed. In the future, the quantitive evaluation will be conducted, especially for BCI-controlled BiEXO.

IV. DISCUSSION

A. Mechanics and Structure

Although the technologies in wearable systems and exoskeleton assistive devices are developing fast in the past two decades, they are still far from being permanently used daily due to their limitations in terms of weight, portability, and ergonomics. We presented the innovative design and preliminary testing of the BiEXO system for assisting shoulder and elbow movements. Wearable exoskeletons should be well designed from the view of biomechanics and ergonomics to provide satisfactory rehabilitation. In this regard, the following key points need to be considered: (1) Being compatible with human joints to uncomplicated kinematic joints. (2) Adjustability of the exoskeleton dimensions with the size of a human arm. (3) Joint implementation should be considering the bulk of the arm. (4) Axis misalignment may cause undesired interaction loads that can make human training uncomfortable. (5) To improve the portability of BiEXO, the key points mentioned above have been considered as much as possible.

In addition, unlike previous research that commonly used a Bowden cable for cable-driven systems [1, 29, 30], this work developed a novel cable-driven system based on carbon fiber tubes. The bamboo-inspired structure can not only increase the strength-weight of the device but also make the configuration more compact.

B. Comparison to Existing Prototypes

Developing the cable-driven exoskeleton for rehabilitation and assistance is a challenging task due to the complexity of the mechanisms. In this consideration, there are a limited number of portable cable-driven exoskeletons. A comparison of the existing prototypes is given in Table III.

TABLE III
COMPARISON TO EXISTING PROTOTYPES

	Name	AM	DoF	TS	Joint	ML
1	Soft Exosuits [7-9],[21]	DC motor	1	BC	E	B
	Soft wearable [10]	Electric actuator	1	BC	S/E	B
2	ShouldRO [40]	Not specified	1	BC	S	B
3	WPCSE [41]	spring-cam-wheel system	1	BC	S	B
4	Soft wearable system [42]	Passive actuation system.	1	BC	S	B
5	Hybrid system [1]	DC motor +FES	3+	BC	S/E/ H	B
6	**BiEXO**	**CDM+PTB**	**3**	**CCFT**	**S/E**	**B**

Abbreviations: Actuation Module (AM), Transmission System (TS), Motor Location (ML), Bowden Cable (BC), Cable with Carbon Fiber Tube (CCFT), Cable-Driven Mechanism (CDM), power transmission belt (PTB), Elbow(E), Shoulder(S), Hand (H), Backrest (B)

It can be seen that most of the existing prototypes have used Bowden cable, which not only increases the friction but also reduces the efficiency of the system. In general, they have limitations in DoF, while the BiEXO system is based on a bamboo-inspired structure that overcomes the above problems. It is undeniable that the main weight of exoskeleton hardware has been occupied by the motor and reducer module, each weighing about 1 kg without accounting for the pulleys and other fittings. This is one of the reasons why the shoulder joint of the exoskeleton was not designed as a complete spherical joint with three DoFs but simplified to two DoFs. Most of the lightweight and portable upper limb exoskeletons do not include the shoulder joint such as studies by Tang et al. and Chen et al. [13, 31, 43]. Some studies chose lighter motors by utilizing cascaded speed reducers, thereby reducing the overall mass. Sui et al. developed a four active-DoF exoskeleton with a weight of 4.2kg (Mechanical part) by the gravity balance design, in which the capstan of the cable plays the role of a secondary speed reducer[44]. Liu et al. employed synchronous belts cascaded harmonic reducer to achieve a total reduction ratio of 300 and a total weight of 5.1 Kg (mechanical part) in the dual-arm 4-DoF exoskeleton [45]. In contrast, we neither sacrificed the power of the motor nor adopted an excessively high reduction ratio, to ensure the power and speed performance of the exoskeleton. In this design, the weight of the wearable part was effectively reduced by remote actuation using the cable, and the mass of other parts in this system is evenly distributed on the backrest (perforated carbon fiber plate). The device can be fixed to the body with a Torso Harness and caused to avoid rotation around the sagittal axis [46]. In this design, the weight of the wearable part was effectively reduced by remote actuation using the cables, and the mass of other parts in this system is evenly distributed on the backrest.

C. Limitations

The present work focuses on the design of BiEXO, while the control issues are not presented, they have been and will be presented in our other papers. The optimal design of the BiEXO system will be performed to increase workspace at the next stage. Since the shoulder joint of BiEXO was simplified and limited to two DoFs, the ROM of BiEXO mainly covered the outer side of the arm and the front side of the head. Therefore, one of the future works is to increase the number of DoFs for the shoulder joint to provide motion in front of the contralateral arm. Furthermore, the hand exoskeleton will also be designed and fabricated. Adding a hand exoskeleton device can facilitate or enable human ADLs. In addition, the functional proficiency of BiEXO will be verified on more healthy subjects, and the clinical investigation on patients will be carried out in the future.

V. CONCLUSION

This work developed a bamboo-inspired exoskeleton (BiEXO) based on the cable-driven mechanism with low mass and inertia. A novel structure was designed for BiEXO inspired by bamboo structure instead of traditional Bowden-cable transmission. The cables and wires were smartly embedded inside the carbon fiber tube that mimics the bamboo tube. Cosmetic design, modular design, and personalized design were also considered. BiEXO has shown the advantages of smart

structure and friendly configuration. The effectiveness of the structure of BiEXO was thoroughly examined in terms of strength and stiffness characteristics. The simulation and experimental tests were carried out to verify the satisfactory performance of the BiEXO prototype.

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