

Article

Design Methodology and Experimental Study of a Lower Extremity Soft Exosuit

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Abstract: Flexibility and light weight have become the development trends in the field of exoskeleton research. With high movement flexibility, low movable inertia and excellent wearable comfort, such a type of system is gradually becoming an exclusive candidate for applications such as military defense, rehabilitation training and industrial production. In this paper, aiming at assisting the walking of human lower limbs, a soft exosuit is investigated and developed based on the considerations of fabric structure, sensing system, cable-driven module, and control strategy, etc. Evaluation experiments are also conducted to verify its effectiveness. A fabric optimization of the flexible suit is performed to realize the tight bond between human and machine. Through the configuration of sensor nodes, the motion intention perception system is constructed for the lower limb exosuit. A flexible actuation unit with a Bowden cable is designed to improve the efficiency of force transmission. In addition, a position control strategy based on division of the gait phase is applied to achieve active assistance during plantar flexion of the ankle joint. Finally, to verify the assistive effectiveness of the proposed lower extremity exosuit, experiments including a physiological metabolic test and a muscle activation test are conducted. The experiment results show that the exosuit proposed in this paper can effectively reduce the metabolic consumption and muscle output of the human body. The design and methodology proposed in this paper can be extended to similar application scenarios.

Keywords: lower extremity soft exosuit; wearable robots; human-robot interaction; efficiency evaluation



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1. Introduction

Wearable robot technology belongs to a comprehensive research field that uses fused sensor information to control and assist joint movement, in attempting to break through the limits of human physical activity [1–3]. Its main application scenarios are physical enhancement for healthy people [4,5] and rehabilitation training for non-healthy groups [6–8]. In both aspects, rigid exoskeleton systems have made great progress, but there are still problems such as the large size and mass of the device and limited movement for the wearer. Different from a rigid exoskeleton, the soft exosuit can provide assistance for humans while being more comfortable and lightweight [9]. These soft wearable systems mainly show the advantages of extremely high movement flexibility and a large movement range that rigid systems do not have [10]. It has the following three characteristics when applied to rehabilitation training for patients or power assistance for healthy people.

(1) It can enhance movement ability. In fact, the soft exosuit is slightly inferior to the rigid exoskeleton in terms of maximum output torque. Considering that both patients and healthy people generally have mild or moderate needs for power assistance in daily life, the soft exosuit can meet the basic functional requirements of physical enhancement to a certain extent;

(2) It has a large degree of freedom of movement. The soft exosuit has no rigid links on the limbs and no slewing mechanism at the joints, due to the application of the flexible

suit and cables to transmit power [11,12]. This allows the entire device not to restrict the joint movement at all. The range of motion is the same as when exosuit is not worn;

(3) It is simple and light in shape, like other soft robotic structures for rehabilitation [13–15]. Unlike rigid systems, flexible ones do not drive limbs through bulky structures such as rotary mechanisms at joints and rigid links parallel to limbs. As a result, they are lighter and more comfortable for the wearers.

Harvard University is an important institution for the research and design of exosuits in recent years, and has achieved considerable technical achievements [16–19]. In 2013, it started to design a new cable-driven lower extremity exosuit with the goal of assisting human walking [20]. This system detects the gait phase information through the foot switch, and uses a geared motor to pull the Bowden cable whose end is connected near the ankle, thereby generating assistive torque at the ankle and hip joints. In 2017, the University of Zurich and ETH Zurich jointly developed a soft wearable device called “Myosuit”, which aims to provide continuous assistance to the gravity-bearing hip and knee joints during daily activities [21]. The system combines active and passive elements with a closed-loop force controller to design a mechanism similar to an external muscle. It uses the tendon force and linearized fabric stiffness to estimate the joint angle, based on which positive and negative power is generated. Thereby, a certain degree of gravity compensation is provided to the wearer. In 2016, the European Union planned to design a soft bionic exosuit “XoSoft” for the elderly and the disabled, proposing concepts such as modular joints, intelligent sensing, flexible drive, bionic control, and user monitoring. In 2018, following the user-centered design principles and targeting people with mild to moderate gait impairments, the first prototype of XoSoft was constructed, consisting of a flexible woven garment, an elastic band controlled by an electromagnetic clutch (to support knee and hip flexion), and a backpack that houses the system’s sensor and control modules [22]. After that, they launched a series of iterative versions [23,24]. In 2020, the Daegu Gyeongbuk Institute of Science and Technology in South Korea developed a soft lower limb exosuit specially designed for assisting up and down stairs, which can provide additional strength to the knee joint [25]. In 2020, the University of Arizona conducted an experimental study to explore the potential of adaptive assistance for ankle flexion and extension with an exosuit, and to analyze the feasibility of improving ground walking performance in patients with cerebral palsy [26].

In general, the soft exosuit needs more specialized design and optimization analysis in fabric configuration to ensure a close fit with the human body, and not too much deformation during force transfer. The driving device should have a high enough output capacity, as far as possible, under the premise of ensuring light weight, to achieve high-efficiency power transmission. The control strategy plays an important role to ensure human-machine collaboration, which requires careful design and testing so that the control system can make appropriate and timely responses after understanding the intention of the wearer. Our research will focus on the above aspects and analyze the performance of related methods through several evaluation experiments.

This paper is organized as follows. In Section 2, the structural design method of the exosuit is described, which mainly includes the soft garment and the actuator. In Section 3, the scheme of the control system is described in terms of software and hardware. In Section 4, the efficacy evaluation experiments are performed to test the metabolic cost and muscle activation. Conclusions and future work are in Section 5.

2. Structure Design

2.1. Soft Suit

The main components of the lower extremity exosuit’s flexible suit include the skirt belt, leg binding and foot accessories, as shown in Figure 1. The webbing along the leg length is approximately 70 cm long and allows for a deformation of more than 14 cm. It can accommodate people of 170–180 cm in height.



Figure 1. Structural composition of the soft exosuit.

The belt is designed with a skirt shape that wraps around the entire waist and hips. To fit the human skin and restrict the movement limit of the joint, it adopts a tailoring method that conforms to the structure characteristics of the waist and hip, which has certain protection functions for sports injury. The belt is made up of two layers of polyester fabric and an intermediate layer of nylon fabric, with a sponge pad on the back, which carries the control box and motors comfortably.

The leg binding contains thigh leg binding and calf leg binding, which fits the shape of the human thigh and calf muscles and is designed according to their circumference. It is made up of high-strength Oxford cloth and adopts an adhesive buckle to realize wearing and fixation. There is a point in the middle of the back of the leg binding which is connected to the actuator through the cable sheath that is used to apply assistant force. The leg binding restrains the direction of the elastic ribbon, so that it starts from the front of the thigh and reaches the middle and lower part of the calf along both sides of the leg over the knee. The thigh leg binding at the anchor point attachment adopts the load bearing belt, forming a triangle shape, so that the force on this point is distributed over the whole thigh part.

The foot accessories consist of an ankle bearing and a heel bearing. The ankle bearing is the fixed end of the cable sheath. The heel bearing part is the fixed end of the Bowden cable, which serves as the bearing end of the cable-driven system.

2.2. Cable-Driven Module

To meet the requirements of light weight, low power consumption and high performance of the flexible system, the motor and the Bowden cable fitted to the human leg are used as an active driving unit to enhance the movement ability of the corresponding muscles. The total weight of the cable-driven module is less than 1 kg. The cable diameter is 1.6 cm, which can withstand the maximum tension of about 1800 N. Through reasonable setting of the force transmission path and accurate control of retraction and release, it simulates the force generation process of human muscle to assist the plantar-flexion movement of the ankle joint. The design of the driving unit mainly focuses on the integration of the driving device, transmission device and executive device.

As shown in Figures 2 and 3, the driving device is mainly composed of a driver, encoder, motor, gear reducer and cable wheel. In the process of operation, the motor decelerates through the reducer and increases the output torque according to the output parameters of the control device, thus driving the cable wheel to rotate, and finally pulling the Bowden cable to provide assistance for the ankle joint.

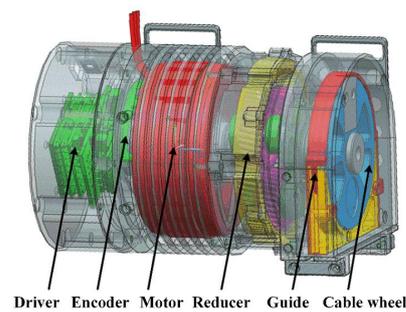


Figure 2. Cable-driven module for lower extremity exosuit.

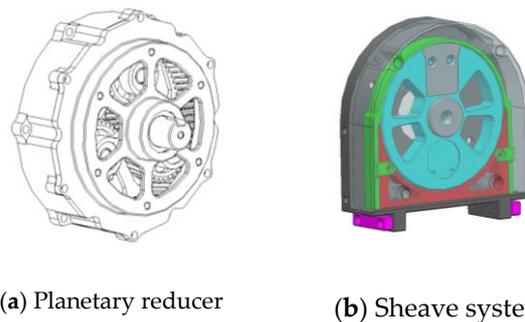


Figure 3. Core components of the cable-driven module.

The transmission device is a flexible scheme that adopts the combination of a cable and sheath between the power source and load. This method combines the advantages of cable transmission and gear transmission, and has the characteristics of large load bearing force, small recoil force and a wide range of reachable motion.

The executive device consists of the Bowden cable and the joint anchor point. It sets clamping for the Bowden cable sheath on the calf strap and anchor point at the heel. During the phase for joint assistance, the Bowden cable pulls the anchor point along the sheath, thus exerting an assistive torque on the ankle.

3. Control System Configuration

3.1. Hardware Composition

As shown in Figure 4, the sensor composition of the lower extremity exosuit is relatively simple, including only inertial measurement units (IMUs) and encoders (Renishaw, MB039 + MRA039). The IMUs are installed on the calf straps by suturing, and are mainly used to measure the change data of the calf swing angle in the gait cycle, which provides a basis for the subsequent gait phase division. The encoders are integrated in the driving units to measure the rotation angle of the motors (Kormorgen, TBM7615), so that the length of the Bowden cable can be calculated to provide data feedback for the position closed-loop control.

In view of the characteristics of the system, such as various sensors and different data structures, the standardization and normalization of the system software and hardware interfaces are carried out. Based on controller area network (CAN) bus, a perception and control system architecture is built, and a scheme suitable for information transmission between each module of the system is studied. On the application layer, we carried out an investigation on real-time transmission control protocol technology for data collection, data encoding and decoding, control command sending or receiving, etc., to achieve a high efficiency of data interaction between various modules, and to further improve the real-time transmission of system information.

The system contains a two-channel CAN bus, which is used for communication between the core controller (STM32), multi-sensor group, and servo driver (Elmo, Gold Twitter). It is mainly responsible for collecting sensor information and human body motion

data, completing the delivery of servo control instructions, and feeding back the location of the actuators, etc. The system information flow chart is shown in Figure 5.

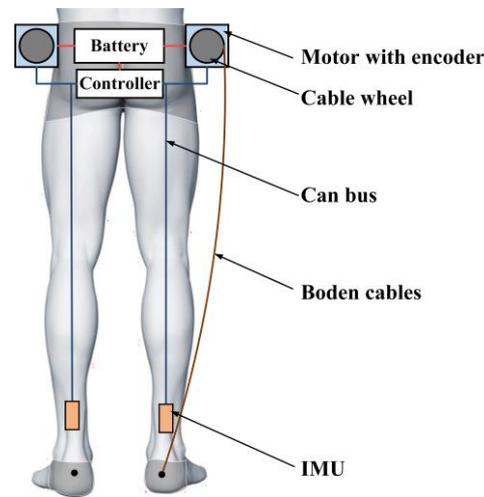


Figure 4. System hardware composition.

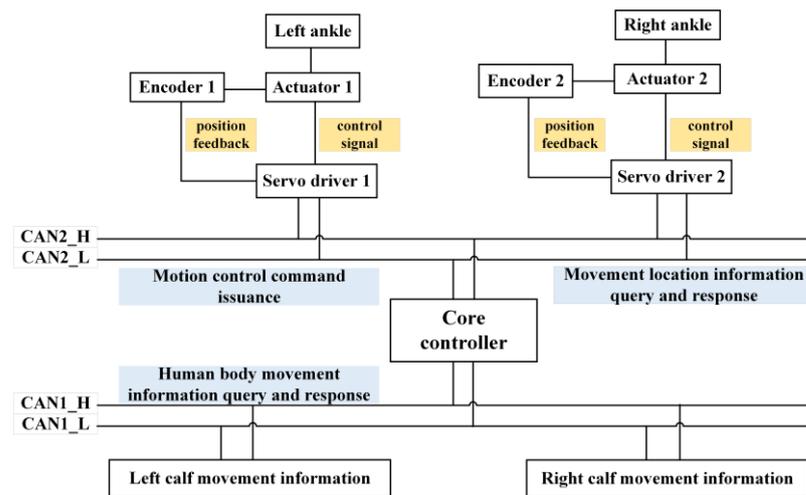


Figure 5. System communication scheme.

3.2. Motion Control Strategy

The time between any two identical motion states in the gait process is defined as the gait cycle, which is usually regarded as the process between two adjacent heel touches, as shown in Figure 6.

In a cycle, lower extremity movement can be divided into the supporting phase (with contact between foot and ground) and the swing phase (without contact between foot and ground), accounting for approximately 60% and 40% of the time, respectively. It can be further subdivided according to whether the left and right legs are in the supporting phase or the swing phase. When both the left and right legs are in the supporting phase, it is called the double-leg supporting phase. When one of the legs is in the swing phase, it is called the single-leg supporting phase. A more specific subdivision can divide the supporting phase into four sub-phases, including the double leg supporting phase, the initial supporting phase, the mid-supporting phase and the terminal supporting phase, according to the order of occurrence. Similarly, the swing phase can be divided into three sub-phases, which include the initial swing phase, the mid-swing phase, and the terminal swing phase, in the order of occurrence. According to the analysis above, we developed a position control strategy based on the gait phase division, which is shown in Figure 7.

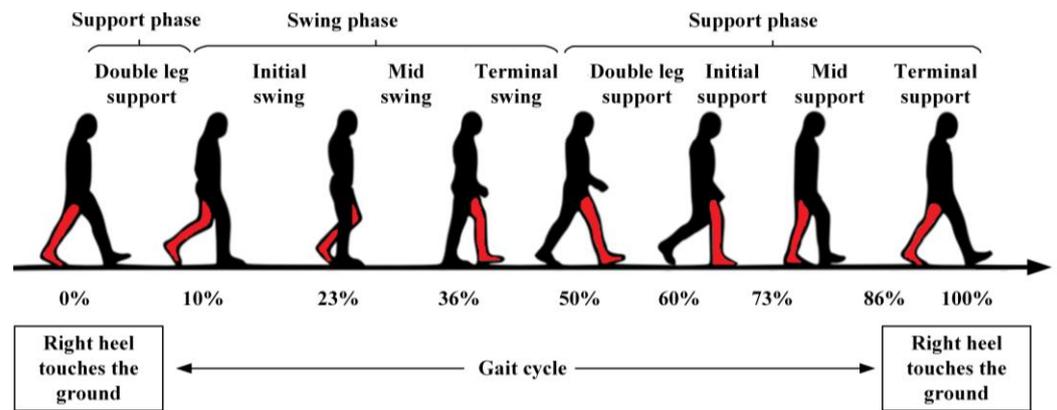


Figure 6. The sketch of the gait division.

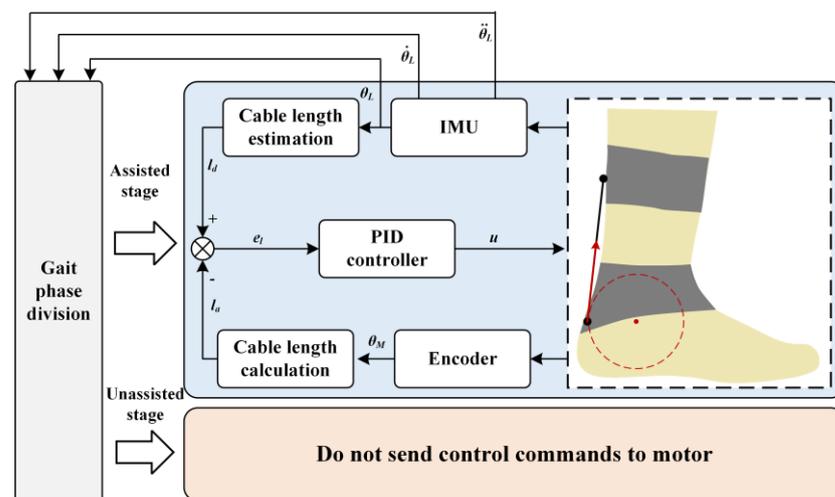


Figure 7. Control block diagram.

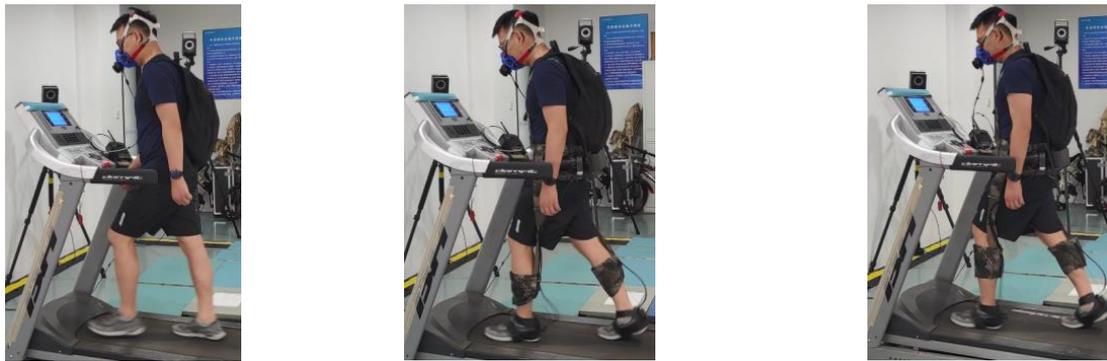
After obtaining information such as limb angle, angular velocity and angular acceleration, the gait phase of each leg during walking can be divided. The system will identify the leg-lifting stages (initial swing and mid-swing) based on that, so as to provide a judgment basis for determining the timing and duration of the active power assistance.

Then, the length of Bowden cable that needs to be retracted theoretically is estimated through the current angle information, and then the actual value is calculated using the motor rotation angle fed back by the encoder. The difference between both will be output to a proportional-integral-differential (PID) controller to realize the regulation of the motor state, ensuring the effectiveness of the power assistance.

4. Experiments

4.1. Physiological Metabolic Test

Oxygen consumption rate is a quantitative indicator that characterizes the metabolic level of human exercise. If under the same motion conditions this physiological data of the human body is significantly reduced after wearing the wearable robot, it can indicate that this equipment can save a part of physical energy consumption. In order to prove the effectiveness of the system proposed in this study, we have used a portable respiratory metabolism monitoring system (K5) to monitor the oxygen consumption data of motion under three conditions: without the exosuit, with the exosuit powered off and with the exosuit powered on. In each test condition, the wearer is required to carry a 5 kg load and walk on a treadmill for nearly 30 min at a speed of 4 km/h, as shown in Figure 8.



(a) Test without exosuit (b) Test with exosuit not powered on (c) Test with exosuit powered on

Figure 8. Physiological metabolic test.

Figure 9 shows the change curves of the oxygen consumption rate during the experiment. It can be qualitatively seen that after the subject put on this wearable system, the oxygen consumption rate with the exosuit powered on is significantly lower than that with the exosuit powered off, which proves the feasibility of saving physical energy through the cable-driven method. However, the oxygen consumption rate with the exosuit powered on is not intuitively lower than that without the exosuit. This is because the extra energy expenditure associated with the system weight and other factors can offset some of the energy savings and even increase metabolic expenditure.

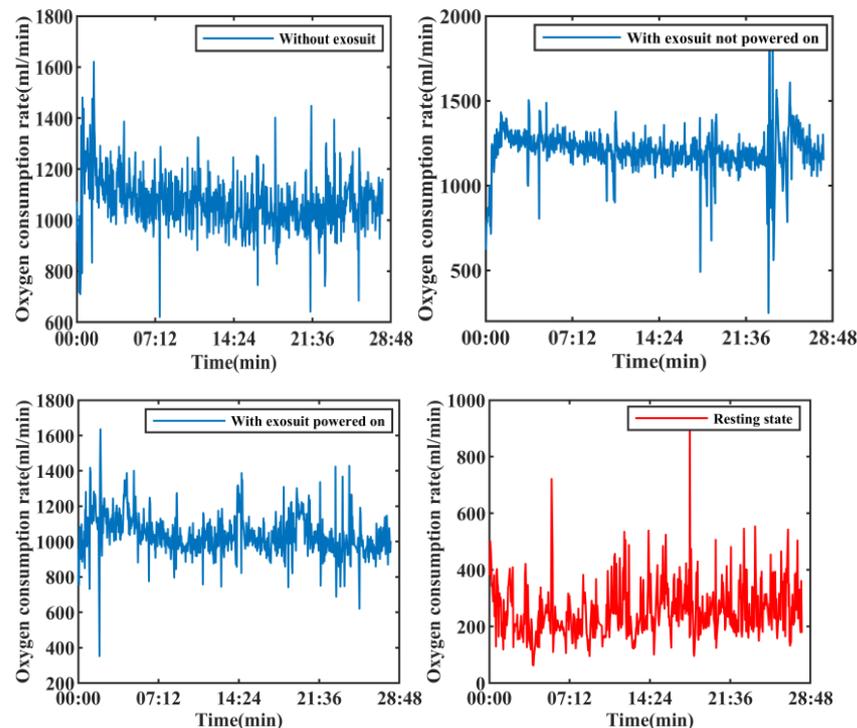


Figure 9. Variation curve of oxygen consumption rate under different test conditions.

For quantitative illustration, we calculate the average values of the corresponding oxygen consumption rates (V_{No_suit} , $V_{Unpowered}$ and $V_{Powered}$), which are 1069.9 mL/min, 1203.0 mL/min and 1032.4 mL/min, respectively. In order to exclude the difference caused by the different initial physiological state, the oxygen consumption data of the wearer at rest is also measured, with an average value (V_{Rest}) of 264.1 mL/min. Referring to the

relevant literature, the net metabolic change and gross metabolic change brought by the exoskeleton can be obtained by the following formulas.

$$\eta_{net\ metabolic\ change} = \frac{(V_{powered} - V_{Rest}) - (V_{No_suit} - V_{Rest})}{V_{No_suit} - V_{Rest}} = -4.65\%$$

$$\eta_{gross\ metabolic\ changes} = \frac{(V_{powered} - V_{Rest}) - (V_{Unpowered} - V_{Rest})}{V_{Unpowered} - V_{Rest}} = -18.17\%$$

4.2. Muscle Activation Test

Assisting in muscle output and providing additional force to the joint are the basic goals for designing a wearable robot. To measure the compensation effect of the lower extremity exosuit on muscle activation, we measured the physiological data of gastrocnemius muscle using sEMG sensors. The test was also divided into three groups: without the exosuit, with the exosuit powered off and with the exosuit powered on. Other experimental conditions are the same as those in the physiological metabolic test.

The change curves of the sEMG signal of gastrocnemius under different test conditions are shown in Figure 10. Root mean square (RMS) is introduced to quantitatively describe muscle activation, as shown in Table 1.

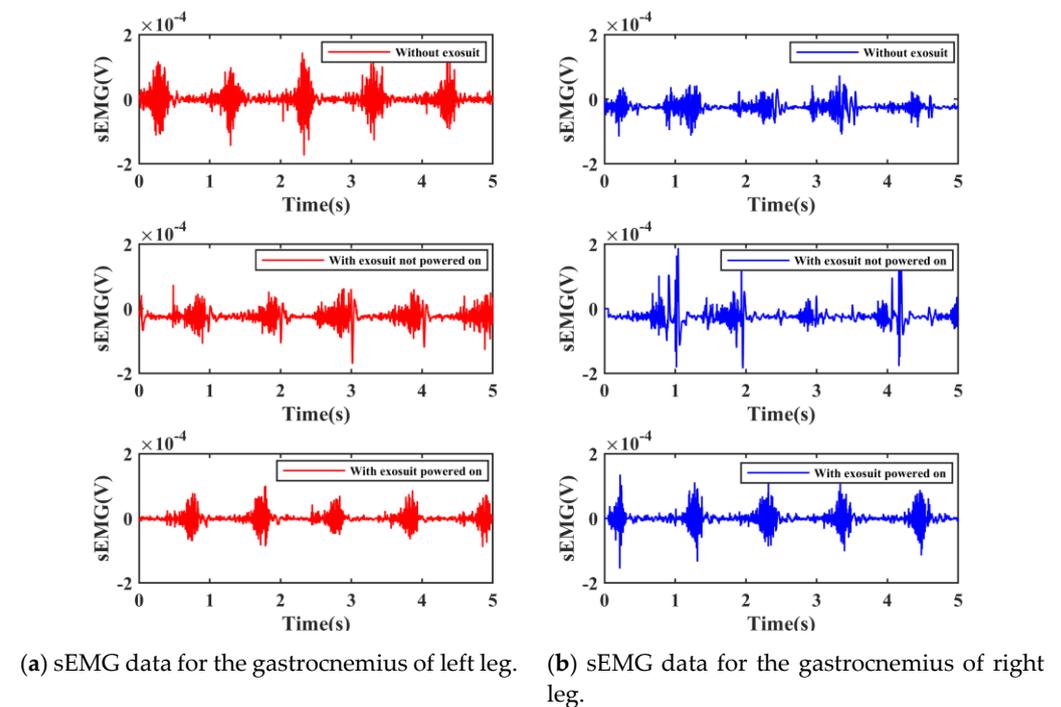


Figure 10. Changes of sEMG data under different test conditions.

Table 1. RMS value of EMG signal under different test conditions.

	Without Exosuit	With Exosuit Powered off	With Exosuit Powered on
Gastrocnemius of left leg	2.044×10^{-5}	3.085×10^{-5}	1.314×10^{-5}
Gastrocnemius of right leg	2.935×10^{-5}	3.293×10^{-5}	1.624×10^{-5}

Therefore, when subjects put on the exosuit and do not turn it on, it is equivalent to carrying a load on their back, which must increase the activation of the muscles. However,

once the system starts working, the additional assistive torque makes the muscle activation drop significantly below the level without wearing the exosuit.

5. Conclusions and Future Work

In this study, a lower extremity soft exosuit for the ankle joint was designed. Through the synthesis of many technical researches such as structure, sensing and control, the goal of walking assistance was achieved. In terms of structure, it focuses on the seamless integration of the soft suit, and realizes the close combination of the human–robot system by configuring a variety of fabrics. Then, a compact cable–driven device was designed to deliver power to the ankle by rewinding the Bowden cables in an orderly manner. In the aspect of perception, multiple sensors are used to feedback the human movement information and system state data. Then, the gait phase can be divided, which lays a foundation for determining the power stage. In terms of control, the hardware architecture for human–robot cooperative control was designed, and the motion control strategy based on position closed–loop was adopted to realize the accurate following and effective assistance of the system for ankle joint movement. Compared with previous studies [27,28], the main contribution of this paper is to propose a novel fabric structure that can work closely with the muscles of the lower limb, and to design an effective motion control strategy based on gait detection.

In order to measure the assistive effect of the system, we carried out the physiological metabolic test and the muscle activation test, using K5 and surface EMG sensors to detect and analyze the oxygen consumption rate and EMG signals under three walking conditions. The results show that the exoskeleton can reduce oxygen consumption during exercise to a certain extent, thus achieving the goal of reducing human metabolism. At the same time, it can also reduce the activation of relevant muscles, demonstrating the effectiveness of compensating joint output.

In the near future, we will design a compensation strategy to improve performance based on the analysis of the nonlinear characteristics of the transmission system. At the same time, it is necessary to provide all–round assistance to multiple joints to enhance the assistive effect.

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