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Design of A Lower Limb Exoskeleton Driven by Tendon-sheath Artificial Muscle*

Mengqian Tian, Xingsong Wang, Jie Wang and Zhenbo Gan
Department of Mechanical Engineering
Southeast University
Nanjing, China
tianmq@seu.edu.cn

Abstract - In the past decades, with the development of science and technology, lower limb exoskeletons have been developed quickly, which can help patients to walk or do rehabilitation training. In this paper, the design of a lower limb exoskeleton, named SEU-EXO, will be presented in detail. The SEU-EXO is driven by a new type of artificial muscle, which actuated by a motor and tendon-sheath system based on Hill muscle model. In this structure, with a controllable clamper, a series spring and a parallel spring, this artificial muscle can mimics muscle's characteristics, and has better compliance and controllability. Based on the principle of bionics, the degrees of freedom for rehabilitation exoskeleton are allocated reasonably, the mechanical structure is presented, and the tendon-sheath transmission path optimization method is studied. Finally, the evaluation experiments are verified, which proves the reliability and stability of the SEU-EXO.

Index Terms - lower limb exoskeleton, tendon-sheath artificial muscle, tendon-sheath transmission path optimization

I. INTRODUCTION

In recent years, with the increase of elderly population, wearable lower limb rehabilitation exoskeletons are widely needed to improve their action ability. The older people's body functions are declined, and some diseases usually lead to patients with hemiplegia or paralysis of the limbs, weakness of the limbs or sensory disturbances of the upper and lower limbs, imbalance of balance ability, unstable standing, stiff joints, and limited walking ability [1]. Wearable lower limb rehabilitation exoskeletons can not only help patients recover action functions, but also can improve their walking ability by freeing themselves from wheelchairs, and achieve autonomy and freedom of walking training, to improve their ability to live by themselves.

Researchers from various countries have conducted extensive research on the exoskeletons of the lower limbs. The first commercial exoskeleton rehabilitation robot is the HAL robot developed by the University of Tsukuba, Japan. The latest model is HAL-5, which can help patients to walk normally and go up and down the stairs [2]. The Ekso exoskeleton, developed by Ekso Bionics of California, USA, is a wearable, battery-powered, bionic mechanical exoskeleton that helps hemiplegic patients to perform gait training, standing and weight-bearing exercises [3]. ReWalk personal and ReWalk rehabilitation wearable exoskeleton devices developed by Israeli inventors. The patient is allowed to stand, walk and climb stairs, and can provide physiotherapy for the paralysis patients [4-5].

The above mentioned exoskeletons are mostly driven by hydraulic cylinders, motors, etc., which belong to the rigid exoskeletons. Because of its disadvantages such as heavy weight and poor flexibility, some researchers have carried out research on exoskeletons driven by artificial muscles or tendon-sheath.

A soft wearable device, Exosuit, developed by Harvard University, were driven by artificial muscles, which can assist the movement of the hips, knees and ankle joints [6-7]. Another soft drive component is tendon-sheath, which is composed of a soft and slender inner tendon and a flexible passing outer sheath. It transmits power through the relative motion of the tendon and the sheath, which has the characteristics of large transmission force, flexible and small transmission path, and light weight [8].

"Tendon-sheath artificial muscle" was a new type of artificial muscle proposed in this paper, which is constructed by utilizing the transmission force of the tendon-sheath, combined with a set of new transmission units according to the muscle model, and simulation of the muscle's movement characteristics [9]. According to the Hill muscle model [10], three basic units are included: the contraction element CE, the serial elastic unit SE, and the parallel elastic unit PE, which describe the physical and mechanical properties of the muscle and can correspond to the biological tissue composition of the muscle. In tendon-sheath artificial muscle, the elastic units in series and parallel were achieved respectively by two linear springs, the contraction element was realized by controllable clamper and tendon-sheath. Among them, through the combined control of the controllable clamper and the tendon-sheath, this artificial muscle can achieve the contraction mode of the human muscles, with the similar elasticity, smoothness and safety.

In this paper, a lower limb exoskeleton of SEU-EXO driven by tendon-sheath artificial muscle were developed. The exoskeleton's degrees of freedom and the ranges of joint motion was presented in Section Ⅱ. More detailed structure description of this exoskeleton can be found in Section Ⅲ. In order to verify the motion results, several experiments were carried out in Section Ⅳ. Finally, the conclusion was made in Section Ⅴ.

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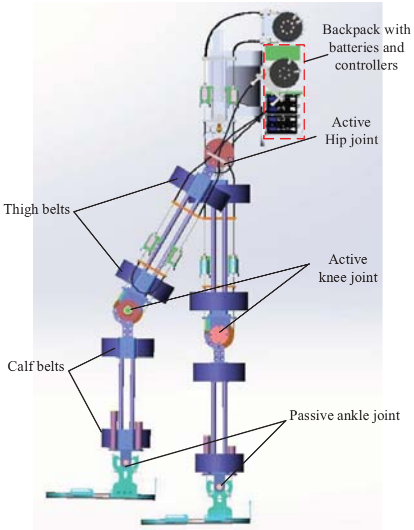
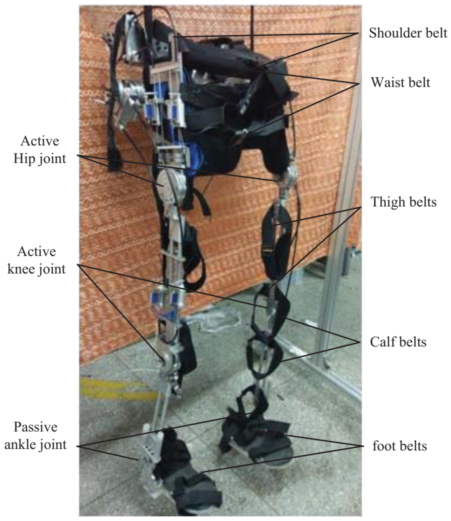
II. EXOSKELETON SYSTEM

A. The entire exoskeleton system of SEU-EXO

The lower limb exoskeleton can help patients who have the walking obstacle to carry on the recovery training and help the olds and the weak patients with assistance. Therefore, the SEU-EXO system is comprised of mechanical structure and a backpack with embedded controllers and batteries. The entire exoskeleton system of SEU-EXO is shown in Fig.1. The mechanical structure consists of active hip joints, active knee joints, passive ankle joints, the necessary links and the fixed belts. Among them, the active motion of the hip joints and knee joints are driven by the tendon-sheath artificial muscles which are connected to motors and their reducers.



(a) The structure of SEU-EXO



(b) The prototype of SEU-EXO

Fig.1 The overall structure of SEU-EXO

B. Principle of lower limb movement

The lower limbs of the human body are mainly composed of three joints: the hip joint, the knee joint and the ankle joint. The hip joint belongs to the spherical joint and can achieve forward flexion/backward extension, abduction/adduction and movements like outside and inside rotation to achieve rotation from three degrees of freedom. The knee joint achieves flexion and extension of the calf. Ankle joint allows foot to achieve plantar flexion/dorsiflexion flexion, internal rotation/ external rotation, inner and outer retroflection movements.

Lower limb rehabilitation exoskeletons are required to be lightweight, comfortable to wear, and safe and reliable under the premise of meeting structural strength requirements. In the structural design, each additional degree of freedom will increase the complexity of the structure and the processing cost. Therefore, according to the actual needs of rehabilitation training, the degrees of freedom should be reduced as much as possible, and the exoskeleton structure should be lightweight and simple.

In normal walking, the human body mainly relies on hip and knee joints for flexion and extension in the sagittal plane to achieve normal gait walking. The degrees of freedom of the hip and knee joints consume more energy and must be applied. So its flexion and extension freedom is set in active freedom. However, the degree of freedom in hip to change the walking direction in the horizontal plane does not need much, so it was ignored in the structural design. The abduction/adduction of the hip joint and the plantar flexion/dorsiflexion of the ankle joint are designed in special structure to provide a limited range of motion in order to ensure the wearer's comfort and flexibility. In brief, the developed SEU-EXO has 4 DOFs for one leg, where the hip and knee joints have one DOF respectively as the active drive, and the hip and ankle joints have one DOF respectively as the passive joint, As shown in Table. I

TABLE I
THE LOWER LIMB DOFS OF THE HUMAN AND THE SEU-EXO

DOF	Hip	Knee	Ankle
Human	3	1	3
SEU-EXO	2	1	1

Taking into account the actual walking situation, each joint motion range should be designed properly. To ensure the safe of SEU-EXO, the joint motion range should be designed to be smaller than human motion range. The detail joint motion range is shown in Table Ⅱ.

TABLE Ⅱ
JOINTS MOTION RANGE OF HUMAN AND SEU-EXO

Joint	Human Motion Range(°)	SEU-EXO Motion Range(°)
Hip flexion / extension	-30 ~ 120	-20 ~ 90
Hip adduction / abduction	-30 ~ 60	-5 ~ 10
Knee flexion / extension	(-120 ~ -160) ~ 0	-120 ~ 0
Ankle dorsiflexion / plantar flexion	-20 ~ (40 ~ 50)	-20 ~ 20

C. Control System hardware

The hardware system of SEU-EXO is composed of a main control module, a sensing module, a communication module, a power module and a driving module, as shown in Fig.2.

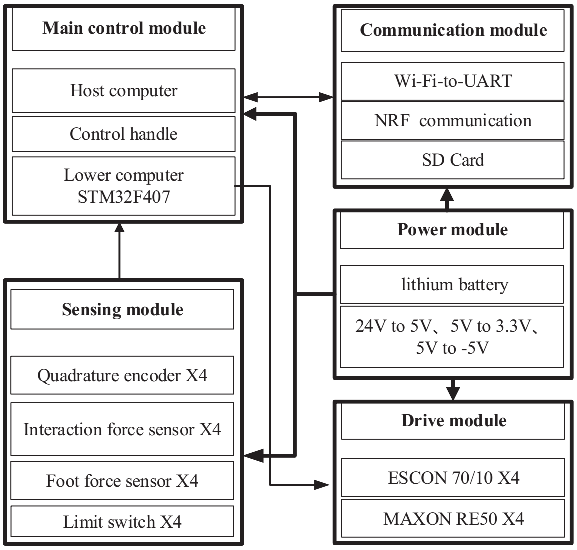


Fig.2 Exoskeleton hardware system

An embedded controller STM32F407ZET6 is selected as lower computer, and the host computer adopts PC. The sensing module consists of a 1024-line quadrature encoder mounted on each joint (Fig.3), a foot force sensor mounted on the sole (Fig.4) with a measurement range of 0-100kg, and an interaction force sensor to collect the interaction force between human and exoskeleton during exoskeleton movement (Fig.5).

Through sensing module, the lower computer judges the wearer's gait cycle, and calculates the angle and speed of the joints in real time according to the result of control algorithm , and thus control the motors to achieve the purpose of closed-loop control.

Fig.3 Quadrature encoder

Fig.4 Plantar pressure sensor

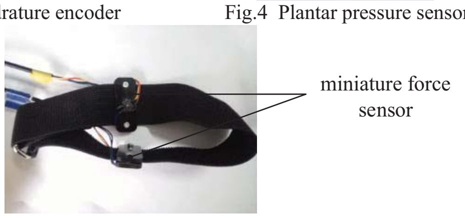


Fig.5 Interaction force sensor

The communication module includes a Wi-Fi module, an NRF wireless module, and an SD card module. The Wi-Fi module is used to provide the communication between the host computer and the lower computer, The main function of the NRF wireless module is to communicate between the control handle and the lower computer, The main function of the SD card module is to store the movement status information of the exoskeleton and the real-time data of the sensing module.

The power module is input by 24V/10Ah lithium battery and provides stable power supply to each module through required voltage conversion circuits.

The drive module includes four sets of MAXON RE50 DC brush motors and ESCON 70/10 drivers.

III. MECHANICAL DESIGN

A. *Tendon-sheath artificial muscle*

The new type of tendon-sheath artificial muscle is proposed based on Hill muscle mode which is composed of three elements: contraction element(CE), serial elastic unit SE, and the parallel elastic unit PE, and describes the contract principle and property of muscles. The structure of tendon-sheath artificial muscle proposed in this paper is shown in Fig.6, the contraction element CE is realized by a controllable clamper connected to tendon.

To mimic the muscle mechanical characteristics, SE and PE are achieved respectively by two linear springs. The series spring is placed in series with CE and inside the clamper to saving space. The parallel spring is placed in parallel with CE. PE takes effects only when muscle is stretched exceeding the original length, so a stopper is set at the end of SE. In the case that the length of muscle is shorter than its original length, PE will not react because the stopper is out of touch with PE. Otherwise, the stopper will push PE to function.

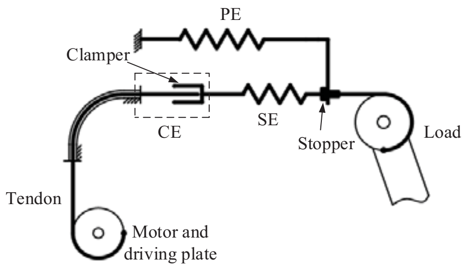


Fig.6 tendon-sheath artificial muscle

The clamper is composed by clamping mechanism and electromagent, as shown in Fig.7. The clamping mechanism is a ball self-locking structure with one-way locking, which clamping tendon with steel ball . The clamper can be controlled to clamp or loosen the wire rope by pressing the electromagnet, which can mimics muscle’s tension and relaxation.

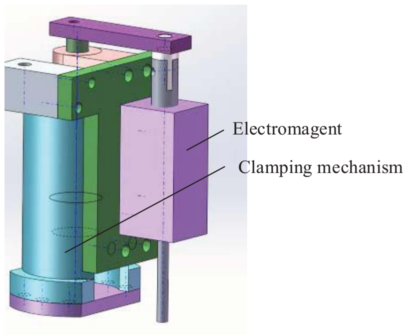


Fig.7 The structure of clamper

In this paper, the double tendon-sheath structure is selected as shown in Fig.8. When the motor starts to rotate clockwise, at the same time, the clamper in left catches the tendon-1 with the control of electromagnet, so it passes the force to the tendon-2 which connect the clamper and executive component, so the executive component can be driven to rotate clockwise. At this time, the series spring inside the clamper is compressed, which is equivalent to the series elasticity of muscle when the muscle contracts, and the parallel spring placed clamper in right is compressed, which is equivalent to antagonizing the muscles in parallel when the muscles relax. When reverse rotation is required, motor will rotate counterclockwise and two clampers will be controlled in reverse.

The series spring, parallel spring and the tendon-sheath transmission system make the whole mechanism more compliance and safe, and absorb sudden shocks for the wearer to feel comfortable. When the wearer wants to move freely, loosen the clamper, it can be detached from the motor, which is equivalent to idling with the rotating joint, only a slight load on the exoskeleton of the lower limb, which is also a major feature of the exoskeleton mechanism.

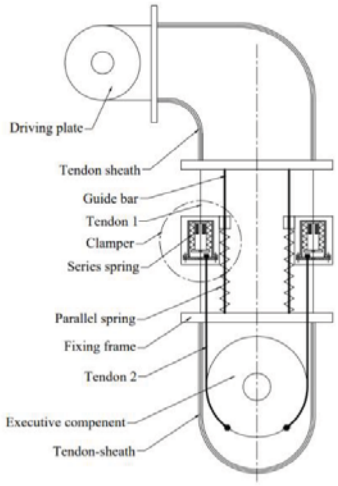


Fig.8 double tendon-sheath artificial muscle

B. *The Hip Joint*

As shown in Fig.9, which is the hip joint module of SEU-EXO, the left and right hip structures are related to the sagittal in-plane symmetry. The main components include a set of waist support plates, a hip motor and reducer, a hip tendon-sheath artificial muscle transmission component, and hip flexion/ extension executive component, hip passive compliant adduction/abduction component. tendon-sheath support plate, tendon-sheath fixing block, tendon-sheath driving plate, and a tendon-sheath pre-tightening mechanism.

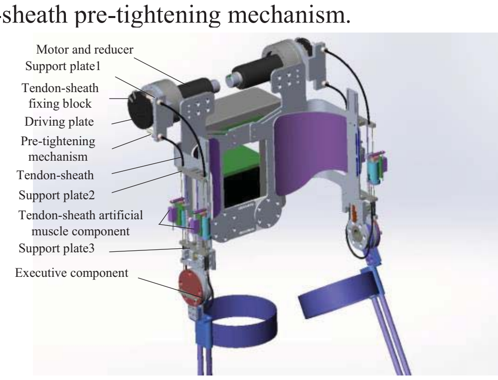


Fig.9 The structure of the active hip joint

C. *The Knee Joint*

As shown in Fig.10, the knee joint module of SEU-EXO is mainly composed of a knee motor and reducer, fixation block, a knee driving plate, support plate, pre-tightening mechanism, tendon-sheath, tendon-sheath artificial muscle transmission , knee executive component. The tendon-sheath artificial muscle is driven by the knee motor so as to transfer motion to the knee joint to perform movement.

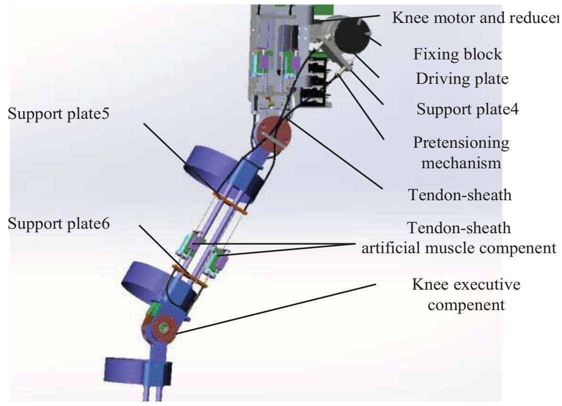


Fig.10 The structure of the active knee joint

D. *The Ankle Joint*

As shown in Fig.11, the degree of dorsiflexion/plantar flexion of the ankle joint is set to be passively flexible and underactuated, and the stiffness of the dorsiflexion/plantar flexion springs are designed to achieve passive energy storage of the ankle joint during walking. When energy is released to a certain level, and the state of the foot is automatically restored when the foot is off the ground. This can effectively increase the comfort of wearer, and the stored energy can be absorbed to reduce the total energy consumption of the exoskeleton.

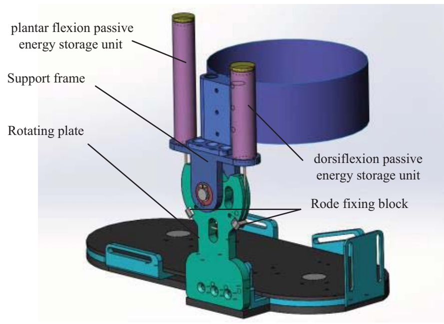


Fig.11 The structure of the ankle joint

The ankle joint torque is set to about 9 (N.m) when the dorsiflexion angle is up to 20°, and the joint torque is about 3 (N.m) when the plantar flexion angle is up to 20°. According to the working radius of the rotation plate at the ankle joint, the spring is selected and designed according to the above design requirements, and the stiffness of dorsiflexion/plantar flexion springs are 26 (N/mm) and 9.23 (N/mm) respectively.

E. *Tendon-sheath Driving Path Design And Optimization*

Tendon-sheath force transmission characteristics depend on the coefficient of friction at the contact surface between the tendon and the sheath in the total curvature of the tendon-sheath bending[8]. In order to optimize the layout of the tendon-sheath drive path, the envelope curve of the tendon-sheath are in line with the human body movement, and its total curvature was selected smaller during the movement of the exoskeleton, so that the tendon-sheath transmission efficiency is increased.

The total curvature reflects the total curvature of the spatial curve. In the lower limb exoskeleton, the spatial curve can be simplified to the plane curve.

$$\theta = \int_0^L \kappa(s)\, ds = \int_a^b \frac{\left|x' y'' - x'' y'\right|}{\left(x'^2 + y'^2\right)} dt \tag{1}$$

Define the total curvature of the plane curve as equation (1), where, θ is the total curvature, $\kappa(s)$ is the curvature of one point on the curve, (x, y) is the coordinate value of the point. a and b is the time corresponding to the starting point and the end point of the curve. The optimization of the tendon-sheath path is to select the position and angle of the motor's support plate to obtain the minimum total curvature.

The hip joint's tendon-sheath transmission path design is shown in Fig.12. When the slope of point A is 90°, the total curvature of curve CA is shown in equation (2).

$$\theta_h \geq \frac{\pi}{2} - \frac{\pi}{180} \times \angle CAE \tag{2}$$

Where, $\angle CAE$ is the angle between AC and x-axis. The distance between point C and point A in y-axis is larger, and the distance between point C and point A in x-axis is smaller, the total curvature is smaller. That is, when the structural design is performed, the motor and pretension mechanism is placed as far as possible on the upper end of the waist without affecting other structures. For the reasonable layout of the motor and other device, the angle between motor's support plate and x-axis is 90°.Because the clamper requires space for movement, the length of the artificial muscle component is 15cm. The distance between point C and point A in x-axis is decided on human parameters, it is set to 10(cm). So the total curvature is adjusted by h, which is the distance between point C and point A in y-axis. Due to the structure constraints, h is set to 20(cm), so that the total curvature is 0.4634 that is reasonable.

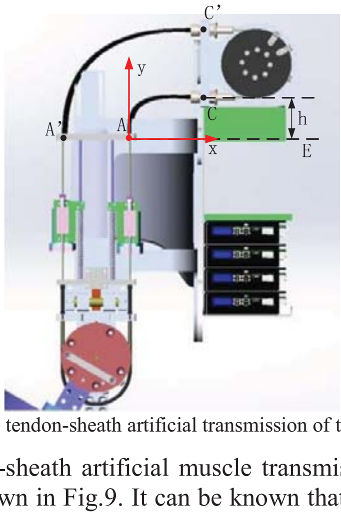


Fig.12 The tendon-sheath artificial transmission of the hip joint

The tendon-sheath artificial muscle transmission path of knee joint is shown in Fig.9. It can be known that the distance from the axis of the knee joint to the axis of the hip joint is always the same, and the distance from the axis of the hip joint to the motor of the knee joint is always kept unchanged. Therefore, the tendon-sheath is passed through the driving plate at the hip joint. When the knee joint is rotating, the tendon-sheath will have a smooth path curve during the entire walking cycle. It will obtain the least variation in the curvature of the tendon-sheath, the smallest total curvature and the highest knee transmission efficiency.

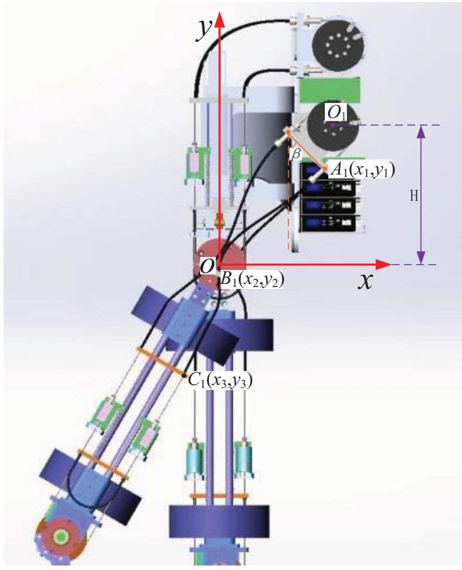


Fig.13 The tendon-sheath artificial transmission of the knee joint

As shown in Fig.13, the coordinates of A_1, B_1,C_1 and the derivatives at C_1 were known, It can be obtained the total curvature by combing equation (1) and The Hermite polynomial interpolation. In the same way, the theoretical length of a single-sided approximate in-plane casing under a certain motion attitude of the desired knee joint can be obtained. Because the distance from the axis of the knee joint to the axis of the hip joint is always the same, the total curvature is decided on the distance between point O and point O_1 in y-axis and the motor mounting angle β. In order to reduce the total curvature as much as possible without affecting the structure and layout, the motor support plate is perpendicular to OO_1, H is set to 35(cm) and β is 15° .

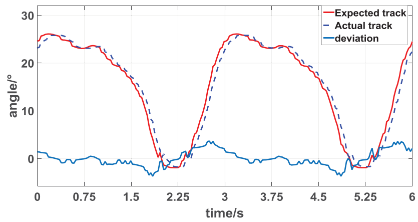
Ⅳ. EXPERIMENT

The motor of the hip joint and knee joint in SEU-EXO are all RE50-370354, the hip reduction ratio is 160, and the knee reduction ratio is 100. And the SEU-EXO can provide maximum 60 (N.m) torque of hip and 40(N.m) torque of knee. The curve of the assist torque is determined according to the curve of the joint torque. After finishing the mechatronics design, the SEU-EXO is tested with a healthy subject simulating the patient who has the walking obstacle.

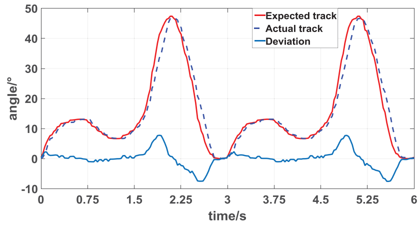
As shown in Fig.14, after the subject wears the SEU-EXO, trajectory tracking experiments are carried out in two conditions, one is the subject walking on crutches, another is normal walking.

Fig.14 Experiment of wearing the SEU- EXO

The result of walking on crutches trajectory tracking experiment is shown in Fig.15, and the result of Normal walking trajectory tracking experiment is shown in Fig.16. The tracking error of the hip joint trajectory under the condition of Walking on crutches and Normal walking is generally in the range of -5° to 5°. The tracking error of the knee joint trajectory under the condition of Walking on crutches and Normal walking is generally in the range of -9° to 9°. The experimental results show that the lag time is very small, so the overall performance of the SEU-EXO is effective.

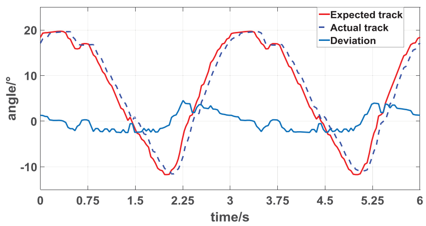


(a) Result of hip joint trajectory tracking

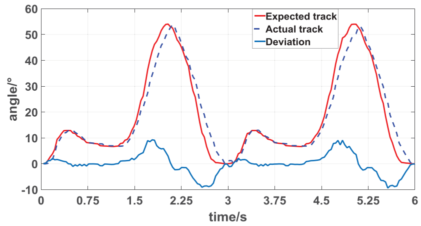


(b) Result of knee joint trajectory tracking

Fig.15 Walking on crutches trajectory tracking experiment



(a) Result of hip joint trajectory tracking



(b) Result of knee joint trajectory tracking

Fig.16 Normal walking trajectory tracking experiment

V. CONCLUSION

Tendon-sheath artificial muscle is a novel actuator proposed in this paper which has the advantages of muscle-like elasticity, compliance and reliability, because of the clamper. series and parallel springs, the mechanical structure is different from others driven by normal tendon. This paper presents the structure design of a lower limb exoskeleton driven by tendon-sheath artificial muscle named SEU-EXO which can help patients who lose of walking ability to do rehabilitation training and help them walk. The experimental results demonstrate that SEU-EXO has good trajectory tracking performance, so that the exoskeleton can meet the training function of patients in the early stage of rehabilitation.

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