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A gait rehabilitation strategy inspired by an iterative learning algorithm

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ABSTRACT

Robotic gait rehabilitation devices enable efficient and convenient gait rehabilitation by mimicking the functions of physical therapists. In manual gait rehabilitation training, physical therapists have patients practice and memorize normal gait patterns by applying assistive torque to the patient's joint once the patient's gait deviates from the normal gait. Thus, one of the most important factors in robotic gait rehabilitation devices is to determine the assistive torque to the patient's joint during rehabilitation training. In this paper, the gait rehabilitation strategy inspired by an iterative learning algorithm is proposed, which uses the repetitive characteristic of gait motions. In the proposed strategy, the assistive joint torque in the current stride is calculated based on the information from previous strides. Simulation results and experimental results using an active knee orthosis are presented, which verify that the proposed strategy can be used to calculate appropriate assistive joint torque to excise the desired motions for rehabilitation.

1. Introduction

As the number of people who have either totally or partially lost the ability to walk due to aging or physical impairment increases [37,30,35,23], the demand for robotic gait rehabilitation devices increases. Robotic gait rehabilitation devices enable more efficient and convenient gait rehabilitation by mimicking the functions of physical therapists. In manual gait rehabilitation training, physical therapists establish suitable rehabilitation strategies depending on the gait disorders patients suffer from. While there is a long list of gait disorders that inhibits patients' ability to walk, the causes of the gait disorders can be classified as degeneration in two categories: (1) in muscular systems and (2) in nerve systems.

If a patient has weakened muscles due to accidents, diseases, or aging, then the patient cannot generate the joint torque necessary to achieve desired gait motion. For these patients, physical therapists try to strengthen patients' muscles by applying appropriate resistive force to muscles. Weight training for specific muscles is one example of the many possible rehabilitation strategies. This gait rehabilitation strategy was mimicked by the robotic gait rehabilitation device for strengthening muscles [9]. If the muscles are too damaged to recover their original function, then power augmentation systems ([16,41,40] among others) may help the patients achieve normal walking movements.

Patients with impaired motor control via spinal cord injury (SCI) or stroke has the problem that they cannot control their muscles properly. Assuming that only their nervous system is degenerated, i.e. their muscles are strong enough to generate muscular forces to achieve the desired gait motions, they need to practice and memorize the desired gait patterns through repetitive exercises. For these patients, physical therapists make patients practice normal gait patterns through force or voice feedback. Physical therapists apply assistive torques to the joints to let them be cognizant of how their gait motions deviate from the normal gait, and guide them to the normal gait trajectory. Also, physical therapists keep talking to patients during the gait rehabilitation training about how they need to move to achieve the normal gait patterns, e.g. bending knee more or pushing heel more.

By mimicking these functions of physical therapists, robotic gait rehabilitation systems that utilize visual feedback [1,25] or assistive torque have been developed [12,7,13,32,38,5,4,18]. Since assistive torque allow patients to practice normal gait pattern easily and effectively, determining required assistive torque in a rehabilitation application is one of the most important factors in the robotic gait rehabilitation system. In fact, the assistive torque should be proportional to the amount of deviation from a normal gait trajectory in order for patients to perceive the right "feeling" about a normal gait trajectory. Through assistive torque, the joint is guided accurately to the desired gait trajectory for rehabilitation.

In the past, rehabilitation strategies that impose a virtual potential field around the desired trajectory was introduced [3]. In this strategy, the induced force by the potential field compels the joint to move to the desired joint trajectory once the joint position

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deviates from the desired joint position. The potential field rehabilitation strategy provides a good method to calculate the required torque for patients to practice normal gait trajectory. However, in order to guide a joint to the correct gait trajectory, a high control gain is required, which may cause instability and overshoot. Inspired by the repetitive characteristic of gait motions, a gait rehabilitation strategy based on an iterative learning algorithm is proposed in this paper. Taking advantage of the repetitive characteristic of gait motions, the joint can be guided to the desired trajectory more effectively and accurately. The proposed rehabilitation strategy utilizes position errors and error derivatives of previous strides to calculate the assistive torque in the current stride. By using information from previous strides, repetitive abnormal gait patterns can be penalized more effectively. The performance of the proposed gait rehabilitation strategy was verified through simulations and experiments with an active knee orthosis.

This paper is organized as follows. In Section 2, the role of assistive torque in robotic gait rehabilitation devices is discussed through explanations of how the gait rehabilitation training takes place. The gait rehabilitation strategy inspired by an iterative learning algorithm and its simulation results are presented in Section 3 while experimental results by the proposed algorithm are shown in Section 4. Finally, conclusions and future work are given in Section 5.

2. Assistive torque in robotic gait rehabilitation devices

2.1. Motion control in a human body

Many models have been proposed to represent the motion control system in the human body. Among the models, the closed-loop control system in Fig. 1 is one of the most dominant [33]. The 'Desired Human Motion' in the figure is created by either an external stimulus or an internally generated intention. In the figure, the 'Brain' includes many parts such as the motor cortex, cerebellum, basal ganglia, and spinal cord all cooperate with one another to act as a controller for the motor control. The muscle control signals (① in Fig. 1) generated by 'Brain' are transferred to 'Muscle' though motor neurons, and 'Muscle' moves 'Body' via appropriate muscular forces (② in Fig. 1). 'Muscle' is considered as an actuator, and 'Body' represents the musculoskeletal part of a human body, which is considered as a plant to be controlled. Human motions, which are sensed by various 'Sensory Organs' such as the eyes, muscle spindles and the Golgi tendon organs, are then compared with the desired motions to achieve precise motions. In this paper, the closed-loop motion control system in Fig. 1 is used to analyze human motions and to design rehabilitation strategies. 'Desired Human Motion' in Fig. 1 is assumed to be given by the motion planning part of the brain.

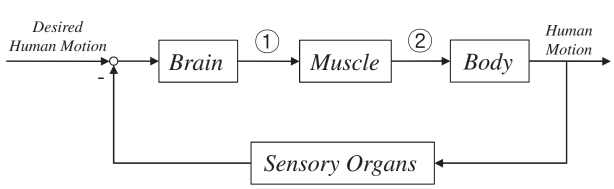

Fig. 1. Closed-loop motion control system in a human body.

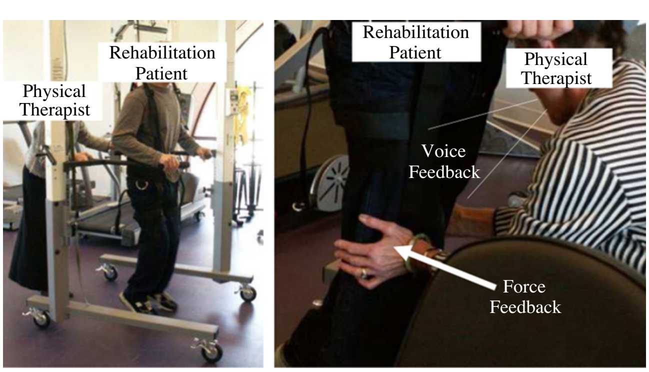

Fig. 2. Voice/force feedback in gait rehabilitation training.

2.2. Assistive torque in robotic gait rehabilitation devices

The goal of gait rehabilitation training is for patients that suffer from gait disorders to restore locomotion through rehabilitation of their degenerated muscular or neural functions. By applying assistive torque to the patient's joint, a patient can either practice the desired gait trajectory for rehabilitation or strengthen muscles. If the patient's problem is an inability to supply sufficient muscle strength to meet the demands of desired gait motions (insufficient ② in Fig. 1), then the patient needs assistive torque in order to achieve the desired motion. In this case, the gait rehabilitation strategies that emphasize the recovery of muscular forces are required. Applying appropriate resistive torque to strengthen muscles is one of the possible rehabilitation strategies. Patients with impaired nerve systems, e.g. spinal cord injury (SCI) or stroke, cannot control their muscles due to abnormal motor control signals (abnormal ① in Fig. 1). For these patients, physical therapists apply voice or force feedback to patients during gait rehabilitation training as shown in Fig. 2. Through force or voice feedback, physical therapists educate patients of normal joint trajectory and also physically guide patients to the desired joint trajectory for rehabilitation. In this paper, the gait rehabilitation strategy on how to determine assistive torque in robotic gait rehabilitation devices in order to practice a rehabilitative gait trajectory is discussed.

3. A gait rehabilitation strategy inspired by an iterative learning algorithm

3.1. A gait rehabilitation strategy inspired by a potential field

The assistive torque in robotic gait rehabilitation devices provides a "feeling" to patients that allows them to sense how far their gait motions deviate from the desired gait trajectories. Through "feeling", the patients can learn the desired gait trajectory and be guided to the correct gait trajectory. Thus, the assistive torque should be proportional to the deviation from the desired gait trajectory and be capable of guiding the joint to the gait trajectory effectively and accurately. Since the amount of torque is related to the deviation from the normal trajectory, it can be considered as an impedance between human and the robotic gait rehabilitation device [17].

Previously, the gait rehabilitation strategy was formulated using a potential field [3]. In this strategy, a virtual potential field is placed around the desired trajectory, which generates induced forces for the joint to stay on the desired trajectory. The concept of the induced force by the potential field is shown in Fig. 3.

The potential field, P_A, for the gait rehabilitation strategy can be expressed as a function of the human joint angle, y_H, and the desired joint angle for rehabilitation, y_R, as follows:

$$P_A = \alpha(y_H - y_R)^\beta \tag{1}$$

The values of α and β can be selected as any values considering the patients' status or the aim of rehabilitation training, as long as P_A has a global minimum at y_R. The amount of the assistive torque is