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Active disturbance rejection control based human gait tracking for lower extremity rehabilitation exoskeleton

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ABSTRACT

This paper presents an active disturbance rejection control (ADRC) based strategy, which is applied to track the human gait trajectory for a lower limb rehabilitation exoskeleton. The desired human gait trajectory is derived from the Clinical Gait Analysis (CGA). In ADRC, the total external disturbance can be estimated by the extended state observer (ESO) and canceled by the designed control law. The observer bandwidth and the controller bandwidth are determined by the practical principles. We simulated the proposed methodology in MATLAB. The numerical simulation shows the tracking error comparison and the estimated errors of the extended state observer. Two experimental tests were carried out to prove the performance of the algorithm presented in this paper. The experiment results show that the proposed ADRC behaves a better performance than the regular proportional integral derivative (PID) controller. With the proposed ADRC, the rehabilitation system is capable of tracking the target gait more accurately.

1. Introduction

Various diseases and injuries, e.g., spinal cord injury and stroke have a dysfunction and impaired mobility in the lower limbs of patients. It is a good and regular way to conduct rehabilitation training to help these patients recover and regain mobility [1]. In the traditional rehabilitation training, physical therapists involve intensive labor and have to provide the patients with highly repetitive and inefficient training [2]. Therefore, it is meaningful to develop assistive devices to help disabled people regain the ability to stand and walk, and release physical therapists from the heavy work of rehabilitation training [3]. Robotic exoskeletons are developed to help patients who suffer from neurological disorders to recover lower limbs' mobility [4]. Compared with traditional manual assistance and training, the application of rehabilitation robotic exoskeletons can perform as well as the physical therapists and more importantly, free the physical therapists from the heavy work of rehabilitation training [5]. In recent years, many studies have been conducted to develop various types of rehabilitation exoskeletons and much progress has been made. Lower extremity rehabilitation exoskeletons can be divided into four categories according to their mechanisms and rehabilitation principles [6], i.e., treadmill-based exoskeletons, e.g., LOPES [7] and ALEX [8], leg orthoses and exoskeletons, e.g., KAFO [9] and HAL [10], foot plates-based end-effector devices, e.g., Haptic Walker [11], and platform-based end-effector robots, e.g., ARBOT [12].

Leg orthoses and exoskeletons, which are parallel with the human body and have anthropomorphic structure, can help the human body to move normally. Generally, patients are able to regain the strength of limbs and recover from the injury gradually through three different stages of rehabilitation training, i.e., the preliminary stage, the intermediate stage and the advanced stage [13,14]. In the preliminary stage, the regular control strategy called the passive control mode, aimed to drive the exoskeleton system by tracking the predefined trajectory, is conducted to help patients reduce muscle atrophy and regain the movement ability to some extent. The patient has a certain degree of movement ability after the preliminary stage and is encouraged to try some active motions under the help of exoskeleton in the intermediate stage. In the advanced stage, the active mode is designed to help the limbs walk according to the patient's motion intention. The preliminary stage is the first and the most important step, which is the foundation of the other two stages. In fact, this kind of method is based on fixed trajectories, which can adapt to different step lengths. For the robotic exoskeleton of assistance and rehabilitation, the control strategies can be divided into three categories according to the approach of acquiring the interaction signal, i.e., biomedical signals based control strategies, control strategies based on human robot interaction signals and control strategies based on signals of mechanical system [15]. With the consideration of training purpose and controller development progress, the control strategies can generally be divided into four categories: position tracking

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control, force and impedance control, bio-signals based control and adaptive control [14].

Among control strategies for rehabilitation robotic exoskeleton, position tracking control is the basis of other approaches. It is essential to achieve continuous and repetitive training by using control algorithms with high accuracy. The rehabilitation exoskeleton, generally, is designed to follow the predefined gait trajectory and to response to predefined action based on gait pattern [16]. Under a predefined gait trajectory control mechanism, the predefined joint trajectory is derived from the clinical gait analysis or recorded by a healthy person, which is the desired trajectory of the robotic exoskeleton. Many kinds of rehabilitation system adopted the predefined gait trajectory control mechanism and achieved the tracking performance. The ATLAS project developed an active orthosis for the children who suffer from quadriplegia. The orthosis obtains the gait trajectory of the hip and knee joint from the healthy children and the deployed control strategy is dependent on the phase identification [17]. The IHMC exoskeleton is developed to help the patient with lower extremity paralysis and it is capable of working in several modes, e.g., zero assistance mode and gait rehabilitation mode. The rehabilitation mode obtains its desired trajectory from the recorded gait of the healthy people [18]. The famous ReWalk is developed to help the patients with spinal cord injury to regain their walking ability. The ReWalk's hip joint and knee joint are controlled to follow the predefined trajectory [19]. The MINDWALKER exoskeleton is designed to help paraplegics to regain locomotion capability and the gait assistance is provided respectively in both lateral and sagittal plane. The desired joint trajectory is recorded from the healthy people [20]. Most of the exoskeleton systems, which have the rehabilitation training mode, take consideration of the predefined trajectory tracking control. However, the disturbances existing in the system affects the performance of joint trajectory tracking. The disturbances estimation and elimination are not reported in those rehabilitation exoskeleton systems.

There are several strategies for position control to track the predefined human gait trajectory. These control strategies can be divided into two categories, i.e., model-based strategies such as computed torque control [21] and model-free strategies such as PID [22]. The model-based control strategy needs a complete knowledge of the robot dynamics to obtain a good trajectory tracking performance. However, this type of control strategy is much dependent on the accuracy of the mathematical model and is not very suitable for problems in the presence of uncertainties, disturbance inputs, non-modeled dynamics, and additive measurement noises [23]. The PD/PID-based controllers are designed with the tracking errors and without considering the coupling effects and their performance is normally affected by the disturbance inputs [24]. Some compensation control laws, e.g., feedforward control, are necessary to improve the tracking performance. The PID control strategy has simple and generic structures, which is not model-dependent with adjustable parameters. With adjustable parameters, the general PID control structure can be applied in industries [25].

In practical situations, an ideal environment without any disturbances does not exist. The existing disturbances need to be compensated for better performance. The central objective of ADRC is to treat the internal and external uncertainties as a total disturbance and to eliminate them actively [26]. The ADRC strategy does not require the complete knowledge of the dynamics and splits the plant to a set of disturbed systems, which are estimated online for a subsequent proper cancellation. In addition, any priori knowledge of the dynamics system is allowed to be incorporated into the ADRC design [27]. The total disturbance existing in the plant can be estimated by the so-called extended state observers (ESOs) [28,29]. Since the performance of the ADRC depends upon the gain selection of the ESOs, it is necessary to tune parameters and obtain accurate estimations to avoid undesired effects [30]. ADRC strategy has been successfully implemented in robotics. An ADRC framework was implemented on a flexible joint manipulator to limit the effects on the plant caused by nonlinear behavior and changeable dynamics parameters [31]. It was proposed to drive a SCARA robot manipulator to track a predefined trajectory and had a superior performance compared with a classic feedback linearization control strategy [32]. The proposed ADRC method could provide good tracking performance and deal with disturbances well. A linear observer-based robust feedback scheme was designed for output reference trajectory tracking for an omnidirectional mobile robot [33]. Han presented that ADRC was capable of replacing PID strategy with unmistakable advantage in performance and practicality and providing solutions for problems under disturbances [34]. However, the ADRC strategy is not reported to be applied in the development of the rehabilitation system.

In this paper, ADRC strategy is applied to drive the lower extremity robotic exoskeleton to follow the human gait trajectory. Based on the mathematical model of the robotic exoskeleton, the ESO is used to estimate the disturbances existing in the dynamics model online. With the estimated disturbances, the ADRC control law is obtained. Simulations are carried out in MATLAB to prove the ADRC strategy is stable and correct. Experiments with real robotic exoskeleton are performed and their results show that the ADRC has superior performance than that of general PID strategy. It is a novel methodology to apply ADRC strategy to replace the regular position control strategy in the robotic rehabilitation exoskeleton. Relevant experiments are conducted to show that the performance of the proposed strategy is superior to regular PID method, especially under external disturbances.

The rest of this paper is structured as follows. The robotic rehabilitation system is given in the second section. The proposed control strategy scheme is developed in the third section. Simulations are shown in the fourth section. Experiments using the proposed approach and results analysis are presented in the fifth section. Conclusions are drawn in the final section.

2. Robotic exoskeleton under studying

Based on principles of biological design, the designed exoskeleton is required to retain adaptability to multi-functionality of human lower limbs. An available powerful tool when designing an assistive exoskeleton is the enormous Clinical Gait Analysis (CGA) data on human walking. The degree of freedoms (DOF) of the hip joint and the knee joint in the sagittal plane are activated by electrical motors, which are embedded in the structure and transfer the rotational motion through bevel gears, as shown in Fig. 1. The mechanical links are made of aluminum alloy and carbon fiber. In the design of the hip joint and the knee joint, bevel gears are used to change the motion direction of the motors, which are embedded in the leg of the exoskeleton to get a compact structure, as is shown in Fig. 1. The connection cuffs play the role of fastening the exoskeleton to the user. The thigh segment of the mechanical leg weights about 5 kg while the shank segment weights about 2 kg. The lower extremity exoskeleton is suitable for the patients whose height ranges from 170 to 190 cm, where length of thigh can be adjusted in the range of 435–485 mm while the shank can be adjusted in the range of 475–525 mm.

For multi-rigid system, Euler-Lagrange is a frequently used modeling method of robotic manipulators. The exoskeleton is a typical human-robot collaboration system, in which the user's lower limbs and mechanical limbs are connected together using interaction cuffs. Mathematical model of a single leg of exoskeleton is obtained because of its symmetry structure. Without loss of

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