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Master-Slave Control of an Intention-Actuated Exoskeletal Robot for Locomotion and Lower Extremity Rehabilitation

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In this paper, a master-slave control system is proposed and applied in an intention-actuated exoskeletal robot to assist user locomotion and lower extremity rehabilitation simultaneously. In particular, to increase users' sense of participation, the motion of the exoskeleton and the wheelchair, which is denoted as slave motion in this study, is actuated by the user's intention, which is denoted as master motion and thus makes patients feel that they are moving the wheelchair. This master-slave motion control system can help to eliminate patients' fear of medical apparatus and instruments. The bicycling motion actuated by one motor is implemented to realize the rehabilitation motion exercise. Experimental results validate a position-force control strategy for the exoskeleton motors, and show that the proposed method can help users to move around and to exercise their legs simultaneously and effectively.

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NOMENCLATURE

PI= proportional integral
DOF= degree of freedom

1. Introduction

Older people and stroke patients with hemiplegia usually suffer from muscle weakness and gait disorders, [1-3] which can produce a severe burden on their families and on societies. According to the United Nations population percentage report,[4] the number of people over 60 years old will increase to about one billion in 2050, about one-tenth of whom will have locomotion problems. Also, a study conducted from 2004 to 2006 in six European countries found that the annual incidence of first stroke per 1000 population is 1.41 in men and 0.94 in women.[5] Because the numbers of lower limb disabilities caused by stroke hemiplegia and older people are increasing gradually, a key aim of research in this field is allowing people with lower limb disabilities to move around and regain locomotivity to improve their daily lives. Moreover, muscle inactivity over a long period of time leads to muscle atrophy, which is bad for human health.[6]

Robots are helpful in solving the above-mentioned problems because of their repeatability and stability.[7-9] Recently, many lower limb rehabilitation robots have been developed to restore the mobility of affected limbs. They can be divided into standing training types[10] and sitting training types.[11] Standing training type robots are usually designed to aid in the recovery of users' walking capability. These types of devices are used for increasing strength[12-14] and assisting walking.[15,16] For these robots, body weight support devices are usually employed for users in weak physical condition, which can be uncomfortable for patients.[17] At the same time, these rehabilitation robots cannot satisfy patients' locomotion requirements during rehabilitation exercises,[18,19] which might make users feel that these exercises are boring and be reluctant to perform them. Conversely, sitting training type robots are used to exercise users' hip, knee and ankle joints without walking, and thus do not require uncomfortable body supports. Most of these robots are designed to help patients actively or passively through bicycling motions.[20,21] Clinical medicine indicates that pedaling motions can facilitate phasic muscle and coordinated muscle activities, even in patients with severe hemiparesis, and are a potential effective mode of muscle reeducation.[22,23] However, most of these robots cannot enable patients to move around. In addition, the previously mentioned negative experience for users is also a problem. For example, Profhand is a pedaled wheelchair developed by TESS Co., Ltd.,[24,25] and is driven by the user using a cycling motion. During cycling, users can exercise their legs. The device is a simple wheelchair that can exercise the lower limbs and enable users to move around. However, it might be dangerous if user's lower limbs are numb, because the cycling motion may damage the numb legs; at the same time, some more frail users might not have enough strength to operate the wheelchair because it has no powered assistance. To correct for the shortages mentioned above, we proposed a new rehabilitation robot in our previous work,[26-28] which can allow users to move around and perform exercise-based rehabilitation simultaneously.

It is well known that patients' willingness to undergo rehabilitation will influence rehabilitation efficacy greatly. Fully passive rehabilitation devices may violate user's rehabilitation will and then will produce fear in patients.[29] The master-slave control method can realize the user's intention-actuated motion to aid in rehabilitation, which is helpful in solving the previously mentioned fear problems. The master-slave control method is extensively used in upper limb rehabilitation robots for tracking users' motions and intentions. Guo et al. have proposed a human upper limb-like robot for elbow joint training using a master-slave rehabilitation system,[30] and have developed a self-tuning fuzzy PI controller to improve the tracking efficacy of traditional PI control.[31] Li et al. proposed an innovative master-slave system with rather a simple structure, bidirectional controllability, and energy recycling, which implements force feedback and motion tracking for a rehabilitation robot,[32,33] and can enable the impaired limb to track the healthy limb's motion. Meanwhile, the master-slave control method is also used in surgical robots[34] and even in farm robots.[35] This force-position master-slave control strategy has great advantages in actuating coordinated human-machine movement,[36,37] which can enable the slave motion to track the master motion in real time.[38,39] These applications inspired our new master-slave control method, which governs master-slave motions between users, the wheelchair, and the exoskeletons.

Generally, the master-slave controls are focused on the slave motion following the tracks, velocity or forces of master motion, as described for example in Refs. 31-35, which are about the duplications of master tracks, velocities or forces for slave motions. In our paper, the master is user's motion intention reflected by the force sensors, while the slave motions are the motions of exoskeletons and wheelchair. How to match these two motions to fulfil the requirements of user's legs rehabilitation and movement in wheelchair is the merit of the proposed control method, that method connects user's motion intention to the motions of motors, which can be seemed as a better way to reflect the motion intention, therefore, the proposed master-slave control is totally different to previous controls. The control method can not only fulfil users' requirements of moving around and performing rehabilitation exercises simultaneously, but can also conveniently adjust the intensity of the rehabilitation exercise, which can be realized just to adjust the control parameters.

This paper extends earlier work[40,41] to propose an intention-actuated master-slave control architecture for the newly designed robot. According to the best of the authors' knowledge, no research has tried to integrate user intention detection algorithms into motion control for wheelchairs and exoskeletons combining both rehabilitation and movement so far, there is no similar control approach as applied to a user-oriented system. Through the proposed method, the user thinks the motions are actuated by themselves, but actually are actuated by motors, and that will give users sense of participation. In addition, users act the motion by themselves and think the motion is controllable, hence it can give users sense of safety. The improvements in senses of participation and safety will persuade users to use our wheelchair robot in their daily lives and then it can improve the quality of lives. This is also one of the contributions of this paper.

The main difference of proposed method with respect to previous research is other than the slave motions duplicate the master's tracks, velocities or forces, our master motion and slave motion is from users' intention to the motions of exoskeletons and wheelchair.

The rest of the article is organized as follows. First, the design issues of the requirements are proposed, in terms of the rehabilitation platform and the core devices for the control implementation. Second, the master-slave control method is introduced with a control flowchart and a designed master-slave controller. Meanwhile, the coordinated motion control of the wheelchair and exoskeletons are described. Furthermore, the experiments and results are described to demonstrate the feasibility of the control method. Finally, we state our conclusions and ideas for future work on optimizing the proposed rehabilitation exercise method.

2. Design Issues of the Requirements

To design a fairly easily-operated and user-oriented rehabilitation robot, users' requirements must be taken into full consideration. Usually, patients and older people are reluctant to accept totally passive instruments because the instrument's start-stop cannot be controlled based on the user's intention, which will make users feel that the instruments are uncontrollable, and thus may cause a lack of sense of safety.

2.1 The kinematic design of the rehabilitation robot

To design a user-oriented, pedal-actuated exoskeletal robot for rehabilitation and locomotion, the proposed method is improved according to previous work.[26] In the new version, the rehabilitation and locomotion parts of the system are divided into two completely separated parts in the mechanical structure. For the new version, the intensity of rehabilitation and the movement speed of the wheelchair can be adjusted by the control algorithm according to user preference, rather than by specific transmission ratios as used in the previous version. Thus, the proposed method can enable users to adjust the intense of rehabilitation and the movement speed of the wheelchair separately and freely and the adjusting just depends on user's intention, which seems to be user-oriented.

Pedal cycling motion has become more and more popular recently for its fixed trajectory characteristics and its motion can exercise all the joints of the lower limbs. With this platform, pedal-actuated cycling motion is used as the trigger for both motions of wheelchair and leg exoskeletons. To simplify the systems, a crank rocker mechanism is applied to the mechanical exoskeleton system.

Based on the above description, the kinematic design for the

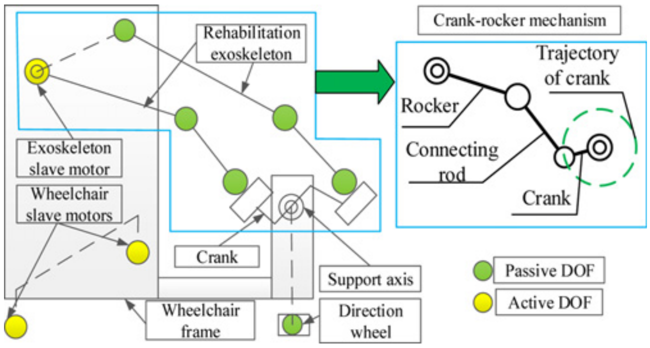

Fig. 1 The new proposed kinematic design of the bicycling intention-actuated rehabilitation exoskeletal robot

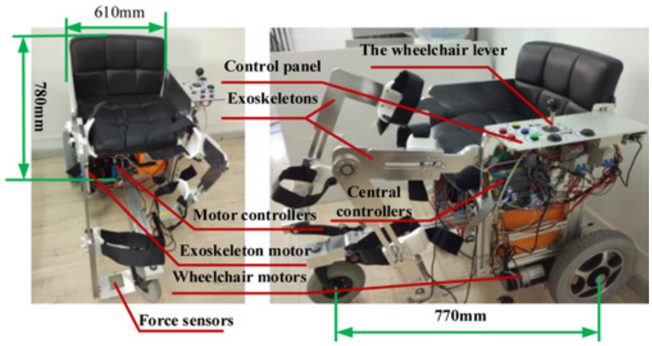

Fig. 2 The new proposed prototype of the bicycling intention-actuated exoskeletal rehabilitation robot at the IRI at the BIT

rehabilitation robot is shown in Fig. 1. The crank-rocker mechanism is used to realize the pedal cycling motion, and the motions of the wheelchair and the exoskeletons are divided into two separate parts. The robot's DOFs are shown in Fig. 1; there are two active DOFs required to achieve the locomotion of the wheelchair. Meanwhile, exoskeleton includes one active DOF to provide power for the rehabilitation exercise when needed, and five passive DOFs are designed to perform and assist motions of the user's hip, knees and ankles.

2.2 The platform of the robot

Based on the kinematic design, a prototype of the proposed robot platform with its components and core control devices, built at the Intelligent Robot Institute (IRI) at the Beijing Institute of Technology (BIT), is shown in Fig. 2. The rehabilitation motor is fixed to the right board of the wheelchair, and connected to the exoskeletons. In general, one actuator for driving the rocker cannot ensure the continuous cycling motion task without the help of inertia. But the reasons of proposed crank rocker mechanism can run normally are as follows: On one hand, when one user is seated in the wheelchair, user's legs have the weights, whose inertia can enable the mechanism to pass the dead center position. In addition, the position of dead point in the designed mechanism is not a balance position because of the weight of crank and pedal, so that the crank will not stop at the dead point position, and that can avoid the mechanism starting to rotate at the dead point position. Consequently, whether at the beginning of the cycling motion, or during running, the mechanism can do the cycling task with one actuator and with the help of users. One motor is sufficient to perform the joint motions of the hip, knees and ankles based on the crank and rocker mechanism in the design. Separately, as the slave motion, the wheelchair's movement is triggered by the user, and the motions of moving forward, moving backward, turning left and turning right are operated by the wheelchair lever from the control panel shown in Fig. 2. On the control panel, functional buttons are provided for users to shift the speed of the wheelchair and to pick different rehabilitation modes for recovery training according to their preference. Overall, the exoskeletons' motions are triggered by the force sensors, and the wheelchair's motion is triggered both by the force sensors and the wheelchair lever.

The main parameters of the wheelchair and leg exoskeletons are

Table 1 Specifications of the new leg-exoskeleton assisted robot in Figs. 1 and 2

Design parameter	Value
DOFs	9
Mass (Kg)	55
Height (mm)	780
Body length (mm)	770
Body width (mm)	610
Running speed (m/s)	1-3
Load bearing (Kg)	100

given in Table 1, with characteristic values for the proposed solution. The robot's size is designed by considering home environments with reference data from traditional wheelchairs. Specifically, the lengths of the exoskeletons can be adjusted based on the user's height. More details of the mechanical design can be found in our previous paper.[26-28]

The rehabilitation and locomotion functions of the robot are operated through two human-machine interactive interfaces. One interface is the force sensors fixed on the pedal, which is the first motion trigger for the motion of the robot. The other is the control panel, which can be operated by users to control the motion of the wheelchair and the exoskeletons, and can be regarded as the second motion trigger. Consequently, the user's motion intentions are reflected by the two aforementioned triggers, and the user's motion requirements can be fully taken into realization by the design.

3. The Robot Control Method

3.1 The control variables of the robot

To realize rehabilitation and movement simultaneously in one robot, we propose a new master-slave control system by combining the slave wheelchair motion with the master-slave leg rehabilitation exercise. The control variables include the passive-active rehabilitation mode, the rehabilitation and wheelchair motion speeds.

The designed control flowchart of the rehabilitation system is shown in Fig. 3, where both the wheelchair's motion and the rehabilitation exercise are triggered by the user's intention. The user's strength is reflected by the force sensors in this control system. The control system judges the rehabilitation modes based on the sensed user's strength,

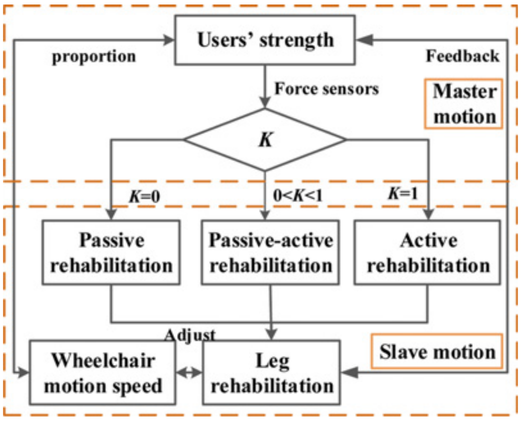

Fig. 3 The designed control flowchart of the robot system

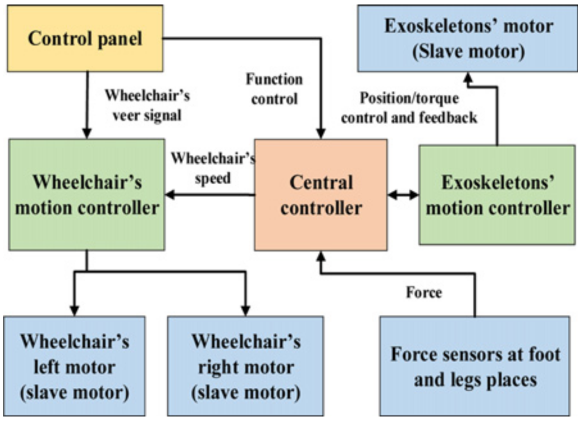

Fig. 4 The components of the designed master-slave controller

which is reflected by the value K ($K \geq 0$):

$$K = \frac{\Delta F_u}{F_0}, \tag{1}$$

where F_0 is a prescribed value for the needed rehabilitation force and ΔF_u is the force variation that can be detected by the force sensors and is generated by the user. During the cycling, one force value is read every 50 ms and twenty values of them are selected following the chronological order, the means of which are calculated and are used as the input of the control. The used force signal value is proportional to the velocities of wheelchair and exoskeletons.

When the user is weak ($K = 0$), the system will run in totally passive rehabilitation mode. In the totally passive mode, the user's legs are fully activated by the slave motors fixed on the exoskeletons as shown in Fig. 2. However, when the user is strong enough to exercise ($K \geq 1$), the system will run in totally active rehabilitation mode, where the exoskeletons are only used for guiding the exercise but not for supplying the force ($K = 1$). In addition, the motor can supply a force opposite to that of the leg movement direction to enable the user's leg to get better exercise ($K > 1$). In addition, it is possible to combine the above-mentioned operation modes with partial action by the user's legs when the user can supply some strength but is not strong enough for the totally active mode ($0 < K < 1$), which is the passive-active rehabilitation mode. The control judgment depends on the force value of the system, and the control process can be expressed as:

$$F_r = (1-K)\cdot\Delta F_m + K\Delta F_u \quad (0 \leq K), \tag{2}$$

where F_r is the needed rehabilitation force for the robot system, and ΔF_m is the force supplied by the exoskeleton motor for rehabilitation. Consequently, the process of rehabilitation is the coordination of control between the user and the rehabilitation motor.

For users, the leg rehabilitation exercise and the wheelchair motion can be regarded as a slave motion, while the master motion is the user's intended motion detected from the force sensors. Thus, the wheelchair motion speed can be controlled in two ways, namely by the proportion of the user's force from the force sensors and by the speed of the legs under rehabilitation. The combinations of the above speeds can be defined as:

$$V = K_1 \cdot \Delta F + \Delta S, \tag{3}$$

where V is the speed of wheelchair locomotion, K_1 is the proportionality coefficient, ΔF is the variation of the detected force from force sensors and ΔS is the adjustment from the rehabilitation exercise. Combining Eqs. (2) and (3), we can get a speed coordinate control method for the motion of the rehabilitation exoskeletons and the wheelchair.

3.2 The designed master-slave controller

To combine the functions of exoskeleton rehabilitation and wheelchair motion, and operate the master-slave control method, a master-slave controller with several components has been designed as shown in Fig. 4. Based on user settings for the different robot parts, the controller will coordinate the robot's rehabilitation mode and the motion of the wheelchair.

The central controller receives the force signals and then controls both the wheelchair's motion controller and the exoskeletons' motion controller. Independently, the motion of the wheelchair is controlled by the control panel, which is one of the human-machine interactive modules. As for the slave motion, the speed is controlled by the central controller and the motion direction of the wheelchair is controlled by the stick installed in the control panel. For the master and slave rehabilitation motions, the feedback from the force sensors installed at the crank pedal are sent to the central controller. Depending on the real-time force feedback and the values of exoskeleton motion features, such as position and torque, from the exoskeleton motion controller, the central controller will send corresponding commands to the exoskeleton motion controller. Then, the motion controller will implement the commands and accommodate the exoskeleton motor's rotation. Thus, with further processing from the control panel, users can maneuver the robot by controlling the handle stick and pedaling the exoskeletons. Thus, the process accomplishes master-slave control between the user's limbs, exoskeleton motion and wheelchair movement.

4. Experiments and Results

Several experimental tests were performed both to check the soundness of the proposed design solution and to describe its

Fig. 5 Snapshots of a video of the experiment in one circle of the crank

characteristic operation by experimental results, which can also be used to optimize the design solution.

4.1 Experiment 1: exoskeleton motor motion features

This experiment was conducted to analyze the relationship between the data from the force sensors on the pedals and the exoskeleton motor motion features, and then certify that the exoskeleton motor motion features can satisfy the control requirements when applying pedaling force data as actuation information and feedback for the whole control system.

Ten healthy male participants were invited to run this experiment (body mass 70.5 ± 12.3 *Kg*; height 175 ± 8 *cm*; age 23.1 ± 3.4 years). Fig. 5 shows snapshots of a video of the experiments. From the picture, we can see the rehabilitation exercise for one person during one circle of the crank. The experimental preparation was as follows: after a volunteer sat in the wheelchair, and tied the strap, the force sensors recorded the initial force value, and then the user pressed the calibration button to record the reference value as the initial force, which might be different for different weight users. After that, the user pedaled the crank and the control system determined the rehabilitation mode according to user's strength, or the user could decide the rehabilitation mode independently and choose one directly.

The first experimental task gave healthy participants a target value of suggested rehabilitation training intensity, which was determined by the specific pedal crank rotation speed. The pressure on the pedal and the motion features of the exoskeleton were recorded simultaneously.

The reported typical experiment results are extracted from the 10 healthy male participants to give a suitable description of the motion characteristics. In the paper, just one typical result is given as indicating the typical outcomes of the results. Fig. 6 shows plots of test results for typical pressure force, motor position and velocity while one participant was pedaling. To collect the most stable and representative data and eliminate uncertainty in the participant's adjustments, the duration of about two periods during the test was selected as the "steady-state" phase, in which the variation in frequency was at a minimum.

Benefiting from the symmetrical design of the exoskeleton and crank-rocker mechanism, pressure, velocity and the position of the motor change over time periodically, and the output force amplitudes of the left and right side pedals F_l and F_r are about 10 *N* (from 15 *N* to 25 *N*), the reason of the different force value of the left and right side pedals shown in Fig. 6(a) is that people pedaling movement is not as symmetrical as the designed exoskeleton and it will vary for different users. When one user's left leg is stronger than right one, his left leg will use much more strength to pedal involuntary when he is cycling. Also, the axis of symmetry is 15 *N* rather than 0 *N*, which results from the weight of user's lower limbs. These values can give us a reference to design the rehabilitation mode for different users.

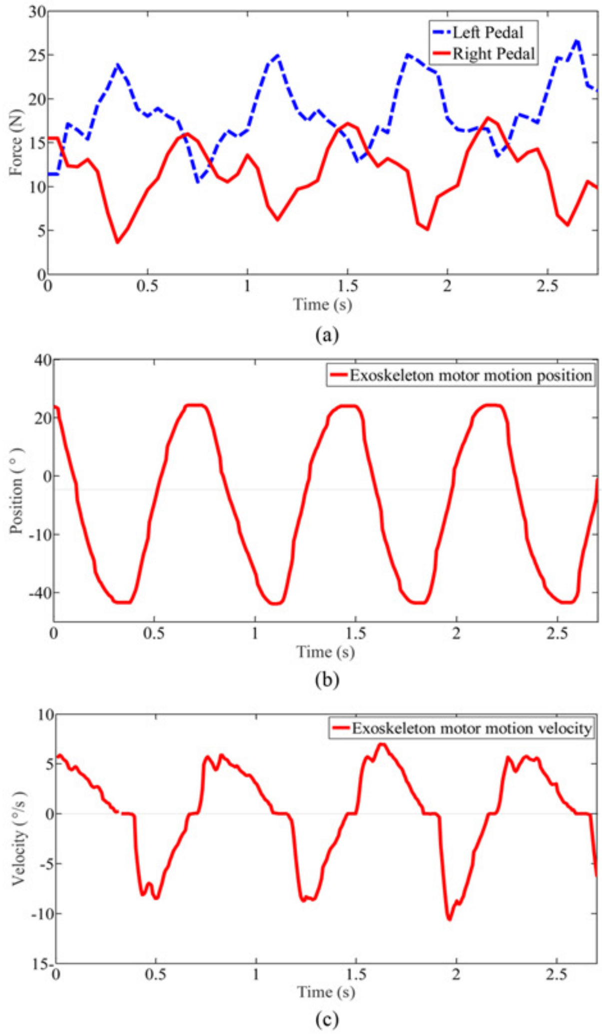

Fig. 6 Plots of experimental results of a typical experiment: a) pressure force at the pedal bottom, b) exoskeleton motor motion position, c) exoskeleton motor velocity

Referring to Figs. 6(b) and 6(c), the curves are bounded and symmetric, so they illustrate that the exoskeleton motion track is determinate. On the one hand, in Fig. 6(b), the exoskeleton motor motion position is shown by the pulse of the motor, and the plot fluctuates over time smoothly. On the other hand, the curve of the exoskeleton motor motion velocity in Fig. 6(c) is extracted from the differential of the motor motion position shown in Fig. 6(b), so it has poor smoothness because the force is different during cycling in one circle. The vibration with the change of time is rational compared to the vibration of motion position shown in Fig. 6(b).

From the curves of pedal force, exoskeleton motor motion position and velocity, the motion position plot has remarkable characteristics, and the correspondence between motor position and pedal force is easy to collect and acquire, which is illustrated by the peak values in Fig. 6.

The lowest point of the motor position curve corresponds to both the peak values of the left and right side pedal pressure (about 0.38 *s* in Figs. 6(a) and 6(b)), and the same relationships exist at the highest point of the motor position. Thus, the motor position curve clearly shows the motion movement relationship with the pedal force value. Its motion features are easy to pick out and analyze, and the correlation between the position curve and the pedal forces is accessible. In the meantime, the motor position fluctuation can be evaluated from the integral relationship of motor velocity to enhance and optimize the motion of the exoskeleton and simulate a real pedaling motion, which is vital for the improvement of user experience.

In summary, the first experiment enables us to determine that the force-position control method is suitable to be used as the rehabilitation control strategy. In addition, the results have showed the continuous motion of crank rocker mechanism and verify the correctness of the system design.

4.2 Experiment 2: master-slave control for exoskeleton under assistance mode

In accordance with the extraction of motion features from the first experiment, we pushed our tests further with participants whose lower limbs were not fully functional because of disease, injury, or other potential reasons, and who were required to perform similar rehabilitation training with the proposed prototype during the recovery process. Here, we present a test result focusing on the verification of the effects of the assistance mode, which is intended to aid users in completing the training process if they are unable to manage it by themselves because of different degrees of deficiency of the lower limbs. The aim of this experiment is to corroborate the validity of the designed master-slave control method for the exoskeleton, and evaluate the user's experience of the assistance of the exoskeleton motor under the proposed control method.

The experimental task used a male volunteer (body mass 72 kg; height 177 cm; age 41 years) whose lower limbs could not finish the pedaling movement actively because of knee-joint injuries, and who could not reach the target rotation frequency value of the exoskeleton alone. In the meantime, we configured the exoskeleton motor to rotate in line with Experiment 1's records to simulate a healthy user's subjective motion and modulate the motor motion with the real-time feedback from the left and right pedals' force sensors. In addition, all the records of motor motion and force sensor data were processed according to steady phase collection principles for more precise analysis.

The output pressure data F_l and F_r are shown in Fig. 7 after ten redressals and measurements. As shown in Fig. 7, the force curve shapes are generally and essentially similar to that of the curve of a healthy user, but the amplitude difference of left and right pedal forces is smaller in the experiment 2 than experiment 1. The similarity between these two data sets accounts for the similarities in exoskeleton motion and training effects, to an extent. The result demonstrates that with the assistance of an exoskeleton, a user who suffers a deficiency of the lower limbs can take controllable exercise to rehabilitate and recover. For the value of the force, the average value of 10 *N* in Fig. 7(a) is much smaller than the average value of 20 *N* in Fig. 7(b), which illustrates that the exoskeleton motor helps the motion of the user's legs.

In addition, according to the comparison of Figs. 6(a) and 7(a), we can get some conclusions from the different force values of the left and right legs shown in Fig. 6(a), in which the user is a healthy man and he will involuntary use his stronger leg, so the force values of left and right pedal are different. In Fig. 7(a), the user is told not to pedal by himself, and the force values of left pedal and right pedal are nearly the same. The reason is that people pedaling movement is not as symmetrical as the designed exoskeleton and it will vary for different users. When one user's left leg is stronger than right one, his left leg will use much more strength to pedal involuntary when he is cycling. That phenomenon can give us a good reference to design the control method to coordinate the different force messages, such as the different weight of users and the different forces of user's left and right sides.

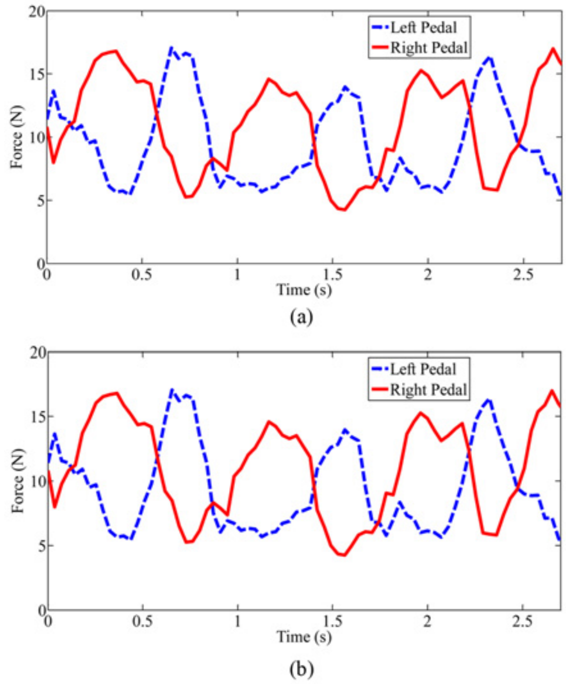

Fig. 7 Time series plots of a typical force curve from (a) a healthy participant and (b) an injured volunteer in Experiment 2

Particularly, the force differences of Figs. 6(a) and 7(a) are analyzed as follows: In experiment 1, the objective was to verify the characteristics of the exoskeleton movement to decide how to design the control method, and a user is asked to cycling by himself. In experiment 2, the experiment was designed to test the control method for patients. In this case, the cycling motion is actuated by the motor, not by users, but the characteristics of exoskeleton movement remain the same as experiment 1. In addition, for Figs. 6(a) and 7(a), participants are different, so the force values are different. The value is different, but the laws of the change are similar.

Fig. 8 displays representative motor position and velocity while the volunteer participant pedals with the assistance of the exoskeletons. As shown in Fig. 8, the curves of the actual motor position and velocity are similar to those of the motion features revealed in Experiment 1, which indicates that in assistance mode, the exoskeleton can enable users to accomplish the training exercise at a lower intensity compared with healthy participants. Meanwhile, it might produce a similar exercise perception as that produced in healthy people.

Fig. 8(a) has shown the different data between proposed position

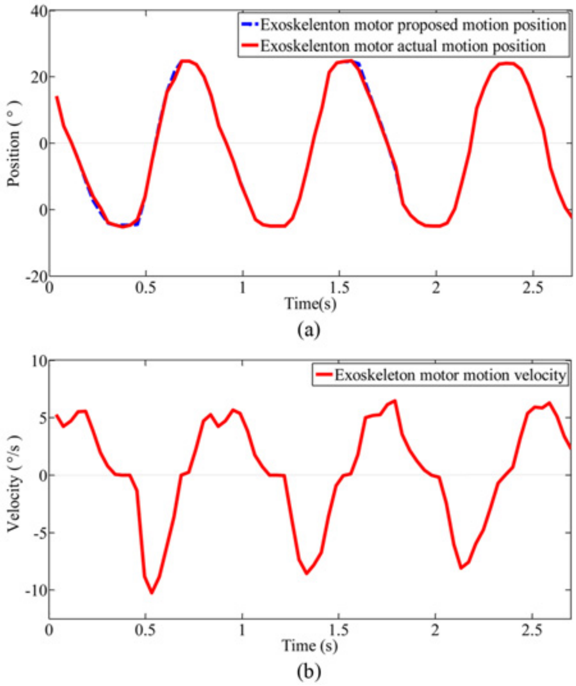

Fig. 8 Time series plots of (a) the typical motor position and (b) the velocity curve in Experiment 2

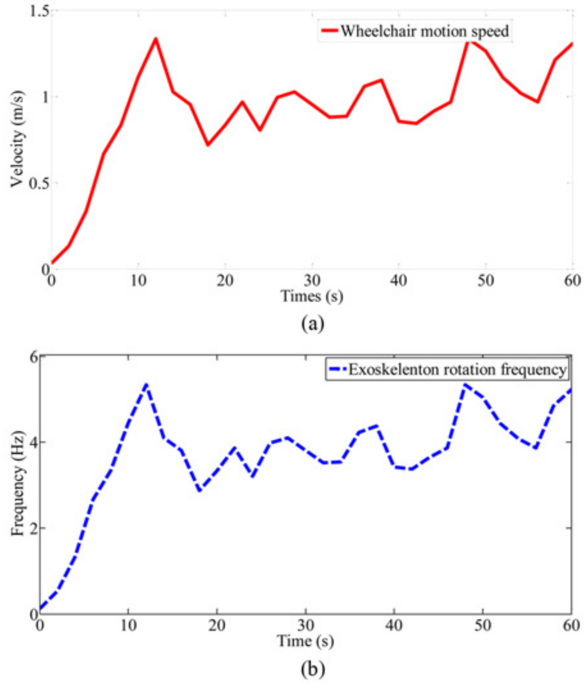

Fig. 9 Time series plots of a typical motor position and velocity curve in Experiment 2: (a) wheelchair motion speed and (b) exoskeleton rotation frequency

and actual position at some positions. The reason is as follows: in the passive-active mode, the user might be strong enough to have impact on the actual movement of the exoskeleton. In this case, it is normal that the two curves are not exactly the same.

The results of the master-slave control of the exoskeleton in the assistance mode experiment show that the passive-active master-slave control method can be used to help the users during rehabilitation exercise.

4.3 Experiment 3: master-slave control for wheelchair movement

The third experiment was conducted to verify that master-slave control could enable the leg exoskeletons and the wheelchair to move simultaneously. Here, the master-slave control method was based on the actual velocity values from the exoskeleton rotation and the wheelchair moving speed. The volunteer mentioned above was given the freedom to pedal the crank at a frequency of his choice. During this process, the exoskeleton rotation frequency and the wheelchair movement speed were recorded. In addition, in line with the response from the user, we made some adjustments to boost the sense that the movement of wheelchair was correlated with the pedaling, and that the process felt natural.

The output data reflect the correlation of exoskeleton rotation speed and wheelchair movement speed. The curves in Fig. 9 indicate that the wheelchair motors could make the wheelchair movement vary with exoskeleton rotation frequency fluctuation. The results demonstrate that the slave motion of the wheelchair can catch up with the motion of the crank; further, the slave motion can be set to boost the user's experience when the proper proportion is chosen.

This latency is set for safety and comfort sense of the users. Although the control method can make the motor speed following the exoskeleton without delay, in the experiment, the users fed back that the latency will make them feel more comfortable, it seems that users need the latency time to prepare for the movement in their own minds, and users feel sense of safety for the latency setting.

5. Conclusions and Future Work

To fulfil the motion and rehabilitation requirements of older people and patients with lower limb problems, a new force-position control method is proposed for a wheelchair with leg exoskeletons. The master motions are the user's pedaling movements, with forces detected by force sensors, while the slave motions are the motions of the exoskeletons and wheelchair. The control system is introduced to characterize the mentioned functions. The experimental results on a prototype show that the slave motions can track the master motions in real time, which is an effective, easily-operated, and user-oriented solution.

In the future, some patients with different degrees of motion conditions will be invited to perform field experiments to optimize the rehabilitation process. In addition, the experimental results will be used to explore more complicated and accurate control algorithms based on the currently presented master-slave control system. Finally, a parameterized evaluation system should be added to optimize the control strategy.

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