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Stair-climbing Auxiliary Device with Self-adaption

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***Abstract*—With the aging of the population becoming more and more serious, it is necessary to design a device to reduce the risk of low-back injury during stair-climbing process. Most of the existing devices maybe inferior in case the application scenario lacks space, so a more compact and user-friendly device is needed. A power-assisting device is introduced to support elder people lacking in physical strength during stair-climbing process. This study presents a new device suitable for daily application. Firstly, the structure of the device is presented and tested in simulation environment. Then, an adaptive controlling algorithm is developed to keep the output in accordance with motion pattern of the user. Finally, the robustness of the algorithm is verified through simulation.**

***Index Terms*—Dynamics, Exoskeleton, Robotics, Stair-climbing**

I. Introduction

In recent years, researches have shown that the aging is accelerating, and with the aging of the population, problems such as the lack of old-age care facilities, shortage of medical facilities, and shortage of nursing resources have occurred [1]. Among them, the lack of auxiliary facilities for the elderly is prominent. Building climbing is an activity that requires higher physical fitness. In areas where infrastructure is weak, most of the residential buildings are multi-storey buildings without elevators. Daily climbing remains a big obstacle for the elderly.

Stair-climbing mainly involves the muscles of the lower extremities, especially those of the knees. However, many elderly people have insufficient strength in their lower extremities. With the degradation of their physical functions, there tends to be various problems with lower extremities, which seriously affect their climbing movements.

A. Stair-climbing assisting device

Some researchers have applied wearable exoskeletons in the scene of assisted climbing. The Berkeley lower extremity exoskeleton device (BLEEX) has been used to enhance the exercise performance of the human body through strengthening the lower extremities [2] [3].

The University of Tsukuba and Cyberdyne have jointly developed the HAL exoskeleton kit for a series of activities such as stair climbing. Using high-precision sensors to make contact with the user's skin surface, it can collect real-time user data. The EMG signal is summarized through a large amount of previous data, and the corresponding relationship between the signal and the user's movement intention is obtained. At present, the HAL exoskeleton kit has been promoted in Japan in a small area, and has a good effect in a series of activities such as stair climbing. It has been used in clinical medicine [4].

B. Human dynamic model

Chen [5] collected and analyzed the plantar reaction force of the upper and lower floor of the stroke patient by designing the shoes with the implanted sensor, and summarized the force distribution pattern of human foot in different walking processes. Dusenberry [6] analyzed the influence of different handrail shapes on grip performance and human walking posture. Chen [7] proposed a new type of handrail rehabilitation system.

In recent years, some researchers have proposed novel theories on the ergonomic model. Yue Hu proposed a compliant analysis model with variable stiffness [8] [9]. Randa Mallat proposed a model to identify inertial parameters of the wearer and exoskeleton [10]. Paul Manns proposed a parameter identification model, which predicts human motion through a computational model, thereby simplifying the designing process [11].

C. Pattern recognition algorithm

Ghannadi [12] introduced a controller working with physics-based models. A minimal-intervention-based admittance control strategy is developed by Wu [13] to induce the active participation of patients and maximize the use of recovered motor functions during training. Guerra [14] developed an accurate approach for classifying UE functional movement primitives, which comprise functional movements.

It can be concluded from the above research that various power assisting equipment for climbing-related activities have been developed, but most of them have some limitations. Firstly, many devices are mostly aimed at medical or military scenarios with wide range of applications, which comes with poor pertinence and limited performance under specific circumstances. Secondly, most of the devices are relatively bulky, and they are not flexible enough for use and operation in relatively narrow corridor spaces. In addition, operations are complicated, which are unsuitable for daily use. Finally, high

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cost is likely to prevent them from large-scale application and popularization.

II. Proposed Approach

In this paper, an upstairs booster device is proposed with adaptive control. Firstly, the structure of the device is presented according to actual scenario. Since the prototype is tested by the tester after its completion to perform theoretical and experimental comparisons, the parameters of human body are based on the testers body during calculations. Therefore, it is necessary to calculate the motor for a certain working condition. The calculation is based on ideal simulation environment, while the prototype test is performed in reality. Therefore, when designing the output parameters, only output range is given and relaxation is made to ensure redundancy.

According to the use scenario, the structure of the prototype is designed. In this paper, the main focus is to ensure that the device verifies the previous theory, that is, to ensure the reliability of the device. From the above, the structural design can be divided into several parts, the design of the clamping and fixing mechanism, the design of the human-machine interaction, and the failure security protection. The design of the clamping and fixing mechanism is crucial, which guarantees the reliability of power transmission and is a prerequisite for later comparison between experiment and theoretical analysis.

Somatosensory operation is mainly achieved by the control system. The stair climbing walker adopts a closed-loop control system with output traction as a control target. Due to the relatively compact size of the device, setting the torque sensor at the motor end severely affects the structural design. On the other hand, the addition of the sensor greatly increases the load inertia and also affects the actuator. Considering that the purpose is to ensure the force acting on the user, feedback signal is derived from sensors set at the hand. To avoid oscillations, the feedback signal is filtered. Somatosensory operation is adopted, so the grip force is used as an input signal for force control, and traction force is measured by another force sensor to generate a feedback signal. Additionally, multiple stages are used to prevent frequent system adjustments resulting in control instability or component fatigue failure.

The simulation environment is verified, and a staircase physical model is set up as an experimental test scene. Using the motion capture system, the feature point tracking extraction is performed for the human body climbing motion in the experimental environment. In order to ensure the universality of the experimental test, testers with different physical parameters use the device to test and adopt different climbing strategies. In the testing process, strict adherence to the principle of single variable is used to test the effect of different usage factors on the effectiveness of the device during actual use, and this is used as a design basis for iterative design of control algorithms.

The simulation environment is built to verify the algorithm. Model of the stairs is built as test scenario. Using the motion capture system, motion tracking is performed during the climbing cycle. To ensure the algorithm is robust under multiple circumstances, testers with different physical parameters and climbing habits are invited to test the device. Effect of different usage habits on the device's performance is recorded and used in the iterative design of the control algorithm.

In this paper, the proposed device has the following features:

- Portable size fit for multiple scenario. The device adopts a crank slider structure which can adapt to various handrails within a certain size range.
- Adaptive control algorithm. With climbing cycle divided into four main stages, the device can stay in accordance with the users climbing pattern under multiple circumstances.
- Fail-safe mode in all conditions. In cases where the device malfunctions, the fail-safe mode can ensure users safety as well as the devices.

To save the torque needed in climbing, the maximum traction force should be 120N. According to related studies [15], the average climbing speed of the elderly is about 0.52m/s, and this speed is used as the target output maximum speed.

A. *Clamping Mechanism*

Since the application object is the handrail in old residential staircases, it should possess some adaptability to round handrail within a certain size range and can clamp firmly. After the clamping is completed, the device can perform a series of actions on the handrail. In usual stair-climbing process, the upper limbs have upward force on the handrail. Therefore, there is a tendency to pull the device out of the handrail during the use of the device, and it is necessary to secure the clamping during the process. The device must generate a force directed at the handrail to prevent it from disengaging.

Based on the above considerations, the clamping device needs to position and clamp the armrest from at least three directions. Considering the fact that there is a mounting bar below the handrail in the actual situation, it is necessary to avoid the corresponding area during the clamping process. Therefore, the upper and lower sides are suitable for clamping.

In the meantime, the size and shape of the handrail is changing all the time, so adaptability must be considered. In order to meet a certain degree of adaptability, the clamping mechanism should be functional within a certain range and perform clamping. Commonly used clamping mechanisms are listed and compared in Table 1, along with their features.

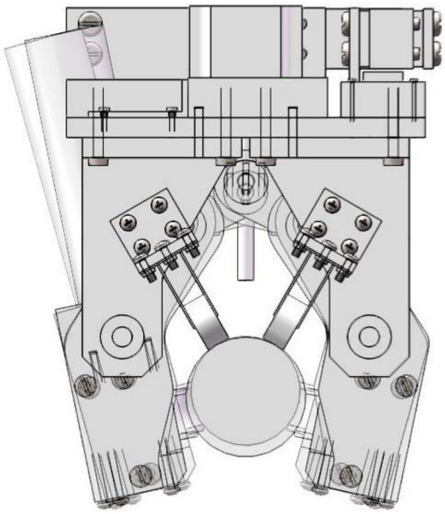

Fig. 1. Adaptability of the device to handrails of different size

TABLE I
COMPARISON BETWEEN DIFFERENT CLAMPING MECHANISMS

Method	Pros	Cons
Linkage	Adaptability	Large size
Cam	Reliable Clamping	Line contact friction with high attrition rate
		Require large drive torque
Track	Guiding structure with smooth motion	Poor adaptability

Through the comparison in Table 1, the stair-climbing power assisting device adopts a linkage mechanism for clamping. The mechanism adopts a crank slider structure, and the slider drives the rotation of the crank through up and down linear motion, and the contact surface is at the end of the crank. During the rotation process, the direction of the clamping force constantly changes, and at the same time the end of the crank constantly approaches the handrail to be clamped, resulting in a pressing force perpendicular to the axis of the armrest, ensuring that the device can generate sufficient friction on the stair armrest.

The device directly interacts with the user. Therefore, safety is one of the key points of the design. It is more important to ensure that the device is clamped under non-signal control conditions. In order to ensure that the system can maintain the clamping state even if the control mechanism fails. The slider drive part uses a stepper motor to drive the screw nut to form a linear motion. This design is based on the following considerations.

Firstly, the screw nut drive pair has the characteristics of self-locking. In case the stepper motor does not provide the drive torque, the position of the nut and the screw can still be relatively fixed, effectively ensuring the clamping state of the clamping mechanism.

Secondly, the screw nut movement is relatively smooth. Since the screw nut is trapezoidal thread, which changes the rotation to a linear motion, the drive is relatively stable. At the same time, the screw nut drive also plays a role in torque amplification, and increase the clamping force.

Thirdly, the stepper motor is easy to control and can reduce the cost of the device to some extent. Stepping motor rotation corresponds to the input signal pulse, which means the control method is relatively straightforward and it has high open-loop accuracy. At the same time, the stepping motor has a large static moment when not operating, which can also improve the clamping effect to some extent.

The upper part of the device is equipped with four driven wheels, which are mainly used to help the device maintain the original posture on the handrail. When the user's hand leaves the device, the structure can ensure safety of the device and the user. Considering stress situation of the device during performance, the structure of the driving wheel is given. When going upstairs, the device is pulled, which means the lower clamping structure generates the main contact force. When designed in the lower position, the driving wheel can make the best of contact force to produce greater traction without slipping.

Fig. 2. Structure of stair-climbing auxiliary device

B. Kinetics Analysis

Analyzing the process of stair-climbing, it can be concluded that under the state where both feet are on the ground and one foot is about to leave the ground, the force of the human knee is near the maximum value, and the traction output of the power assisting equipment is at the maximum. Therefore, load calculation is performed at this point as the maximum operating condition.

According to D'Alembert principle, we have

$$\sum_i C_i \cdot \delta r_i = 0 \tag{1}$$

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For stair-climbing process, D'Alembert principle is transformed to be

$$\sum_i (F_i - m_i a_i) \cdot \delta r_i = 0 \tag{2}$$

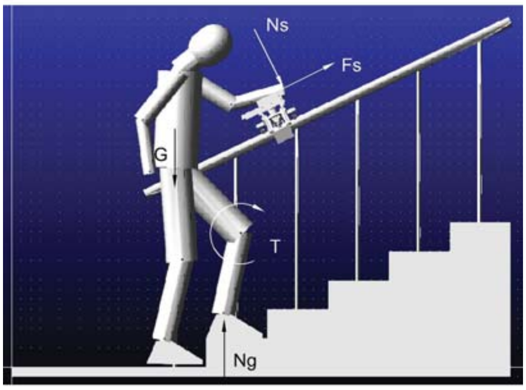

Fig. 3. Force analysis of maximum working condition under simulation environment

Assume that the left hand of the experimenter generates a virtual displacement $\delta_{s\tau}$ in the direction of the stair railing. In the left knee joint, the following results are obtained by the D'Alembert's principle

$$\begin{cases} \vec{\mathrm{F}_s}\vec{\delta_{s\tau}} - m\vec{a}\vec{\delta_m} + \vec{N_s}\vec{\delta_{s\tau}} + \vec{T}\vec{\delta_\theta} = 0 \\ \vec{a} = \vec{a^n} + \vec{a^\tau} \end{cases} \tag{3}$$

where $\vec{F_s}$ denotes traction of the device along the stair railing. $\vec{N_s}$ denotes the contact force of the device perpendicular to the stair handrail. $\vec{\delta_{s\tau}}$ denotes virtual displacement of the device in the direction of the staircase handrail. $\vec{\delta_m}$ denotes virtual displacement of the human body centroid acceleration direction. m denotes mass of the experimenter. $\vec{a}$ denotes acceleration of human body centroid. $\vec{a^n}$ denotes normal acceleration of human body centroid. $\vec{a^\tau}$ denotes tangential acceleration of human body centroid. $\vec{T}$ denotes torque of left knee. $\vec{\delta_\theta}$ denotes virtual angular displacement of left knee.

Substituting the measurement data into the calculation, it can be obtained that under the maximum working position, the traction force in the direction along the handrail has a linear relationship with the torque of the knee joint, and the drawing is as Figure 4.

C. Control Algorithm

The device is used to assist the user in the process of going upstairs and provide the necessary traction during the climbing action. The strength of the upper extremity compensates for the lack of joint strength of the lower extremity. The driving motor is used to assist the user in the entire stair-climbing process and it outputs torque and angular displacement. In order to properly function, its output pattern must stay in accordance with the user's pattern. If the output fails to stay in line with the user's pattern, it may be counterproductive, increase the user's upstairs load, and even cause serious injury, such as muscle strain.

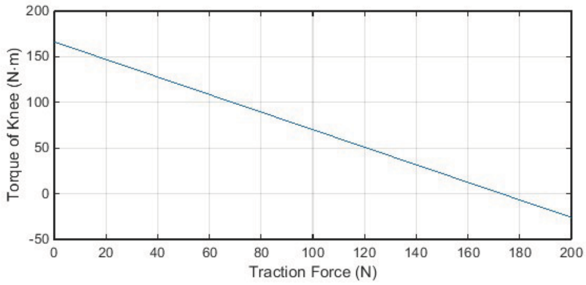

Fig. 4. Linear relationship between traction and force of knee

Apparently, the physical structure and health status of each user is different. The pattern presented in stair-climbing process is not the same. It is necessary to look for general patterns and find a feasible algorithm. Based on different users, the output rules should adjust accordingly. Since the control algorithm of the device is integrated into the device after it is manufactured, it is unrealistic to adjust the original algorithm one by one based on the users differences. The control algorithm must ensure certain self-adaptability under the premise of security.

Motion capture system is used to obtain a series of data such as displacement, rotation angle, velocity, angular velocity, acceleration, and angular acceleration in the process of stair-climbing. Some of the data are plotted as Figure 5.

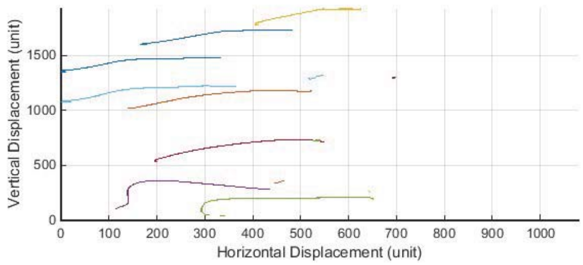

Fig. 5. Track of motion in a single stair-climbing cycle

From the analysis of the collected data, it can be found that during the process, the movement patterns of the various parts show an obvious periodicity, that is, the movement patterns during each cycle are relatively similar to each other. Based on the above reasons, the movement pattern in a single cycle is mainly analyzed.

In accordance with the motion in a cycle during the stair-climbing process, the motion can be roughly divided into the following stages corresponding to the speed and traction, and different modes are adopted in different scenes. In the first stage, the device operates at low speed and low torque, and the traction is control within a certain range. In the second stage, the force on the device is increased, and the traction is controlled to increase at a certain rate while ensuring that the acceleration is lower than the maximum value. In the third stage, constant torque output is provided and the control speed fluctuates within a certain range. In the fourth stage, the output torque of the device is reduced to the set value, and the control speed fluctuates within the range below the threshold.

The controlling algorithm is shown in Figure 6, which consists of four modes, corresponding to four stages.

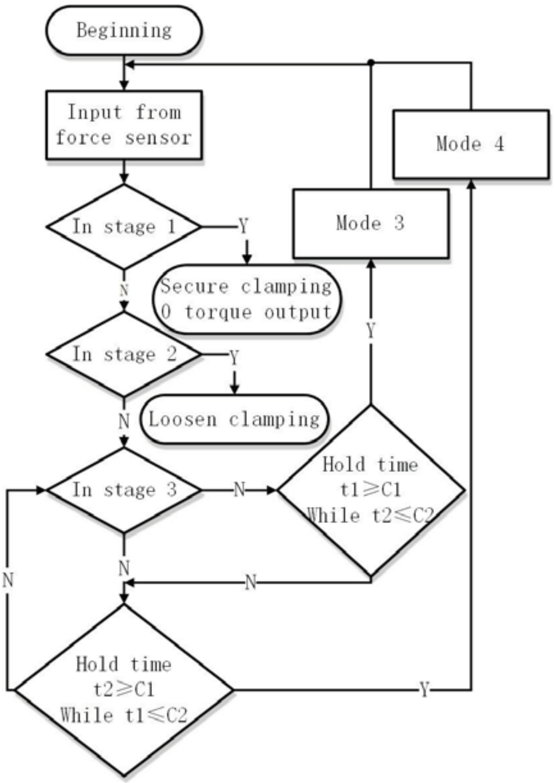

Fig. 6. Four-mode device control logic diagram

To ensure the effectiveness of the simulation, noise is added to the body's effect on the force sensor. A three-dimensional model is built by modeling software and a virtual simulation environment is set up. The dimensions of the stairs and the structure of the handrails in the environment are based on standards of the construction industry and are in accordance with the design and use scenarios. Contact force parameters between materials of the components of the device and contact surfaces are decided based on relevant information such as mechanical design manual.

In the meantime, during dynamic simulation, relevant data of the traction and speed provided by the device's control algorithm is measured and recorded in the simulation environment. In order to verify the universality and stability of the control algorithm, several simulations are performed on the device's assisting process by adjusting the user's physical structure parameters and climbing patterns. The performance is compared, evaluated and quantified before and after the optimization control algorithm is added.

III. SIMULATION

In this section, approaches and designs proposed in this paper are validated through simulation. By running dynamic simulation, the reliability of the device structure is verified. Figure 7 shows the establishment of friction when the clamping mechanism clamps the handrail in the constant torque mode.

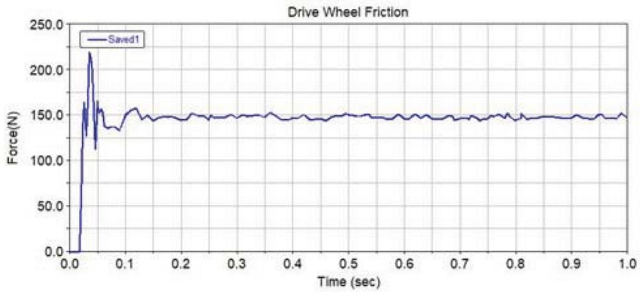

Fig. 7. establishment of friction under constant torque mode

By introducing a control algorithm, the torque and speed output modes of the device are changed. Figure 8 demonstrates the comparison of traction force of the device and hand force of the user in the simulation results. By comparing with the constant torque output mode and the force pattern of the hand in the process of stair-climbing, it can be found that although there is a certain degree of deviation in the beginning and end of the cycle, the control algorithm can track the force of the hand to some extent and the force output in the process is more in line with the pattern of human behavior. After several simulations, it can be found that the algorithm has a certain optimization effect or users with different body parameters and stair-climbing patterns. The algorithm improves the coordination between the device and the user.

IV. CONCLUSION AND FUTURE WORK

This paper has given an account of power-assisting device in stair-climbing. With the structure designed, the device can be used to assist people during stair-climbing process. Algorithm is developed to ensure the device operates in accordance with users climbing patterns. Simulation is run to verify the robustness of the algorithm.

Some problems still need further research. Firstly, prototype needs to be manufactured to test the performance of the

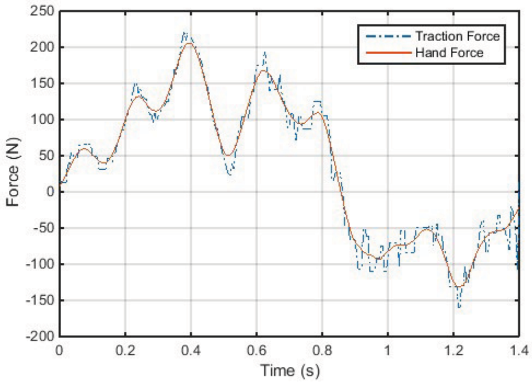

Fig. 8. Hand force compared with traction force during stair-climbing

device in real situation. Secondly, experiment is needed to test the validity of the algorithm. Finally, the algorithm requires further optimization to improve its performance under various working conditions.

In the near future, the above problems will be solved and the device will be improved to realize its designed features.

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