A Portable Soft Exosuit to Assist Stair Climbing with Hip Flexion

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Abstract: Soft exosuits are an emerging class of robots that have been shown to significantly reduce the metabolic cost of daily human movement. However, most soft exosuits are currently being studied for walking and running, and relatively minor research has been carried out on exosuits for stair climbing. Numerous exoskeletons used for stair climbing have a more rigid structure and are heavier, which may result in a greater force required by the wearer to overcome the weight from the exoskeleton when ascending stairs, which can result in metabolic costs. As a result, a reduction in rigid structures can reduce the weight of the exoskeleton and further reduce metabolic costs during stair climbing. In this paper, a waist-wearable soft exosuit was designed that assists hip flexion to aid stair climbing in older adults, in order to demonstrate the importance of choosing to assist hip flexion during stair climbing. An admittance delayed feedback control method was also proposed to use the angular information measured by the IMUs to enable the exosuit to adapt to different staircases. Metabolic experiments have shown that people who use soft exosuits have an average decrease of 6.9% in metabolism when they climb stairs than those who do not. The muscle fatigue experiments demonstrated a reduction in muscle fatigue of approximately 9.35%, 38.75% and 9.65% for the rectus femoris, lateral femoris and gastrocnemius muscles, respectively, when compared to cases without the soft exosuit. The results show that assisted hip flexion during stair climbing is a reasonable approach to effectively reduce metabolic consumption and muscle fatigue.

Keywords: soft exosuit; stair climbing; hip flexion; metabolic rate; muscle fatigue

1. Introduction

With progress in science and technology, a growing number of wearable lower limb exosuits have emerged, including those for assisting daily functions such as walking and running [1,2]. Some researchers are also investigating how to identify different terrains for exosuit control with depth cameras to further enhance the usefulness and versatility of exosuits [3]. At the same time, researchers are constantly optimizing and improving the actuator of the exoskeleton system. Jung-Wook Suh et al. [4,5] mentioned a harmonious nonlinear cable actuation structure to mechanically provide the required cable actuation length without increasing the number of actuators. During the use of the exoskeleton robot, higher stresses cause damage to the entire robot structure. To solve this problem, Ref. [6]...
proposed a fish-tail-inspired method to optimize the stress distribution along the serial compliant joints. The team then used 3D topological optimization techniques to optimize the robot’s flexure joints and enhance the torsional stiffness of the continuum robot [7]. With the application and development of the aforementioned technologies in the field of exoskeletons, exoskeletons can better assist the wearers in their daily life. Stair climbing is also a demanding physical activity that is often performed as part of a daily routine. Considering that many countries are experiencing a rapid increase in the population of elderly people, an exosuit that can help elderly people with ascending stairs becomes important [8]. The exosuit should work in the real world, and must be lightweight, have an independent power supply, be easy to wear, etc. The exosuit should also have high safety and reliability, because the exosuit directly acts on the human body [9]. Therefore, the choice of a soft exosuit as an aid has advantages over a rigid exoskeleton [10].

Soft exosuits have been developed to assist multiple joints. Depending on the number of assisted joints, soft exosuits can also be classified as single-joint assisted or multi-joint assisted [11]. Enguo Cao et al. designed a multi-resiliency exoskeleton to assist uphill walking and stair climbing [12], and this exoskeleton system was designed based on inverse kinetic estimation of design parameters. Marshall K. Ishmae et al. designed a hip exoskeleton that utilized high torque for walking, running and stair climbing [13]. Ying Fang et al. designed an ankle exoskeleton to help people with cerebral palsy walk up and down stairs and improve their motor performance [14]. Hanseung Woo et al. designed an exoskeleton that assisted both hip and knee joints, in order to assist healthy young adults in stair climbing [15]. Ronnapee Chaichaowarat et al. designed a smart passive rigid knee exoskeleton that used the knee braking torque to assist stair climbing [16]. All the above mentioned exoskeletons or exosuits have shown good performance, which also reflects the ability of exoskeletons to assist different joints. However, these exoskeletons are heavy, difficult to wear and take off, and cause a lack of safety that can affect the elderly when going up stairs. Based on these factors, a soft exosuit with a wearable waist was designed to help hip flexion while climbing stairs.

Assisted force trajectory control is another major factor affecting the soft exosuit. In previous studies, it has been shown that the metabolic rate of exosuit wearers can be reduced by giving them timely and appropriate auxiliary forces during exercise [17]. This requires the controller to be stable and robust. Bokman Lim et al. designed a delayed output feedback control based on hip exoskeleton gait assistance, which could be applied to the change of the user’s walking pattern [18]. However, this algorithm required constant tuning of the control parameters to achieve good control. Jiang Han et al. designed a lower limb exoskeleton robotic system based on a fuzzy two-degree of freedom control method that could perform adaptive deterministic robust control [19]. However, this approach required elevated performance in the controller, which increased the size and weight of the controller, leading to an increase in the overall weight of the exoskeleton and causing discomfort to the wearer. Ye Ding et al. designed a soft exosuit based on iterative control of hip joint extension based on IMU parameters. This control method could provide a predefined assistant profile to assist hip joint extension [20]. However, this exoskeleton system was based on a laboratory platform and this control method relied on the choice of IMU parameters and data parameters, meaning this option was not suitable for practical scenarios.

Based on the aforementioned issues with exoskeletons or exosuits, a soft exosuit system was designed to help hip joint flexion. The admittance controller and proportional differential control, which were designed before, were added to this system [21] and, on this basis, delayed feedback control was added. The proposed method was able to adapt to changes in stair form and improve the auxiliary force profile through feedback from changes in hip angle to adapt when climbing different stair forms. In this paper, the soft exosuit system was used to address the increase in metabolic consumption and muscle fatigue in the elderly during walking upstairs. The overall structure of the article is as follows. Section 2 introduces the soft exosuit prototype, the analysis of the auxiliary force strategy and the control strategy. Then, Section 3 illustrates how the performance
of the flexible exosuit was evaluated through metabolic consumption and sEMG signal experiments [22]. In Section 4, we discuss the comparison between this exosuit system and other exosuit systems. Finally, Section 5 summarizes the whole paper.

2. Exosuit System

The portable soft exosuit was designed to assist the hip flexion during stair climbing. To improve the robustness of the soft exosuit, we intended to use various sensor data information to compute the gait pattern of the wearer and the gait phase delay feedback method [18] to track the assistant force trajectory and provide the assistant torque in real time [23]. In this section, we describe in detail the design concept, system overview, auxiliary force trajectory generation and control strategy of the soft exosuit.

2.1. Portable Soft Exosuit

The whole system mainly consisted of six parts: wraps (shoulder wrap and hip wrap), actuation system, controller, IMUs, load cells, and Bowden cable, as shown in Figure 1.

![Figure 1. Illustration of the soft exosuit system.](image)

The exosuit system weight was 2.32 kg, and it contained a battery with a voltage of 24 V and a weight of 300 g. Because the system was primarily made of flexible materials, there were fewer restrictions on the wearer [24]. The masses of the major components and their positions are shown in Table 1.

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass (kg)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waist belt</td>
<td>0.32</td>
<td>Waist</td>
</tr>
<tr>
<td>Actuator</td>
<td>0.314</td>
<td>Waist</td>
</tr>
<tr>
<td>Battery</td>
<td>0.30</td>
<td>Waist</td>
</tr>
<tr>
<td>MCU</td>
<td>0.08</td>
<td>Waist</td>
</tr>
<tr>
<td>Conduits</td>
<td>0.052</td>
<td>Waist</td>
</tr>
<tr>
<td>IMUs</td>
<td>0.024</td>
<td>Thigh</td>
</tr>
<tr>
<td>Wraps</td>
<td>0.48</td>
<td>Thigh</td>
</tr>
<tr>
<td>Load cells</td>
<td>0.05</td>
<td>Thigh</td>
</tr>
<tr>
<td>Other component</td>
<td>0.7</td>
<td>Waist</td>
</tr>
</tbody>
</table>

In order to solve the problem of weight and comfort when wearing the soft exosuit, the controller, motors and energy components, which accounted for most of the weight of
the whole system (2.32 kg), were fixed in the waist protection shell of the wearer. Since the center of gravity of the human body is at the waist, the main actuator of the exosuit (most of the weight) was placed in the waist protective shell and attached to the waist by the belt. By setting an anchor point suitable for force on a rigid part of the human body and then designing a force transfer path using flexible materials, the driving force of the driver was transferred to the anchor point through the Bowden cable, which could realize the flexible binding and transfer the power torque [25,26]. At the same time, the shoulder wrap was used to transfer part of the weight to prevent the waist discomfort in the waist when applied by the assistant force. The entire exosuit system was loaded by multiple joints of the whole body to improve the comfort of the exosuit.

(1) **Actuation system**: The actuation system consisted of two high-power low-inertia motors (M2006, DJI, China) that assisted the flexion of the left and right hip joints. Each motor was connected to a 36:1 ratio gearbox to drive a reel (radius of 10 mm). The structure converted the torque generated by the motor into auxiliary force, which was transmitted to the thigh wraps via Bowden cable outlets. The Bowden cables used high-rigidity casing on the outside and steel wire (lasso) on the inside. The externally rigid casing ensured that the casing was practically incompressible along its length and when the casing was held in place, the wire inside transmitted force;

(2) **Controller**: The microcontroller (Robot Master Board A, DJI, Shenzhen, China) used CAN communication technology to receive the measurement data of IMUs and load cells and generate the desired force profile by calculation;

(3) **Sensors**: Two IMUs (LPMS-B2, I/O Research Corporation, Tokyo, Japan) were fastened to the thigh wraps to measure the wearer motion station at 100 Hz sampling frequency. Then, the data transfer between the IMUs and the microcontroller was carried out through the Bluetooth connection. The load cell (ZNLBS-v1, Chino Sensor, China) was connected between the Bowden cable and thigh wraps, and was integrated with the IMUs in black box. When the motor drove Bowden cable recovery, assistant force was generated to promote hip joint movement. The load cell measured the tensile force exerted on the textile and returned the measured data to the microprocessor via a signal amplifier.

2.2. Hip Joint Angle Perception and Assistant Force Trajectories

When people go upstairs, a regular gait cycle is formed [27]. In this paper, the gait of going upstairs is divided into two stages (support stage and swing stage). Taking the single leg of the left leg as an example, the gait of going up stairs includes five moments: heel landing (HL), foot flat (FF), heel off the ground (HOG), toe off the ground (TOG), and heel landing again (HLA). The moment when the left heel touches the step and the moment when the left toe leaves the step are called the support phases. The moment when the left toe leaves the step to the moment the left heel touches the step again is known as the swing phase. The main poses during an entire gait cycle are shown in Figure 2.

Andriacchi et al. and Livingston et al. reported that subjects required greater hip flexion to climb stairs. The maximum hip flexion occurred from 60.45% to 100% of the gait cycle [28,29]. The maximum average hip angle was 65.06 and the maximum hip extension moment was 0.76 (Nm/kg) when going up stairs [29]. Because a soft exosuit does not interfere with the wearer’s gait when providing assistance, the hip joint angle can be used as a basis to provide appropriate and real-time assistance such as the lower extremity exosuit [30]. In this paper, an algorithm is designed to generate the auxiliary force trajectory. The gait phase on the stairs is divided into several phase points (based on hip joint angle) [31], as shown in Figure 3.
Figure 2. Schematic diagram of the division of a single gait cycle up the stairs. (a–e) stand for heel landing (HL), foot flat (FF), heel off the ground (HOG), toe off the ground (TOG) and heel landing again (HLA), respectively. (f) represents the beginning of the next phase.

Figure 3. According to different gait angles, the soft exosuit generates different force assistance. The unit of Nm/kg is the normalization of torque, in order to produce different torque sizes according to different weights of people.

The curve \((n + \sin(\text{phase} \cdot \pi/a - \pi/b))\) is used to generate the auxiliary force trajectory, where \(\text{phase}\) is the current stair phase, and \(n, a\) and \(b\) are the parameters set by the user (according to different stair spacing, height and slope). After detecting a change in the phase point, the system sends information about the current phase point to the microprocessor every 0.05 s. Based on the recorded data, the specific formula for calculating the required auxiliary force at the present moment can be expressed as follows:

\[
F = f_p \cdot (n + \sin(\text{phase} \cdot \pi/a - \pi/b)/2)
\]

where \(F\) represents the actual generated assistant force produced by the motor, and \(f_p\) represents the ideal assistant force, which is calculated by the assistant force algorithm with the hip joint angle.

2.3. Control Strategy

Compared to traditional industrial robots, the lower-limb exosuit robots have multi-input and multi-output mechanisms with high uncertainty and nonlinearity, thus placing high demands on the control capabilities of the motors. Cao et al. improved the iterative learning approach and used a hierarchical control strategy to control the soft
exosuit [21]. Chen et al. simplified the iterative learning control strategy [32]. In this exosuit system, the iterative learning control strategy is simplified and the admittance delay feedback strategy is added. Based on the admittance control, the corresponding delay feedback control is further added. Delayed feedback can handle sudden changes in gait when the height of the staircase changes, allowing the soft exosuit to generate more accurate auxiliary force control. The soft exosuit control system is shown in Figure 4. The proportional differential (PD) admittance controller can improve the performance of the exosuit control system. The PD admittance controller formula is as shown in Equation (2):

\[ u_t = K_p e_t + K_d \Delta e_t \]  

(2)

where \( K_p \) represents the proportional controller and \( K_d \) represents the differential controller.

![Figure 4. The soft exosuit control system.](image)

\[ F_{\text{meas}}: \text{Measured force}, \quad F_{\text{des}}: \text{Desired force}, \quad e_f: \text{Force error}, \quad P_t: \text{Target position of the motor}, \quad P_M: \text{Measured position}, \quad \theta_{\text{meas}}: \text{Measured angle.} \]

When the exosuit system started to function properly, firstly, the angle of the hip joint was obtained through IMUs to analyze the gait information of the human body and generate the current gait phase data for the staircase. Then, following the power-assisted trajectory generation strategy introduced in the previous chapter, an auxiliary force was generated to help the users to reduce metabolic costs. When the state of the stairs (step height, step slope) changed, the angle of the hip joint was also altered. At this time, the delay feedback system was triggered, and the control system updated the assistance information to change the magnitude of the assistance force and the assistance time in real time. The system also reduced errors based on force feedback and motor position feedback.

3. System Validation

We validated the performance of the exosuit system through two experiments on an electric stair machine. In the first experiment, we measured the level of metabolic expenditure during stair climbing to validate the applicability of the soft exosuit. In the second experiment, we used a surface EMG signal to measure the fatigue of the relevant muscles during stair climbing, thus reflecting the reliability of the soft exosuit during stair climbing.

3.1. Metabolic Test

3.1.1. Preparation for Experiment

Four subjects participated in the metabolic test experiment. The subjects were not physically unwell on the experiment day and had no additional medical history or adverse habits. The basic conditions of subjects are shown in the Table 2.
Table 2. Basic conditions of subjects.

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Gender</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Age (Years Old)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>Male</td>
<td>174</td>
<td>76</td>
<td>24</td>
</tr>
<tr>
<td>YS</td>
<td>Male</td>
<td>179</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>FL</td>
<td>Male</td>
<td>177</td>
<td>78</td>
<td>28</td>
</tr>
<tr>
<td>SC</td>
<td>Male</td>
<td>181</td>
<td>74</td>
<td>24</td>
</tr>
</tbody>
</table>

As shown in Figure 5, we conducted the experiment on an electric stair machine. Metabolic rate was calculated using the Wearable Metabolic System (COSMED K5, Rome, Italy), which measured metabolic rate by analyzing the concentration of oxygen \( \text{O}_2 \) and carbon dioxide \( \text{CO}_2 \) during exhalation and inhalation during use. Based on the obtained data, the calibrated Brockway equation (Equation (3)) \(^{[33,34]}\) was used to calculate the time the subjects required for climbing the stairs:

\[
E_{\text{Metabolic}}(W) = \frac{(k_1 \text{VO}_2 + k_2 \text{VCO}_2)}{60} \tag{3}
\]

where the \( E_{\text{Metabolic}} \) is the energy consumption rate, coefficients \( k_1 \) and \( k_2 \) are 16.68 and 4.51 respectively, and \( \text{VO}_2 \) and \( \text{VCO}_2 \) are the volumes of oxygen in and carbon dioxide out, which were measured through K5 Metabolic System.

![Figure 5. The metabolic experiment of soft exosuit with K5 Metabolic System on an electric stair machine.](image)

In order to reduce the disturbance to the metabolic rate, the experiments were performed on two days, one for training and the other for testing. Training days were necessary to familiarize subjects with the functions of the soft exosuit and the use of the electric stair machine \(^{[35]}\). The main task of the training day involved subjects wearing a soft exosuit and then performing a stair-climbing test using an electric stair machine for at least 10 min. On the test day, the experiment involved climbing stairs on an electric stair machine with or without the exosuit. Each trial lasted 20 min. The subjects remained in a standing position for the first 5 min and were asked to climb stairs for the second 15 min to measure the metabolic rate of the exercise. The calculations were based on the 4th to 8th minutes of the standing stages and 9th to 20th minutes of the stair-climbing stages. The calculated net
The metabolic rate was the metabolic rate when climbing stairs minus the metabolic rate when standing. Since the degree of muscle fatigue can affect the accuracy of metabolic experiments, the subjects needed sufficient rest time to recover from muscle fatigue. Therefore, a half-hour rest period was maintained between each experiment to ensure adequate rest for the subject. On the day of the experiment, each subject was assigned a random order.

3.1.2. Metabolic Result

The choice of assisted time and the magnitude of the assistant force were critical for reducing the metabolic cost of the exosuit [36]. The metabolic consumption of all subjects is shown in the Figure 6. Four subjects performed metabolic tests under three conditions: wearing the exosuit without assistance, not wearing the exosuit and wearing the exosuit with assistance. The results showed that, under the condition of wearing the exosuit with assistance, the metabolism of the four subjects on the stairs was reduced, and the metabolic reduction of YS was the largest, reaching 15.9%. The average reductions in the condition of NO Exo and With Ass were 6.9% and 11.8% compared to wearing an exosuit without assistance.

![Figure 6. Experimental data on metabolic expenditure for four subjects. * denotes statistical significance (p < 0.05) between two bars.](image)

3.2. Electromyography Measurement

During stair climbing, muscle fatigue increases over time, which can lead to a loss in muscle strength. This limits the completion of the exercise task [37]. Although indirect calorimetry-based metabolic cost can assess the performance of the exosuit, it is difficult to visualize the effect of assistance due to the insufficient sampling frequency of the device and the perspective of external influences [38]. Therefore, surface electromyography (sEMG, sampling frequency of 1000 Hz) was used to collect surface electromyography signals and analyze the degree of muscle fatigue [39]. A wired portable sEMG (PS850, biometrics Ltd., Newport, UK) was used to monitor corresponding muscle activity in the lower extremities at a sampling frequency of 1000 Hz. The sEMG electrodes were attached to the muscles of the left leg, including the rectus femoris, vastus lateralis and gastrocnemius, which are commonly used for stair climbing [40].
The procedure for the sEMG experiment was similar to the metabolic procedure described above. In the muscle fatigue experiment, each subject was required to complete three 10-min tests, each in a different state, to ensure that stable experimental data were collected. After that, the results of measuring human muscle fatigue using sEMG signals on an electric stair machine, which were generated by the soft exosuit. The formula used to calculate the RMS of sEMG is as follows:

\[ EMG_{RMS}(n) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} sEMG(i)^2} \]  

where \( sEMG(i) \) is the experimental data collected by each muscle.

Because the collected raw EMG signal collected contained electrical noise, the sEMG signal was first filtered through a low-pass filter to remove the physiological noise, environmental noise and baseline noise [23]. Since the sEMG signal was mainly used for evaluation, the signal was processed using time domain analysis, i.e., the RMS value of the EMG signal was calculated. The root mean square (RMS) of EMG was chosen as the main index to quantify muscle fatigue [41], as shown in Figure 7.

Figure 7. The degree of muscle fatigue was obtained using sEMG. Muscle RF, VL and GAS represent the rectus femoris, vastus lateralis and gastrocnemius muscles, respectively. Without Exo and Exo Assist denote the states without exosuit and with exosuit with assistance, respectively. Initial state represents the initial muscle fatigue level before the test. * denotes statistical significance (\( p < 0.05 \)) between two bars.

It was found that the muscle fatigue levels were reduced by about 9.35%, 38.75% and 9.65% with the use of the lightweight soft exosuit compared with no exosuit. The results show that the exosuit system is effective in reducing muscle fatigue in the wearer when climbing stairs.

4. Discussion

In this study, a soft exosuit system was proposed that assists in stair climbing; the system is lighter and more comfortable to put on and take off than other stair-assisting exosuits. Our team used Vicon (a motion capture device) to capture the motion of the human hip joint when going upstairs, obtaining the angle and torque data of the hip joint going upstairs as a reference for the exosuit system to assist the system, and referenced these data to the exosuit system to provide the appropriate assisting force to the system.
Biologically, human gait requires greater gluteal torque and force as walking speed and incline increase [42]. Climbing stairs requires greater hip torque than walking on level ground [29]. In the experiments, it was demonstrated that the exosuit system could reduce the metabolic cost and muscle fatigue of the wearer when ascending stairs.

In ascending stairs, assisting the lower limb extremity joints to help reduce joint pressure and lower limb muscle work can reduce human metabolic consumption and muscle fatigue. Max Böhme et al. designed a novel exoskeleton robotic system [43] to assist stair climbing using knee joint angles, moments and reaction force characteristics, and measured surface EMG signals, showing an average reduction of 19.3% in knee extensor muscles with the assistance of this exoskeleton system. However, the exoskeleton system used a rigid structure and the weight of the exoskeleton for each leg reached 6.1 kg, which caused discomfort to the wearer. At the same time, the exoskeleton relied more on customization to suit the user’s needs. Conversely, our soft exosuit system, with its lighter weight, has no effect on the wearer’s lower-limb freedom of movement and is more suitable for daily stair assistance. Sikai Zhao et al. designed a soft knee exosuit with twisted string actuators for stair climbing assistance [44]. The exoskeleton system was based on bionic principles and was designed with a novel structure that simulated human muscle contractions to provide additional strength to the human lower limbs. The overall weight of the system was 3.5 kg and the average efficiency of the assistance was 29.8%. Although the system was lighter in weight and had a good assistant effect, the team did not carry out further metabolic cost and muscle fatigue tests. Our soft exosuit system, based on an electric stair machine, was subjected to metabolic and muscle fatigue tests, which demonstrated that the soft exosuit system could assist the wearer well on stairs. Payman Joudzadeh et al. designed a cable-driven lower limb exoskeleton (ADAMS) for stair climbing [45]. The total weight of the exoskeleton system was 13.5 kg, which increased the torque that the body needed to overcome while climbing the actual stairs, causing unnecessary energy expenditure and muscle fatigue. Although the exoskeleton system reduced the target muscle fatigue by 28% in the sEMG experiment, it lacked practical application effects. In contrast, our soft exosuit system is lighter and designed to enhance the safety of the exosuit. Reducing the weight of the exosuit effectively reduces the fatigue level of the target muscles.

Although our assisted hip flexible soft exosuit system has been implemented for metabolic reduction and muscle fatigue reduction, this work has some limitations. First, the soft exosuit used in the experiments was tested only functionally, not for mechanical stability and system durability. Second, there is still room to reduce the overall weight of the soft exosuit. The current weight causes slight discomfort to the wearer when used. In the future, the weight of the soft exosuit will be reduced by optimizing the mechanical structure and control units. Finally, the evaluation experiments were conducted only on an indoor stair machine, and it is expected that much of the usage will be conducted outdoors.

5. Conclusions

In this paper, an assistive hip flexible soft exosuit for stair climbing was proposed. By obtaining hip joint angle information through an IMU strapped to the thigh, it was possible to generate an assisted torque suitable for stair climbing, considering the interaction between the human and the exosuit using an admittance feedback control algorithm. We conduct experiments on metabolic cost and muscle fatigue. The results of the metabolic cost experiments showed that the average metabolic cost rate of the soft exosuit system was reduced by 6.9% when going upstairs on an electric stair machine compared to not wearing an exosuit. Muscle fatigue experiments showed that wearing a soft exosuit reduced the fatigue of the rectus femoris, lateral femoris and gastrocnemius muscles by approximately 9.35%, 38.75% and 9.65%, respectively, compared to values without a soft exosuit. Therefore, this paper demonstrates the effectiveness of the exosuit system. The exosuit system improves comfort and reduces the weight of the entire system as much as possible while ensuring control efficiency. In the future, we plan to measure the effect of
the exosuit on the metabolic cost in the stair climbing mode at different speeds and further measure the effectiveness of the exosuit in assisting different stair states in a real-time environment to further improve the exosuit’s assistance performance. Finally, we will attempt to apply the soft exosuit to the elderly to validate the role of the exosuit system in assisting the elderly while using stairs.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Sample Availability: Samples of the exosuit system are available from the authors.

Abbreviations
The following abbreviations are used in this manuscript:

IMU Inertial Measurement Unit
STM32 STMicroelectronics 32-bit Series Microcontroller Chip
PD Proportional-Derivative
sEMG Surface Electromyography
RMS Root Mean Square

References


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