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Research article

Tracking control of time-varying knee exoskeleton disturbed by interaction torque

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ABSTRACT

Knee exoskeletons have been increasingly applied as assistive devices to help lower-extremity impaired people to make their knee joints move through providing external movement compensation. Tracking control of knee exoskeletons guided by human intentions often encounters time-varying (time-dependent) issues and the disturbance interaction torque, which may dramatically put an influence up on their dynamic behaviors. Inertial and viscous parameters of knee exoskeletons can be estimated to be time-varying due to unexpected mechanical vibrations and contact interactions. Moreover, the interaction torque produced from knee joint of wearers has an evident disturbance effect on regular motions of knee exoskeleton. All of these points can increase difficultly of accurate control of knee exoskeletons to follow desired joint angle trajectories. This paper proposes a novel control strategy for controlling knee exoskeleton with time-varying inertial and viscous coefficients disturbed by interaction torque. Such designed controller is able to make the tracking error of joint angle of knee exoskeletons exponentially converge to zero. Meanwhile, the proposed approach is robust to guarantee the tracking error bounded when the interaction torque exists. Illustrative simulation and experiment results are presented to show efficiency of the proposed controller. Additionally, comparisons with gradient dynamic (GD) approach and other methods are also presented to demonstrate efficiency and superiority of the proposed control strategy for tracking joint angle of knee exoskeleton.

1. Introduction

Recently exoskeletons have emerged as a new type of service robots, drawing widespread interests from both researchers and engineers in multiple communities. Exoskeletons are wearable robots for people to make up for a deficiency during accomplishing jobs such as compensating movement, augmenting strength, and carrying load. In order to assist motion of humans, lower-extremity exoskeletons are often utilized to help subjects to fulfill gait training. In the past decades, there are several representative exoskeleton systems designed and developed, and various modeling and control approaches are proposed according to different implementation scenarios. As one of the most famous exoskeletons, the Berkeley lower extremity exoskeleton (BLEEX) was initially used to transferring load of walking solders [30,5]. In this BLEEX exoskeleton, sensitivity amplification control algorithm is applied aiming at reducing the complexity of sensory system. The goal of such control algorithm is to constrain the interaction force as small as possible during motion synchronization between human and exoskeleton [10,24]. Another famous exoskeleton system in human strength augmentation is hybrid assistive limb (HAL) which was developed by Sankai et al. [22]. In this exoskeleton system, impedance control and human intention detection were both incorporated to enhance human power, by calculating the reference patterns of pilots and predicting human-exoskeleton interaction directly from electromyography (EMG) sensors [14,9]. Other exoskeletons have been further proposed to manage the changing dynamics for various types of movement by additionally equipping inertial and acceleration sensors for realizing closed-loop control strategies [2].

Knee exoskeleton is one kind of mainstream exoskeletons which achieve daily movement training, and provides power to enable knee joint of humans to move and follow reference knee angular trajectories [8]. In addition to drive human knee joint movement externally, knee exoskeletons can be used as active orthoses for injured pilots to correct abnormal gait as well [23]. Many related works on knee exoskeletons have been proposed in past twenty years. Knaepen et al. analyzed powered knee exoskeleton of kinematics during human-robot interaction and found different kinematic parameter settings might not have clear impact on control performance, suggesting that powered knee exoskeleton should be optimally designed unilaterally and in one

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degree-of-freedom [11]. Zanotto et al. studied effects of knee exoskeleton misalignments which change human-robot interaction forces, and this effect can be attenuated by actively compensating for robot inertia [25]. Aguirre-Ollinger et al. applied active impedance control to improve the user's agility of motion by considering virtual viscous (damping) factor ahead of controller, which indicates modulating varying viscous (damping) coefficients might benefit to compensate for perturbations from the environment [1]. Laffranchi et al. pointed out that involving physical variable damping factors into robot dynamics might enhance compliant control performance toward exoskeletons [13]. From aforementioned representative works we can conclude that, there are increasingly needs to investigate knee exoskeleton model with time-varying issues such as dealing with time-varying inertial and viscous parameters, and thus developing relevant control strategies to attain better compliance becomes more urgent. However, many current knee exoskeleton models are primitively studied with time-independent (static) inertial and viscous factors, and the corresponding control algorithms are established based on such stationary parametric models without considering disturbance interaction torque. However, there is still lack of novel control approaches which can specifically handle time-varying knee exoskeleton models with compliant interaction components. Robust and adaptive control approaches are thus required urgently to improve the control performance of time-varying and nonlinear plants such as exoskeletons with uncertain disturbance and time-varying issues. For example, in a recent work [16,17] by Li et al., a novel output feedback control is proposed for control of such type of complicated systems. Most recently, the sliding mode control against the disturbance in control of electrical actuation systems has been becoming popular, some good works have been proposed for control of power converters to reject external disturbances by Liu et al. [21,19,20]. Chen et al. [4,3,15] have proposed novel robust control strategies for torque actuator systems to overcome the disruption from external disturbances. Inspired by these promising works to achieve superior control performance, we try to propose a specific control approach that can manage the aforementioned control issues on knee exoskeleton systems.

In this paper, we focus on designing a control strategy for time-varying knee exoskeleton with interaction torque. A novel systematic framework for solving series of time-varying problems initiatively proposed by Zhang et al. [28] can be considered to be incorporated. Such Zhang's method is not only able to solve linear/nonlinear time-varying algebra problems, but also can drastically improve control performances on some nonlinear/linear systems, overcoming disadvantages of traditional numerical methods and remedy current approaches for tacking with time-varying issues appeared in relevant fields. For instance, in [29], Zhang dynamics (ZD) was proposed to solve for online solution of nonlinear time-varying equation. In [27], a sort of Zhang neural network was proposed for time-varying full-rank matrix Moore Penrose inverse solving. In [26], Zhang dynamics assisted control algorithm was applied to tracking control of a class of chaotic systems with singularity-conquered, via repeatedly applying Zhang function (ZF) for processing the tracking error elegantly [18]. In [6], redundant-manipulator kinematic control via time-varying Jacobian matrix pseudoinversion by Zhang neural network was developed. As seen from these works, Zhang's method has been sealed to be a powerful alternative when applied in tackling time-varying computing and control issues. Inspired by these properties and characteristics of ZD, we involve such novel ZD method into our proposed paradigm of tracking control of time-varying knee exoskeleton with interaction torque. Zhang function (ZF) is defined twice and used to ensure the tracking error of knee joint exponentially converge to zero. The resultant ZD based controller takes advantage of time-derivative information of the desired joint trajectory, and can be depicted in an algebraic expression. Illustrative examples including experimental results validate the proposed controller based on ZD for controlling time-varying knee exoskeleton model with interaction torque, and demonstrate its superiority as compared with the conventional gradient dynamics (GD) based controller.

The main contributions of this paper can be summarized and emphasized as follows. 1) We proposed a control approach based on ZD principle for tracking control of knee exoskeleton with time-varying inertial and viscous parameters, and such time-varying control issue on exoskeletons is seldom investigated in past literature; 2) The proposed controller is robust to make the knee exoskeleton with interaction torque disturbed to follow the desired joint trajectory with bounded tracking errors; 3) Moreover, if the interaction torque is assumed to be zero, such ZD based controller is with exponential convergence to make the knee exoskeleton track the desired trajectory; 4) The tracking error bound of knee exoskeleton synthesized by the proposed ZD-based controller can be lowed down via increasing the design parameter; 5) As compared with the conventional GD based controller and other controllers (e.g., PID controller), the proposed control method shows superior and robust tracking control performances for such specific control issue.

The rest of the paper is organized as follows. Section 2 addressed the design and theoretical analysis of the proposed ZD based knee exoskeleton controller, in the meantime, the conventional GD based controller is also addressed in this section. Section 3 shows illustrative simulation and experiment results on controlling of time-varying knee exoskeleton with interaction torque, and comparisons with GD based approach is presented as well. Afterwards conclusions are drawn finally in Section 4.

2. Model description and methods

According to studies of biomechanics and dynamics of human gait [12], the normal walking gait can be generally divided into several distinct phases. Regarding to a single leg, a stance phase for load transfer and a swing phase for unloaded movement can be involved. In the first version of BLEEX, the control algorithm was implemented in the swing phase since the swing phase has large motions with high bandwidths compared to the stance phase. The schematic diagram of a knee exoskeleton system is shown in Fig. 1 [7]. This figure depicts a human leg attached with the knee exoskeleton flexibly in a swing movement. The knee exoskeleton is powered by a actuator which exports and transfers torque to knee

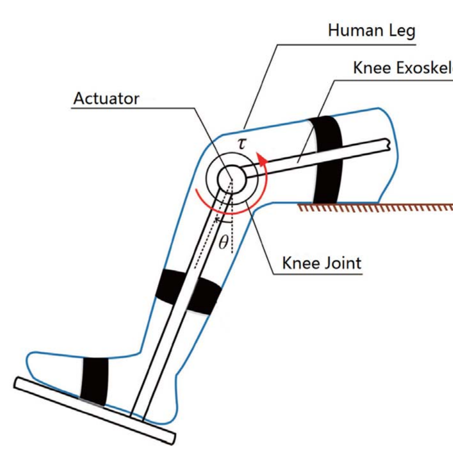

Fig. 1. The schematic diagram of a knee exoskeleton for training movement of a pilot.

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