Multi-modal Ankle Muscle Strength Training Based on Torque and Angle Sensors

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Abstract. With the aggravation of aging, a series of ankle injuries, including muscle weakness symptoms, caused by stroke or other reasons have made the problem of ankle rehabilitation increasingly prominent. Muscle strength training is one of the main rehabilitation methods for the ankle joint complex (AJC). Based on the current incomplete development of muscle strength training modes for all forms of ankle movement, this study developed six muscle strength training modes for the human ankle on our parallel ankle rehabilitation robot, namely continuous passive motion (CPM), isotonic exercise, isometric exercise, isokinetic exercise, centripetal exercise and centrifugal exercise, based on position inverse solution of the robot combining with the admittance control or position control. The dorsiflexion (DO) movement was used as an example to analyze the training effect of each training mode, with the results showing good function performance of the developed ankle muscle strength training methods.

Keywords: Ankle muscle strength training · Multi-modal · Ankle rehabilitation robot · Admittance control

1 Introduction

With the aggravation of aging, a series of ankle injuries, including muscle weakness symptoms, caused by stroke or other reasons have made the problem of ankle rehabilitation increasingly prominent [1–5]. Ankle rehabilitation mainly includes rehabilitation training and muscle strength training; Rehabilitation training focuses on the process of regeneration and repair of the central nervous system [6–8]; By comparison, muscle strength training is mainly aimed at the needs of muscle strengthening and symptoms such as muscle weakness caused by diseases, the muscle groups can be improved, the muscle atrophy can be reduced and the muscle strength level can be improved [9, 10]. In addition, muscle strength training programs are also recommended for muscle function recovery in clinical applications [11, 12]. The commonly used muscle strength training mode is the isokinetic exercise.

To achieve muscle strength training, many muscle training systems have been developed to improve the motor function of the relevant joints in the human body [10, 13–17]. Also, many muscle strength training devices have been developed for providing specific

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tasks, human-machine interaction and assessment analysis for ankle joint [18–20]. During the initial stage of ankle muscle strength training, the patient's ankle is unable to move on its own, so continuous passive motion (CPM) is used to gradually improve muscle strength and restore the ankle's range of motion [21–23]. Further, the patient's muscle strength level can be improved through active exercise when the patient has a certain level of muscle strength. To enhance the suppleness and interactivity of active exercise, a force/torque sensor system is incorporated, which also ensures safety during training. Currently, many muscle strength training methods have been developed, such as passive training, isotonic exercises [9, 21, 24], et al. However, the development of muscle strength training in the three degrees of freedom (DOFs) of the ankle joint at this stage is relatively small and one-sided, and cannot meet the plyometric needs of different groups for different training periods. Our previous work proposed different compliant rehabilitation training strategies, including isokinetic muscle strength training based on the position inverse solution and admittance-controller, and isotonic exercise, et al. [9, 21].

Based on the current incomplete development of muscle strength training for ankle joint, this paper developed six muscle strength training modes by using the 2-UPS/RRR ankle rehabilitation robot [21], namely CPM, isotonic exercise, isometric exercise, isokinetic exercise, centripetal exercise and centrifugal exercise. The ankle joint complex (AJC) has 3 DOFs, dorsiflexion/plantarflexion (DO/PL), eversion/inversion (EV/IN), and abduction/adduction (AB/AD). The proposed training strategies can meet the muscle strength demands of the human ankle joint in all directions of freedom from the beginning to the end of training. The DO was used as an example to analyze the training effect of each training mode based on the experiments.

The remainder of this paper is organized as follows. Section 2 introduces the developed muscle strength training strategies. Section 3 presents the experiments and results of the developed six muscle strength training modes in the direction of DO movement. Conclusion and future works are presented in Sect. 4.

2 Muscle Strength Training Strategies

2.1 Control Strategies of Robot-Assisted Ankle Muscle Strength Training

The development six robot-assisted ankle muscle strength training methods are realized by using the admittance controller, the position inverse solution and the velocity Jacobian matrix, with the training strategies shown in Fig. 1, where, $\dot{d}_1$, $\dot{d}_2$ and $\dot{d}_3$ denote running speed of each motor; z_{13} and z_{23} denote the corresponding direction vectors; Q denotes coefficient matrix. Inside, the CPM combines with position inverse solution controller and velocity Jacobian matrix controller for exercise muscle strength at the early stage; Isotonic exercise combines with admittance controller and position inverse solution controller to meet the demand of resistance during the training; Isometric exercise realizes the training function of a specific position through a position inverse solution controller; Isokinetic exercise achieves the goal of keeping the ankle training speed constant on the basis of resisting the resistance demand by combining the position inverse solution, admittance controller and velocity Jacobian matrix. Centripetal and centrifugal exercise are based on isotonic exercise and isokinetic exercise to analyze and train the stretching and contracting states of specific muscles.

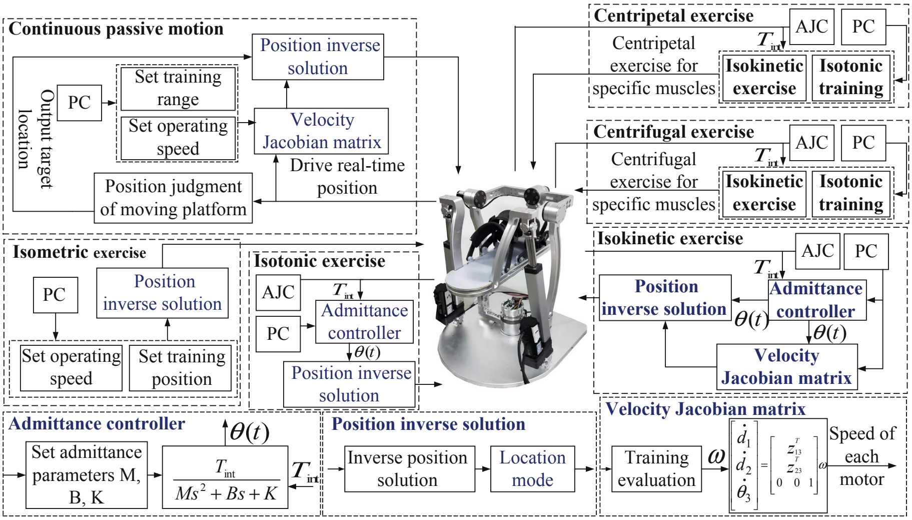

Fig. 1. Control strategy diagram of six muscle strength training modes.

2.2 Principles of the Six Muscle Strength Training Modes

2.2.1 Continuous Passive Motion

The CPM is the passive exercise of the limbs through the equipment to increase the range of motion. This mode can drive the ankle joint back and forth at a fixed speed. It is used for early stage of ankle muscle strength training and plays an important role in the recovery of the range of motion and preliminary muscle strength. At the same time, extremely low-speed passive activity can overcome stretch reflex. The control strategy is shown in Fig. 2.

Before training, the moving platform of the parallel ankle rehabilitation robot is in the horizontal position; the training range (P_{max}) and speed of passive exercise (ω) are set by the host computer, and the ankle movement mode is selected. CPM takes the training speed set by the host as one of the inputs of the velocity Jacobian matrix. During the training process, the movement angle of the ankle is finally mapped to the movement position of each joint motor through the position inverse solution. At the same time, during the training process, it is judged whether the upper limit of the training range is reached or not by constantly detecting the position of the joint motor (P), and the current angle of the motion platform is fed back as another input of the velocity Jacobian matrix. If the upper limit of the training range set at the beginning has been reached, the return motion will be performed, otherwise it will continue to run towards the upper limit of the training range set, thus achieving reciprocal motion.

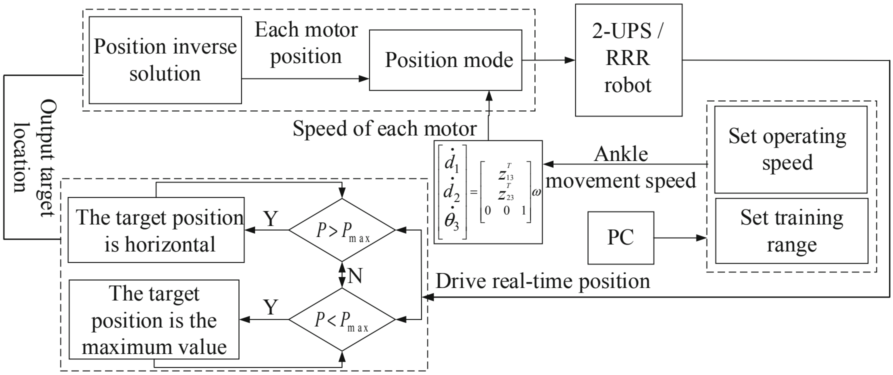

Fig. 2. Control strategy chart of CPM.

The position inverse solution and the velocity Jacobian matrix used in CPM can be found in our previous work [25].

2.2.2 Isotonic Exercise

Isotonic contraction refers to muscle contraction with constant tension and varying length, to realize various acceleration and displacement movements of human body. When the applied load is large, the muscle takes a long time to overcome the load, and the contraction speed is slow. When the muscle tension reaches the maximum, the muscle contraction speed is zero, and then the isotonic contraction occurs. In this exercise mode, when the patient's muscle strength remains stable, the degree of muscle extension is basically unchanged. When the patient recovers a certain muscle strength, isotonic exercise can strengthen the patient's muscle, make the patient get rid of the completely passive state, stimulate the patient's active movement consciousness, and improve the rehabilitation efficiency. In this mode, the admittance controller is used to resist the active motion of the patient by continuously detecting the interaction torque and using it as an input to obtain the output angle θ(t). The final position of each joint motor motion is obtained by using the output angle as the input to the position inverse solution. At the same time, the difficulty of training can be changed by changing the admittance parameter. Admittance control used in isotonic exercise can be equivalent to the mass-spring-damping system. Equation (1) is obtained according to Newton's second law and Laplace transformation [21].

$$\frac{X(s)}{F(s)} = \frac{1}{Ms^2 + Bs + K} = \frac{\frac{1}{K} \cdot \frac{K}{M}}{s^2 + \frac{B}{M}s + \frac{K}{M}} \tag{1}$$

where, M denotes mass, B denotes damping coefficient, K denotes stiffness coefficient. θ(t) is the output of the admittance controller for isotonic exercise, which can also be found from our previous work [21]. The control strategy is shown in Fig. 3.

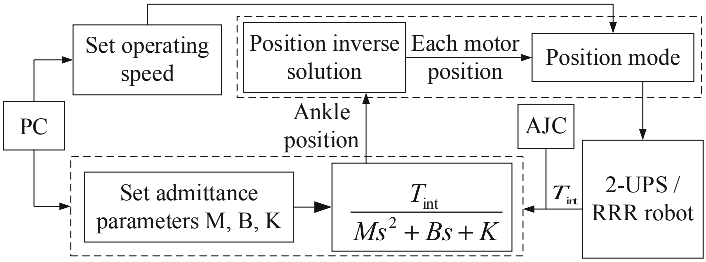

Fig. 3. Isotonic exercise control strategy.

2.2.3 Isometric Exercise

Isometric exercise refers to the muscle contraction without shortening the muscle fibers, and the muscle tension increases while the muscle length and joint angle remain unchanged, that is, the angle is constant and the resistance changes. Isometric exercise can effectively increase muscle strength and reduce joint exudation. Isometric contraction refers to muscle contraction with constant length and varying tension. The isometric exercise runs at a fixed speed to the set end position by setting the end angle position of the exercise, and constantly detects the interaction torque. The control strategy is shown in Fig. 4.

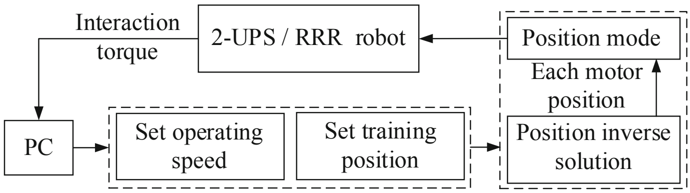

Fig. 4. Isometric exercise control strategy chart.

Before training, the ankle rehabilitation robot is kept level in the initial position. The initial operating speed of the robot and the position angle to be trained can be set on the host computer, and then the training position angle is mapped to the operating space of each joint servo motor based on the position inverse solution. After the ankle rehabilitation robot runs to the exercise position at the initial set running speed, the interaction torque of the patient is continuously detected by the six-axis torque sensor. In this state of contraction, muscle tension can be increased to a maximum. Although the displacement does not exist, physically speaking, the muscle does not perform external work, but it still needs to consume a lot of energy.

2.2.4 Isokinetic Exercise

Isokinetic refers to the movement at a fixed speed (constant angular velocity), and the patient must use the maximum force to resist the resistance. The speed and angle are constant, and the resistance varies with the patient's application of force. Isokinetic exercise is achieved by admittance controller, position inverse solution and velocity Jacobian matrix. By setting the ideal ankle movement speed, the interaction torque is constantly detected during the exercise process, and the real-time output angle is obtained by admittance control, the angle and the speed are used as the input of velocity Jacobian control, and the speed of each joint motor at different exercise angles is obtained to ensure the constant ankle speed. The control strategy is shown in Fig. 5.

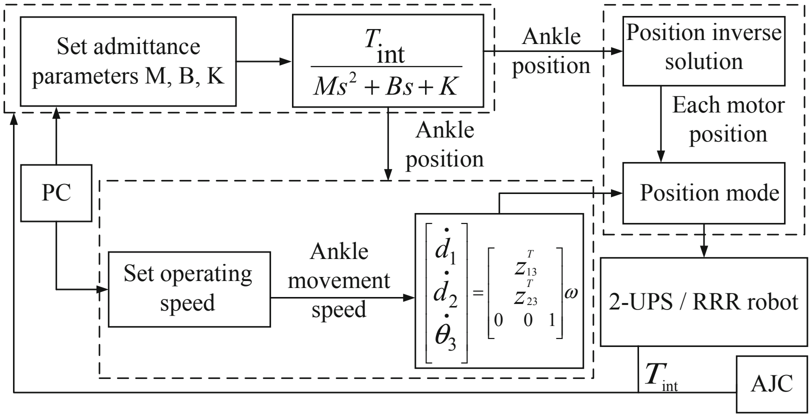

Fig. 5. Isokinetic exercise control strategy chart.

An initial training assessment was performed prior to training to determine the maximum applied torque for the subject, and the training speed (ω) will be determined based on this, which is called speed segmentation processing. During the training process, according to the real-time detected interaction torque, the movement angle of the moving platform of the robot is obtained through the admittance controller, and then ω is obtained by speed segmentation. Together, they are used as the input of the velocity Jacobian matrix control to obtain the running speed of the equipment motor, and finally they are mapped to the running results of each joint drive through the position inverse solution, to achieve the goal of isokinetic exercise at the ankle joint.

2.2.5 Centripetal and Centrifugal Exercise

Centripetal contraction refers to the contraction state of muscles when, for example, the weight is lifted upwards during weight lifting exercise and the length of muscle fibers is shortened. Centripetal exercise can be divided into isotonic exercise mode and isokinetic exercise mode. Centrifugal contraction is a kind of contraction in which the muscle is stretched while producing tension, and the muscle is gradually stretched under resistance, so that the movement link moves in the opposite direction to the muscle tension. Centrifugal contraction is a kind of dynamic contraction, also known as retreating contraction, and it can also be divided into isotonic exercise mode and isokinetic exercise mode. The control strategy is shown in Fig. 6.

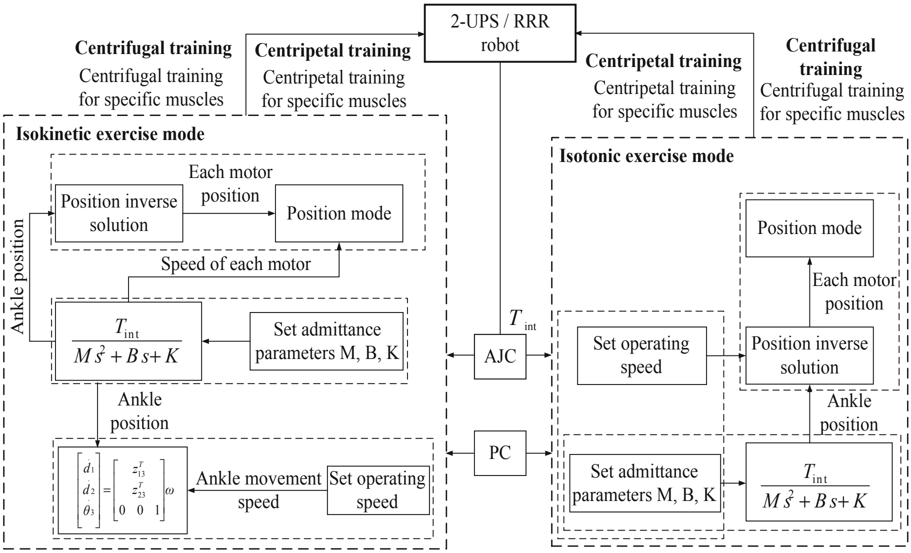

Fig. 6. Isotonic centripetal/centrifugal exercise, Isokinetic concentric/centrifugal exercise.

Take the DO of the ankle as an example. During the training process, tibialis anterior (TA) is a kind of eccentric exercise, while lateral gastrocnemius (LG), medial gastrocnemius (MG) and soleus (SO) are centripetal exercise. Based on isotonic exercise and isokinetic exercise, the training forms of muscles are analyzed, and the training states of each muscle in different exercise modes are obtained.

3 Experimental Scheme and Results

3.1 Experimental Scheme

One healthy male experimenter volunteered for the experiment. Prior to the experiment, the experimenter's left ankle was immobilized on the powered platform of the 2-UPS/RRR ankle rehabilitation robot. The ankle joint was driven by the rehabilitation robot to achieve six exercise muscle exercise modes in six movement directions DO/PL, EV/IN, AB/AD. The experimenter rested for five minutes between each plyometric mode to avoid muscle fatigue. During the ankle training period, we recorded the interaction moments and angles of motion of the subject and presented the experimental results with DO direction motion as an example.

The initial parameters of the admittance controller were determined as M = 1, B = 0.8 and K = 1 based on experimental tests and experience.

Before training, set the threshold of the device in the six directions of ankle movement to avoid secondary injuries caused by exceeding the range of motion of the human ankle during the operation of the device. The set angle thresholds were shown in Table 1.

Table 1. Motion angle threshold

Axis	X		Y		Z	
Direction of motion	DO	PL	EV	IN	AB	AD
Threshold (°)	20	37	10	15	16	22

3.2 Experimental Result

3.2.1 Continuous Passive Motion

The range of motion set in the DO direction of motion during CPM is 13° and the training speed is 50 rpm. During the experiment, no active force was applied by the subject, and the ankle rehabilitation robot drove the experimenter's ankle for continuous passive training. The experimental results of the DO motion direction at the ankle site of the subject are shown in Fig. 7.

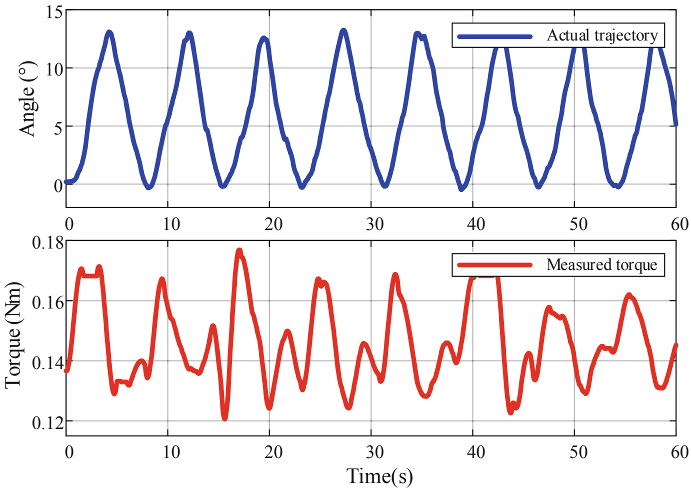

Fig. 7. Experiment results of continuous passive motion in DO.

According to the experimental results, it was concluded that during the CPM, the experimenter was driven by the ankle of the device and generated interaction torque, but the level of the torque was low and was suitable for the initial arousal process of the experimenter's muscle strength and increasing the range of motion.

3.2.2 Isotonic Exercise

After setting the training parameters, the isotonic exercise started to open the interactive torque into the guide channel for exercise. In this rehabilitation training mode, the physician can adjust the parameters of the admittance controller M, B and K to meet the desired resistance. The results of this experiment are shown in Fig. 8.

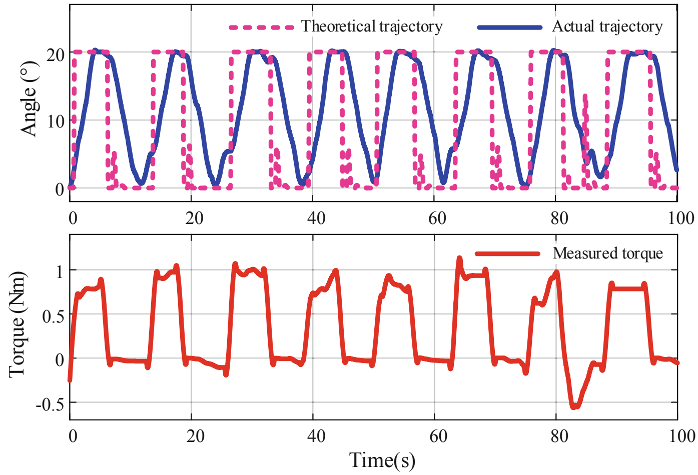

Fig. 8. Experiment results of isotonic exercise in DO.

According to the experimental results, we can see that during the training process, the experimenter applied a torque in the direction of DO and the level of torque could reach the set level of admittance resistance so that the device got the theoretical angle. After the equipment was sensed by the admittance controller, a corresponding offset was made in the direction of the torque with respect to the initial position (horizontal position), which could be used to strengthen the recovered muscle strength.

3.2.3 Isometric Exercise

The initial position was chosen for isometric exercise to facilitate the experimenter's perception of force generation. The experimenter's muscle length was kept constant while the tension was constantly changing to reduce joint exudation. The results of this experiment are shown in Fig. 9.

According to the experimental results, it can be concluded that the subject performed multiple cycles of training, the equipment platform didn't move during the force. The experimenter continuously applied torque, the tension changed without muscle length change, which was conducive to maintaining muscle strength and low fatigue.

3.2.4 Isokinetic Exercise

The subject's training speed was obtained by exercise assessment prior to exercise, and the channel of the moment to the admittance controller was opened. And the velocity Jacobi matrix controller and the position inverse solution were trained and the training speed of the ankle was kept constant. The results of this experiment are shown in Fig. 10.

According to the experimental results, the experimenter applied a torque in the direction of DO motion during the training process, and the torque level could reach the set level of the admittance resistance so that the device got the theoretical angle. After the equipment was sensed by the admittance controller and the velocity Jacobi matrix

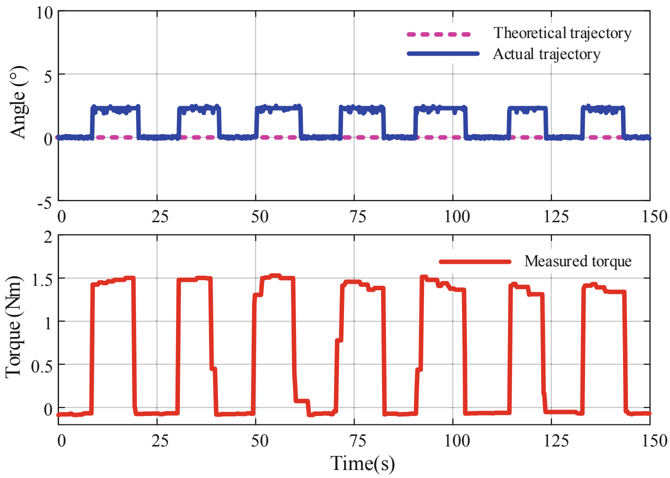

Fig. 9. Experiment results of isometric exercise in DO.

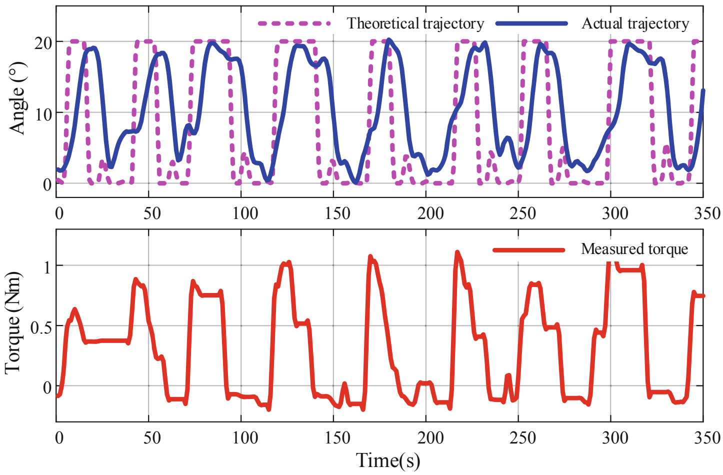

Fig. 10. Experiment results of isokinetic exercise in DO.

controller, it made a corresponding equal velocity offset in the direction of the torque relative to the initial position (horizontal position), while the experimenter's torque level and the sustained high torque application capability.

3.2.5 Centripetal and Centrifugal Exercise

Centripetal and centrifugal exercise are available in isotonic exercise and isokinetic exercise respectively. For muscles, TA is centrifugal training and LG, MG and SO are centripetal training under the training behavior of DO. Therefore, to a certain extent, it could be assumed that the other three muscles were trained centripetally during the centrifugal training of the TA. The results of this experiment are shown in Fig. 11 and Fig. 12.

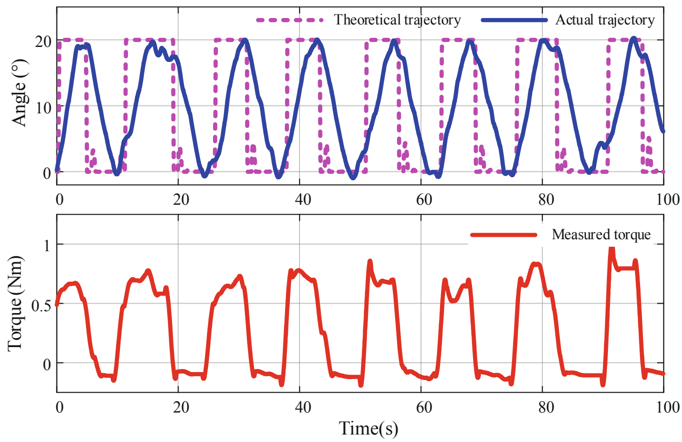

Fig. 11. TA – isotonic centrifugal/LG, MG and SO – isotonic centripetal

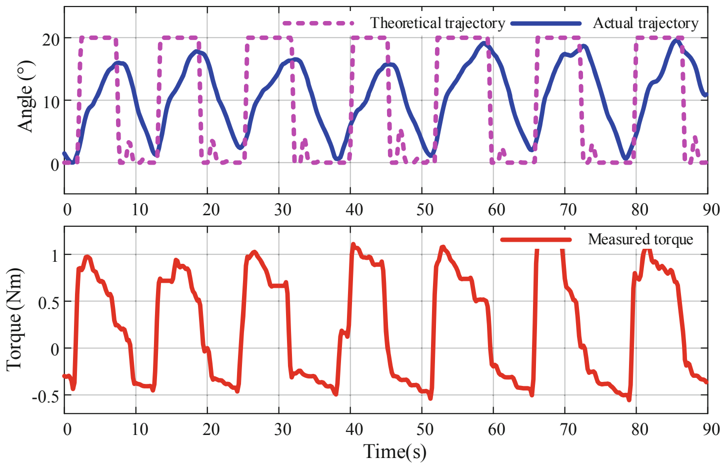

Fig. 12. TA – isokinetic centrifugal/LG, MG and SO – isokinetic centripetal

According to the experimental results, the division of centripetal and centrifugal exercise modes based on isotonic exercise and isometric exercise was highly targeted for muscle training. In contrast, isometric exercise had advantages in terms of moment and moment sustained output, and muscle training was more effective.

4 Discussion and Future Work

In this work, we developed six muscle strength training modes for the ankle joint, namely CPM, isotonic exercise, isometric exercise, isokinetic exercise, centripetal exercise and centrifugal exercise. And the DO was used as an example to analyze the training effect of each training mode. According to the experimental results, in CPM, the level of the torque was low and suitable for the initial arousal process of the experimenter's muscle strength and increasing the range of motion; In isometric exercise, the subject applied torque periodically, so that the muscle tension changed while the length remained the same; In isotonic exercise and isokinetic exercise, the subject applied torque in the direction of DO and the level of torque could reach the set level of resistance, and a corresponding offset was made in the direction of the torque with respect to the initial position, which could be used to strengthen the recovered muscle strength; In isokinetic exercise, the velocity Jacobi matrix controller allowed the subject's ankle joint to run at a constant speed; Centripetal and centrifugal exercise were analyzed for specific muscles on the basis of isotonic exercise and isometric exercise, and experimental results showed that muscle strength training can be used to strengthen recovered muscles. The developed muscle strength training methods can meet the muscle strength demands of the full phase of the ankle joint.

Future work will evaluate the effect of muscle-specific training by combining surface EMG (sEMG). We will evaluate the training effect of the selected muscles by preconditioning the collected sEMG and extracting features of the muscle activation level, combining force and actual trajectory. And later we will perform real-time variable resistance training based on the evaluation and detection of sEMG.

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