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Development of a soft knee exosuit with twisted string actuators for stair climbing assistance

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***Abstract*—Stair climbing remains one of the toughest tasks of the elderly in activities of daily livings (ADLs). However, most of the existing stair climbing assistance devices are large and heavy, such as the automatic stair climbing wheelchair, the rigid exoskeleton and so on. They all lack applicability in the daily life. Based on this starting point, in this paper, a soft knee suit (Hitexosuit) has been developed to assist people climbing. It is a lightweight and wearable assistance suit for human lower extremity in climbing the stairs. This paper finds out the certain phase of stair climbing motion that requires the most muscle strength and locates the target muscle that contributes most when people climb the stairs through the biomechanics analysis. Furthermore, this research draws inspiration from the human muscles, which contract to generate force for knee extension and help people lift their body to go upstairs. Based on that bionic principle, a new type of artificial muscle is developed. It simulates human muscle contraction by shortening the length of steel wire to give extra strength to human lower extremity. And textiles have been adopted in the suit, soft straps and belts to make up the structure of the suit instead of rigid and heavy materials. In addition, to minimize the whole weight of the exosuit system further, we develop a lightweight and portable actuator using twisted strings. This twisted string actuator (TSA) weighs 390g and the whole exosuit weight is 3.5kg with two TSAs. The exosuit is tested with three different users and the mean assistance efficiency is 29.8%. It will improve the living quality of the aged by guaranteeing them more confidence in ADLs and self-caring.**

Keywords—wearable, exosuit, exoskeleton, stair climbing, twisted string actuator, IMU

I. INTRODUCTION

Nowadays, lower extremity dyskinesia caused by aging and diseases such as stroke has become a major concern in our society. Stair climbing is especially challenging for those who suffered from low extremity dysfunction because when you climb the stairs, you have to work against the gravity of your whole body weight and keep the balance as well in one-leg support phase. Therefore, many researchers have kept their attentions on stair climbing assistance to help people.

A variety of studies have been conducted on analyzing the stair climbing locomotion [1]-[3]. Francine Malouin *et al* [4] have compared the key features between stair climbing and level walking. The study focuses on the difficulties of stair climbing by analyzing biomechanical information. And the results indicate that knee extension movement plays as the dominant role during climbing the stairs. Costis Maganaris *et al* [5] have found that the elderly might adopt the alternative strategies to climb stairs to compensate for the decreased knee capability. Yoshiyuki Sankai *et al.* [6] have figured out a way to determine different phases in the period of stair ascent motion by tracking the trajectory of the center of ground reaction force. Chenglong Fu *et al.* [7] have proposed a robust environmental features recognition system to help prostheses detect environmental context when climbing the stairs.

A wearable hip-assist robot, developed by Samsung Electronics Co., Ltd., is a stiff assistance equipment that generates assistive power to each hip joint with a maximum torque of 12 Nm [8]. Yanhe Zhu *et al.* [9] have developed a lower extremity exoskeletion to improve human mobility in climbing stairs when carrying the load. Payman Joudzadeh *et al.* [10] have developed a tendon-driven lower limb wearable exoskeleton that can empower both knee joints and ankle joints with only two motors during people walk upstairs. BoLi *et al.* [11] have designed a spring-based passive knee-assisting exoskeleton. This equipment stores the energy into the spring when the user bends the knee and releases the energy to assist lifting the body when the knee extends. However, most existing exoskeleton are still relatively bulky so that they still cannot be easily carried away. As for the passive assistive exoskeleton, although it is simple and light in weight, it has no measurement and control when the stored power is released, which increase the risk to cause damage to knees.

Given these defeats, the current approaches have limitations to be applied in daily life situation. Harvard team first came up with the idea of "exosuit", which is a wearable suit-like device to assist people walking and running [12]-[14]. This team has developed several generations of exosuit so far. In their latest research, the exosuit is designed based on different kinds of soft textile and can transmit the driving force to empower the hip and ankle joints by Bowden cable. As for the control part, problems such as when the motor works, how long it works and how much torque it gives, have been given optimized solutions through deep learning to minimize the energy cost [15]-[17]. And the hip extension assisted exosuit can reduce metabolic rate of walking and running by 9.3% and 4.0% respectively [18]-[19].

Exosuit gives a new definition to the exoskeleton researches, but it only focuses on the level walking assistance and hasn't proposed a strategy for stair walking assistance. Furthermore, exosuit provides assistive torque only to the hip and the ankle joint, yet the knee joint is not included. Therefore, it cannot cater to the demands for ADLs and how to assist people to climb the stairs more efficiently, more agilely and more comfortably still remains a major problem which needs tackling.

For that reason, Hitexosuit is proposed. Compared with exosuit by Harvard team, it provides assistant moment for human knee joints which are majorly needed when climbing the stairs. Hitexosuit is a wearable suit-like device with twisted string actuator and steel cord based artificial muscle transmitting the required force to each hip when the user walks upstairs. The suit-like structure gives the wearer no limitation of lower-limb free motion. Modular construction ensures the possibility of quick dressing/undressing and easy carrying. What's more, twisted string actuator and steel cord based artificial muscle replace the traditional decelerator and rigid transmission parts. In this case, the exosuit caters to the light weight demands.

II. BIONIC STRUCTURE DESIGN OF EXOSUIT

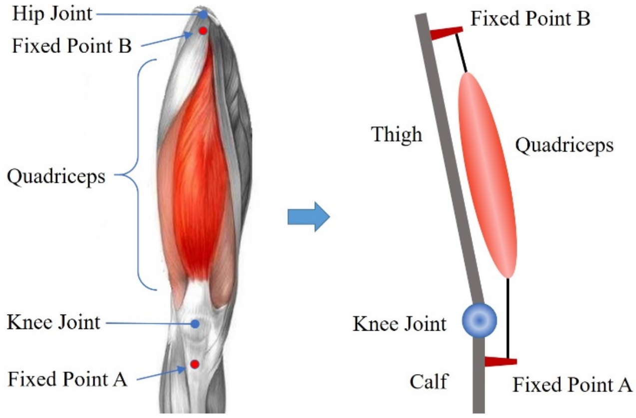
A. Bionic Principle Overview

The structure and function of the human body has evolved for millions of years to adapt to the living environment. It is like a perfect machine that can finish the task in the most efficient way. Thus, researchers can get inspired from the working of human body system to improve the human assistance robot. During the process of climbing upstairs, the most difficult thing is how to lift the whole body weight from one stair to the next. When people put one foot on the stair and tend to climb, the muscles of the corresponding leg are activated to help lifting the body to next stair. Among all the related muscles, which are the major muscle groups of the human leg, the quadriceps play the pivotal role, which are the major muscle groups of the human leg. The quadriceps consist of the four muscles, including the Vactus Lateralis, Medialis, Intermedius and the Rectus Femoris. Just as shown in Fig.1(a), the quadriceps lie alongside the thigh bone with one end connecting to the hip joint and the other one fixing on the knee joint. The two connection ends are labelled to be as Fixed Point A and Fixed Point B. When the muscles contract, they will generate force and enable the knee extension. The human leg can be regarded as a two-rod mechanical system. Thigh and calf bones are just like the two rods, and the knee acts as the rotating hinge. The quadriceps perform as kind of the elastic actuator, which fixed between the two rods. When the elastic actuator contracts, the force between Fix Point A and Fix Point B will produce a moment on the rotating hinge. Thus, two rods are actuated to rotate.

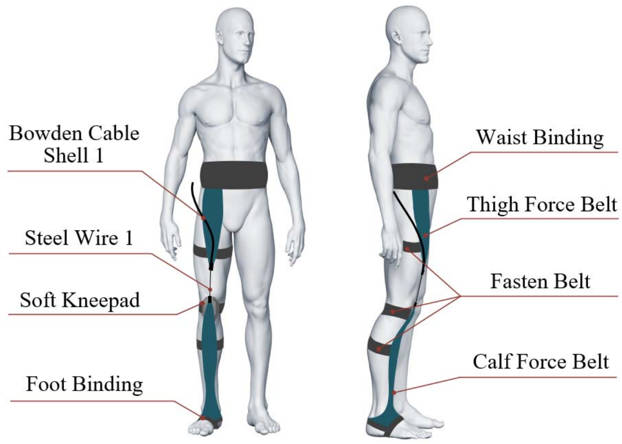
B. Bionic Structural design

Based on the working principle of the quadriceps, the lightweight and soft exosuit has been introduced. The Fig.1(b) shows the principle form of the exosuit, which mainly consists of the Bowden cable, soft straps and non-elastic belts. The Bowden cable has two parts. The outer part is the Bowden Cable shell and the inner part is the steel wire. They are combined to transmit the driving force from the actuation unit to the knee joint.

In the Fig.1(b), binding and fastening fixed parts of the exosuit are made of soft straps, including the Foot Binding, Waist Binding and the fasten belt. They have certain degree of elasticity and can be attached to the human body without introducing additional interference. The Waist Binding and Foot Binding are two ends of the exosuit. The former one is attached to the human waist, and so that it can withstand the downward pull force. Similarly, the latter one is fixed on the foot and balance the upward pull force. The Thigh Force Belt and Calf Force Belt are lain around the surface of thigh and calf separately between the two bindings. They are made of Nylon, which is non-stretchable along the axial direction of human leg bone. And both of them can be fit firmly to the leg with the help of the fasten straps. As the Bowden cable consists of Bowden cable Shell and steel wire in the shell, it can connect the two belts in series. By using the Bowden cable, the two belts are connected in series. One end of the Thigh Force Belt is fixed on the Waist Binding and the other end is



(a) Bionic Principle of Human Muscle (Quadriceps)



(b) The Structure Design Schematic Diagram

Fig. 1. Bionic Design of the Exosuit

designed to be attached to the Bowden Cable Shell 1. The latter connection point will work as the Fixed Point B in Fig.1(a). In the meantime, one end of the Calf Force Belt is fixed on the Foot Binding and the other end is attached to Steel Wire 1. The latter connection point performs like the Fixed Point A. Combining force belts, soft straps with the Bowden cable, we develop an artificial muscle which have the function of quadriceps.

C. Working Principle of the exosuit

According to the biomechanics of climbing upstairs, the exosuit has the ability to offer force assist for the knee joint. As the Fig.2, before the user steps up, the Bowden Cable is on the unactuated state, and the length of steel wire between Point A and Point B is l_0. For this time, the steel wire is on its slack and normal condition. And the angle between calf and thigh becomes θ_0. When people climb the stairs, the user should make a force to step up. The Bowden Cable will be actuated and it will pull the Thigh and Calf Force Belts to move closer. Thus, the length of steel wire between Point A and Point B shortens to be l_1 ($l_1 < l_0$). At this moment, the steel wire is on its tensioning condition and the angle between calf and thigh turns to be θ_1 ($\theta_1 < \theta_0$, $\theta_1 \rightarrow 0$). This movement will generate moment on the knee. It could be used to provide additional force with knee extension in the climbing motion. Thus, the supporting leg turns to be straight and people pedal over the stairs.

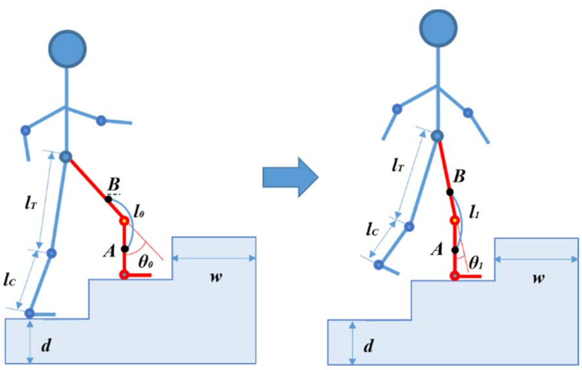


Fig.2. Upstairs Assistance Principle of Hitexosuit

III. Portable Twisted String Actuator

A. The Actuation Principle

The new actuator produces force by the way of twisting strings [20]-[22]. The two ends of the soft strings are attached to electric motor and the load separately. In the initial state, the motor stops and the strings lies peacefully along the axial direction of the motor. Thus, the load will not move at all. When the motor is actuated, it will rotate and produce torque, which can transmit to the strings. In that way, these strings are able to twist together and the length turns shorter in the meanwhile. With getting contracted, the twisted strings produce force to drive the load on the other end. In the actuating process, these twisted strings act as a gear of the traditional driving system. Furthermore, the strings will output high liner force when being twisted by a relatively low torque Therefore, it is the twisted strings working principle that gives a much simpler and more lightweight robot driving system.

B. The Structure Design

In this work, the twisted strings working principle is combined with practical uncomplicated mechanical structure, in order to decrease the system weight as much as possible. The mechanical design of the actuator is show as Fig.3. In the actuation unit, a Maxon EC 4-pole 200W motor is connected to a connecting shaft by a flexible coupling. The motor chosen has a no-load speed of 16,500prm. One end of the twisted strings is connected to the shaft, and the other end is attached to the connecting ring. Outside the twisted strings, a supporting shell is placed coaxially with the strings alongside the axial direction. The supporting shell is fixed in series between the supporting mount and the end cap. Considering the demand of low density and axial compressive strength, carbon fiber cylinder is chosen to make the supporting shell, of which external diameter is only 14mm and the thickness is just 1mm. Along the supporting shell, two guide slots have been designed for the connecting ring to move forward and backward along the axial path. Thanks to the guide slots and the convex plates of the connecting rings, the torque produced by the twisted string will be offset. Because of the thin thickness and the cylindrical convex plate, the kinematic pair between the two parts contact becomes equal to point contact.

Thus, it serves as an easy method to offset the torque caused by the twisted strings without introducing large friction resistance. In addition, we incorporate steel wire to transmit the axial force since it can be used to transmit power ignoring the distance restriction. The supporting mount, connecting shaft, connecting ring and end cap are all made of aluminum alloy further weight reduction. The maximal diameter of this actuator is 30mm, the same as the motor. And its length can

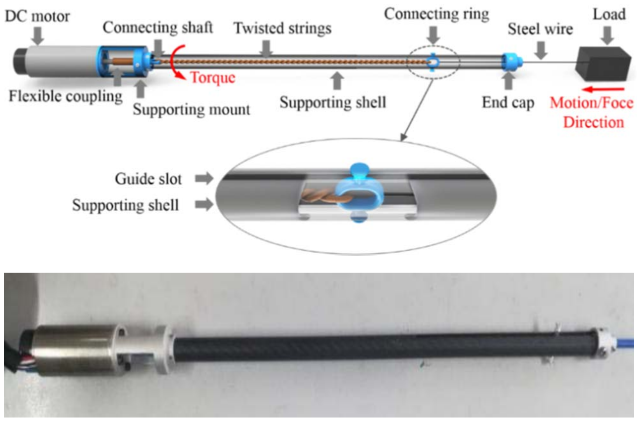


Fig. 3. Portable Twisted String Actuator

be changed according to the implementation. However, the least length for normal use will be 14mm, considering the size of the motor, supporting mount and end cap. The flexible actuator total weight is just 390g, when the supporting shell is 350mm.

C. Experiment Evaluation

The load-free maximum speed of motor is 16500prm, and in the test the given motor output speed is set up to be 14000rpm (233.33r/s). We use a pull-wire placement sensor to measure the placement of the steel wire end. However, the pull-wire placement sensor has pretightening force. To solve this problem, another same pull-wire placement sensor has been tied to the steel wire end in the opposite direction to balance out this force, while it could not induce extra inert and the load is equal to zero. The placement sensor could record the placement of the load and give out the velocity indirectly. As show in Fig.4, the maximum driving velocity of the actuator device is 1601.25mm/s when the motor speed is modulated to 14000rpm. According to the leg length and the angle variation of the knee joint, the contract length of the steel wire will be no more than 150mm when people climb upstairs. On that condition, the one-way actuating time will cost less than 0.1s. In the meanwhile, considering the frequency of climbing upstairs cannot exceed 10Hz, thus the velocity of the twisted string actuator will be able to satisfy the driving velocity of human climbing upstairs.

In order to test the maximum driving force, a high-stiffness spring has been used as the load. One end of the spring is attached to the cable and the other end is fixed to the ground. The DC motor continuous current is 5A and the torque constant is 27.6mNm/A. The relationship between driving force, motor current and the number of motor rotations can be obtained. Thus, to produce the certain driving force, the motor

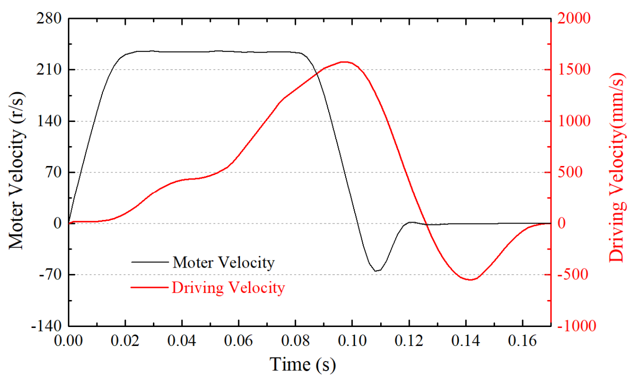


Fig.4. Maximum Velocity

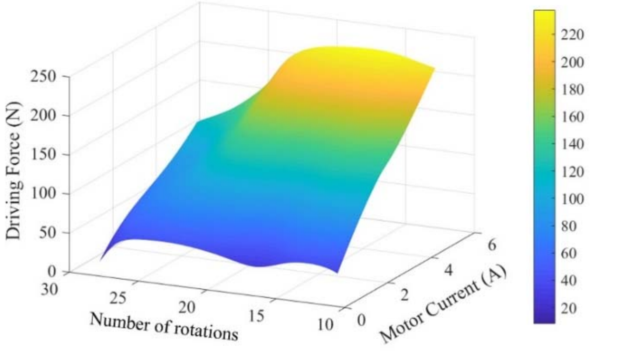


Fig.5. Driving Force Characteristic

current and rotations can be well regulated. We also explore the driving performance of the actuator when the motor working current is more than its continuous current. In this method, we could obtain the force changing trend with respect to the motor working current and predict the upper limit of the actuator driving ability. For the motor's stall current is 124A, the instantaneous driving force could be very high. Thus, it is feasible to increase the working current of the motor, when needing larger driving force.

To explore the displacement characteristic of the actuator device, we measure the displacement of the cable end and the rotations of the motor according to different load. The motor speed is modulated to be 300rpm, which will not have any effect on the displacement characteristic and the displacement curve is relatively smoother. Therefore, we can obtain better experiment results. The maximal rotations of the motor is designed to be 25 turns, on which condition driving soft strings will not be overtwisted. Overtwisting is a phenomenon that multiple soft strings will not twist to each other orderly. The displacement characteristic will change a lot into another style and be hard to utilize. In addition, it could increase the string abrasion and reduce the string's working life seriously. In the test, the driving system have 6 twist strings and the load is designed to be 25N, 50N, 75N respectively.

When the motor rotates in one direction, the strings will twist together and it makes the contraction stoke of the actuator. Thus, when the motor rotates in the other direction, we get the relaxation stoke of the actuator. As shown in Fig.6(a), the driving placement increases exponentially along with the number of rotations grows. When the motor rotates for 25 turns, the maximal placements are 64.47mm, 62.42mm, 57.73mm on the diverse load conditions. For the soft nature of the strings, the whole actuator system stiffness will change and have effects on the driving performance. In addition, there are also some differences between the contraction and relaxation stoke. According to a certain working condition, the displacements of the relaxation stoke for all rotation cycles are bigger than the counterparts of the contraction stoke. Thus, there is a "hysteresis phenomenon" during the reciprocating movement of the twisted strings system. It might because of the friction between the twisted strings, which hinders the twisted strings from relaxing.

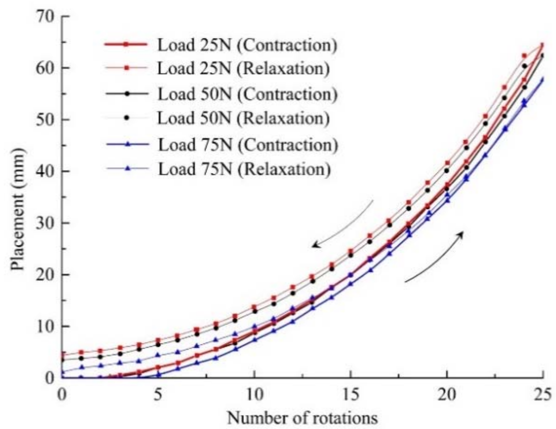


Fig.6. Placement and Motor Rotations

Compared to conventional actuators, this new actuation unit eliminates the need for decelerators and rigid transmission parts, making the device lightweight. What's more, the new actuation unit can perform a smooth drive in the wearable exoskeleton robot, which can protect the human joint and avoid the user from injury due to unstable driving as well.

IV. Working Performance

A. Wearing Performance

The proposed exosuit is designed to help its user to climb upstairs easily and comfortably. The main components of the suit structure consist of textile, Nylon straps and some other flexible or soft materials. And all these soft components are distributed across the human leg without limiting motion capability. Because these soft materials are much lighter than the rigid ones, the suit will be light enough to avoid introducing additional burdens to the legs. With the help of kneepad, the pressure on human knee joint generated by the Bowden cable can be reduced to provide more comfortable wearing experience for the subjects. The exosuit does not affect the normal movement of the human body, and can adapt to the basic movement of the human body. Due to its actuation mechanism and structural design, it gives no restriction on the basic movement of the human body. The tester can perform lunging, squatting and hip abduction with the exosuit on.

And the twisted string actuators, control unit and batteries are integrated to the knapsack. The soft suit system and the control system adopt modular design. By using aviation plugs, these two systems can be connected and disconnected fast. To improve the portability, the soft suit part can be folded up and packed into the knapsack. And the whole weight is 3.5kg (The batteries weigh 0.75kg), including the suit structure, sensor system, two twisted string actuators, control unit and batteries. In the daily life, the user can just carry the knapsack easily, and take on the suit on one's own easily.

Fig. 7. Representation of Wearing the Exosuit

B. Gait Cycle Detection

To assist the people climbing the stairs promptly and properly, the climbing intention is the foundation. It is related to the intention identification of human body movement. Most of the researchers attempt to identify human intention on based on the fusion of the various sensor signals. To minimize the number of sensors and reduce the total system weight, we choose the Inertial Measurement Unit (IMU) as the sensor to measure the lower-limb angle variation. And we have made the portable IMU with the communication function of CAN-Bus. The IMU sensor obsesses the advantages of lightweight, compact structure and high reliability. It is nice and suitable for the wearable sensors.

In this work, four 9-axial IMU sensors are used to measure human locomotion and they are all integrated into the suit by the way of sewing. Two of them are used to mounted on the thigh and calf separately for each leg. The exosuit uses IMU sensors to gain the angle information of the user's leg. Based on the thigh and calf angle degree values, the knee joint degree trajectory can be tracked. In the meanwhile, angle information can serve as the trigger to tell when pilots need the exosuit to assist them while climbing the stairs. There is some kind of rhythm existed in people climbing the stairs. Thus, the angle signals of the two IMU sensors will vary in period. And the identification of human body movement will be reduced to the gait period detection. The gait period detection algorithm is set up based on the signal data from the IMU sensors. Time between two adjacent foot strike is regarded to be one climbing gait cycle $T_{c(i)}$. And for this current cycle when people intend to step up, it is designed to be $t_{a(i)}$. The counterpart of the last gait cycle is time $t_{a(i-1)}$. Thus the difference value of $t_{a(i)}$ and $t_{a(i-1)}$ can be defined as the gait cycle duration $T_{c(i)}$. According to the lab-based training data, the force time is shown to be 0% (or 100%) of the gait period and has nothing to do with the cycle duration.

In addition, to improve the adaptability of the gait cycle detection under the condition of fast motion, the velocity information has also been considered. And we use the velocity vector synthesis as the gait cycle identification parameter. To maximize the signal characteristics, we propose the equivalent energy concept by squaring the velocity data. In this way, the large values turn to be bigger and the little ones becomes smaller. Thus, the effective differentiation information can be obtained, which is adaptable for fast climbing stairs. With the combination of angle and velocity information of IMU sensors, the gait cycle can be detected accurately and quickly, even to the extent that the pilots climb faster than their normal comfortable speed.

C. Actuating Method

Unlike people with lower limb disability, the elderly still have moving ability. And they only need a certain amount of assistance to complete climbing stairs. In addition, much more extra force exerted on the joints arbitrarily might be harmful. Different from rigid exoskeletons, the exosuit tends to provide joint moment partially, not to serve as the substitute of human locomotion. Thus, the moderate assisting force is designed to help the aged, which will cover one third of the force people need to climb the stairs.

Based on the gait period detection results, the repeated gait cycle can be obtained. During this process, the extra force should be given to help wearers to extend their knee joint and lift their bodies when climbing the stairs. According to the experiment results of the portable twisted string actuator, the driving force can be controlled by the motor current. During the climbing process, human knee joint degree can tracked in real time. The actuator controller uses the knee join trajectory as the input. And the model of joint degree and the assisting torque has been set up. Based on the driving characteristic, we can obtain the desired force of the actuator by adjusting the motor current. The actuator controller is designed to work during the early period of supporting phase and maintain the maximal force to help climbing the stairs.

D. Experiment and Result

To get the evaluation of the exosuit assisting performance, we carry out the climbing stairs experiments on three healthy male subjects (age 26.3±3 y.o., weight 67.4±3.3kg, height 1.81±0.04m). Before the measurement, each subject has one hour to receive training on this assistive suit. And they will make sure to be familiar with the device of climbing assistance, including taking on and off by themselves, turning on and off at the proper time and climbing in synchronization with the exosuit. We choose the daily life stairs as the experiment platform. The staircase includes 11 steps and the slope is 28.2° with step height 15cm and step width 31cm. All the subjects are required and trained to climb at their normal and comfortable speed.

During the process of the climbing the stairs, and pull force of the actuator and the knee joint angular displacements will be measured. As the steel wire is placed on the human leg closely, the equivalent arm of force can be seen as unchanged. In the test, the arm of assisting force is chose to be constant value 0.06m. With the help of the actuated force and the equivalent arm, we can obtain real-time assistance torque for the knee joint. In the Fig.8, the red bold solid line indicates the average (n=3) rotating angle variation and the black solid line represents the joint assisted moment on the knee joint for the sagittal plane in stair climbing.

One stair climbing period is chosen to be the time between two successive foot strike of the same leg. Thus, the gait cycle begins on the point when the pilot tends to step up the stair, and that is to be the time of 0% gait cycle. As the red bold solid line shows, the knee joint degree decreases from foot strike to knee maximal extension. This time covers 35% of the whole gait cycle. During this time, people needs assisting power most to lift the body up. Therefore, we exert a constant assisting torque on the knee joint to help wearer overcome the gravity. The actuator is controlled to work at the time of treading the stairs and maintain the peak force for rest time of

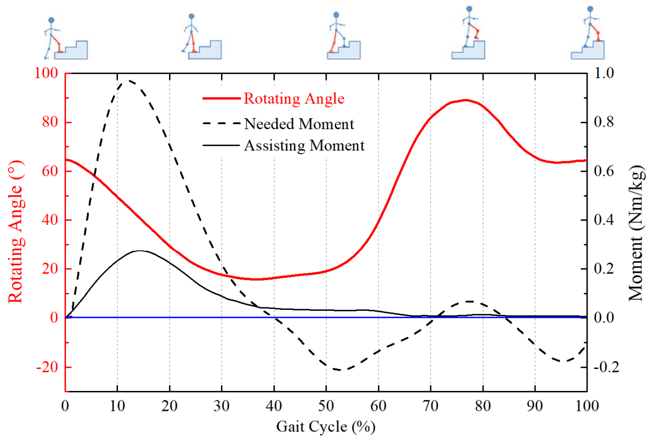


Fig. 8. Knee Kinematics and Assisting Moment

standing phase to assist climbing the stairs by providing extra torque for the knee extending movement. From 35% to 55% of this process, the human leg movement is like an inverted pendulum and the knee joint degree stays stable. The above two sections consist the standing phase of the staring climbing cycle is 45%, which is the swing phase. In the middle of the swing phase, the knee degree increases to the peak value 89.1° to pedal over the stair. Considering the mean body weight of three subjects, the mean maximal assisting torque is measured to be 0.28Nm/kg.

Based on the result, the assisting performance of the suit is able to be evaluated. By comparing with the moment people needed when climbing the stairs, the efficiency of assistance can be obtained by the equation (1).

$$\eta = \frac{\int_{\theta_0}^{\theta_1} M_a d\theta}{\int_{\theta_0}^{\theta_1} M_n d\theta} \cdot 100\% \tag{1}$$

where the M_n is knee moment people need and M_a is assisting moment when climbing the stairs. As the first 35% of gait cycle is the assisting period when people need extra help most. The θ_0 and θ_1 are in accord with the knee degrees on the time of 0% and 35% gait cycle. Thus, the numerator represents the energy the exosuit has provided and denominator is the total energy the wearer needed during this period. η is the mean efficiency of assistance for people climbing the stairs. The dashed line in Fig.8 indicates the existed mean moment needed for knee joint extension [4]. And the thin solid line shows the assisting moment. Based on the measured and referenced needed assisting moment, the mean assistance efficiency of the exosuit is calculated to be 29.8%.

V. CONCLUSION

In this paper, we have developed a knee exosuit that can be easily applied to assist the elderly climbing the stairs in the daily life. We also have designed the lightweight actuator based on multiple twisted strings and the practical evaluation of the actuator has been conducted. The whole weight of the actuator is 390g. Thus, the actuator obtains the advantage of lightweight and better portability, in which enables the actuator to be used in portable exosuit system. All the soft suit, sensors, two twisted string actuators, control unit and batteries can be packed into a knapsack, and the whole weight is 3.5kg (The batteries weigh 0.75kg). It is easy for people to carry and use in the daily life. The exosuit has a mean assistance efficiency of 29.8% when the user climbing the stairs at the normal speed.

In the future, our goal is to improve the identification of human intention and provide the variable assist torque in synchrony with the aged people needed during the climbing process. We will also widen the practicability of the exosuit to adapt to the outdoor environment.

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