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Designing a backstepping sliding mode controller for an assistant human knee exoskeleton based on nonlinear disturbance observer☆

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ABSTRACT

In present study, a knee exoskeleton was designed to assist human movements in the flexion/extension of the knee. Moreover, a control method was proposed for the exoskeleton to track the desired position trajectory of the knee. Subsequently, an integrated human shank and exoskeleton model based on the sitting position was considered. A nonlinear disturbance observer (NDO) was used to reduce the influence of the uncertainties and external disturbance in modeling of the whole system. Furthermore, a backstepping sliding control (BSC) approach combined with the nonlinear observer was presented. To improve performance of BSC, genetic algorithm (GA) was employed to determine the optimal backstepping sliding control law parameters. The asymptotic stability of the presented controller and nonlinear disturbance observer convergence were mathematically verified based on the Lyapunov theory. The superiority of the proposed control method is shown in comparison to some recent new methods. The suggested controller can reduce the disturbance rejection time. The chattering and tracking error of NDO sliding mode control was also reduced. The proposed controller was simulated in MATLAB (a registered trademarks of The MathWorks, Inc.) and OpenSim was used to model the human knee. Moreover, some experimental results verified the designed system and its simulation and illustrated that the backstepping sliding mode controller based on the nonlinear disturbance observer can track the reference position by considering a nonlinear model of the identification errors and the external disturbances.

1. Introduction

The knee exoskeleton is a simple exoskeleton which add power to the knee so as to assist flexion and extension of the knee in the sagittal plane [1]. This exoskeleton consists of a linear series elastic actuator (SEA) connected to the upper and lower portions of the knee brace [2]. By applying power to the knee joint, this device can allow greater control on gains, while exhibiting a physically low-impedance interface to the wearer, and remaining safe to the operator. Moreover, the knee exoskeleton is used in cases with musculoskeletal disorders at the knee joint . This kind of exoskeleton can be used for rehabilitation or assistance purposes to strengthen or aid damaged limb function [3]. As an example, in patients with osteoarthritis, which affects the ligaments or cartilages, this exoskeleton can be used to strengthen the muscles, reduce the stiffness and provide joint stabilization. Similarly, after total arthroplasty, the knee exoskeleton is used to reduce knee stiffness and increase knee range of motion by performing static progressive stretch. Furthermore, patients who have had a stroke, or those with spinal cord or traumatic injuries can use an exoskeleton to regain control of their limbs and perform daily activities [4].

A single axis knee joint is a common structure in existing knee exoskeletons [5,6]. Regarding single-joint artificial orthotics, a simple hinge structure is used that can be constructed easily and have good durability. However, it can only control the swing phase and cannot control the stance phase sufficiently. In real human knee joints, when the knee joint moves with a polycentric motion, the center of rotation changes during the rotation [7]. Due to this characteristic, a single-joint exoskeleton cannot completely track the human knee-joint motion. In addition, this center misalignment results in loss of energy. Currently, a four-bar linkage is used in assisting devices [8,9]. However, the features that the four-bar linkage is used for in assisting devices is different from those of prostheses. The relative motion between the wearer and the assistive device can be reduced by using the four-bar linkage, since it can provide a polycentric motion similar to that of a human knee joint. If the relative motion is not reduced, the resulting friction will cause skin abrasion and become a source of loose binding force. Thus, four bar linkages can minimize these problems and, due to the similarity of their motion to human knee joints, improve comfort during wearing the

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exoskeleton. In this research, a four-bar linkage based on the study by Norton [10] for the designed knee joint was selected and implemented .

To date, many researches have been attracted to the field of control strategies in the lower limb exoskeleton [11]. Some earlier works in this field will be presented in this section. Roboknee assists the thigh muscle during flexion and extension to enhance the wearer's performance by using a proportional controller [12]. To evaluate the user's contribution, two load cells are, normally, placed in the users shoes to measure the ground vertical reaction force. However, the users effort was determined in the study by Fleischer and Hommel [13] using electromyogram (EMG) electrodes placed at his/her thigh and linked to the knee joint. The desired behavior of the system composed of the lower limb and the exoskeleton is defined by the term adaptability of the exoskeleton parameters.

The systems stiffness is reduced by adding an elastic brace parallel to the knee joint, and this causes the raise in running abilities [14]. Then, damping and inertia parameters of the system are modulated with respect to the wearers intention. In fact, the knee exoskeleton system inertia, viscous/damping coefficients and the subject's properties (e.g. mass and height) vary in the time that from a subject to another [15]. In addition to this, there are parameter uncertainties in the whole system such as errors in parameter identification, and external disturbances such as involuntary movements performed by the wearer as well as external interactions with the environment. Therefore, the use of a robust controller is an obligation. To date, different robust controllers have been proposed in this regards. The First Order Sliding Mode Controller (FOSMC) has been used by Jezernik et al. to drive the Lokomat system for the restoration process of a dependent subject's lower limbs movements [16]. Tzu-Hao Huang used the same control strategy (FOSMC) to drive a Lower Limb Exoskeleton. Besides, determining the sliding control law and the optimal sliding surface, the genetic algorithm (GA) was applied to progress the effect of SMC [17]. A robust terminal sliding mode control (RTSMC) method combined with a nonlinear disturbance observer (NDO) is also used to reduce the required time for eliminating external disturbances [18].

This study proposed a control method of a designed knee exoskeleton, that has one revolute joint in the sagittal plane and can assist patients in strengthening their muscles in the sitting position. A nonlinear disturbance observer was presented to estimate the muscular torque developed by the wearer and the uncertainties of the modeling [20]. Moreover, a robust Backstepping Sliding Control (SBC) with NDO was proposed, instead of a basic sliding mode controller that can estimate the external disturbance, improve the tracking precision and extend the control bandwidth, which is a major disadvantage of the basic sliding mode. To validate the proposed controller, first, it is simulated in OpenSim and MATLAB, and then, it is compared with four published methods (basic SMC, NDO based SMC, and RTSMC). Finally, the proposed controller is applied to the knee exoskeleton designed based on the four-bar linkage at the knee joint.

The paper is organized as follows. In Section 2, the knee exoskeleton design and its mechanical structure is presented. The nonlinear knee exoskeleton motion mathematical model with disturbance is established in Section 3. The NDO-based SBC approaches and analysis of its stability by means of Lyapunov theory are presented in Section 4. In Section 5, the identification parameter of the knee-exoskeleton is described. The simulation results are presented in Section 6 followed by experimental results, discussions and conclusions.

2. Knee exoskeleton design

The designed exoskeleton consists of two main segments related along by a four bar mechanism and a curved one. One segment of it is connected to the human thigh whereas the other is attached to the shank using braces (Fig. 1). This system is designed to carry out the flexionextension movement of the human knee joint. Two main supports (lower and upper) are fixed on the leg by means of velcro closures that tighten themselves over a soft rubber part. The soft part provides comfort and prevents dry friction between the human leg and the exoskeleton. The knee exoskeleton has one DOF at the knee joint. The rotational power of the exoskeleton is provided by a linear actuator that converts linear motion into rototranslational motion. Since the actuator is fixed, the curved segment as seen in Fig. 1, is used to convert the linear motion of the actuatorin in to circular motion.

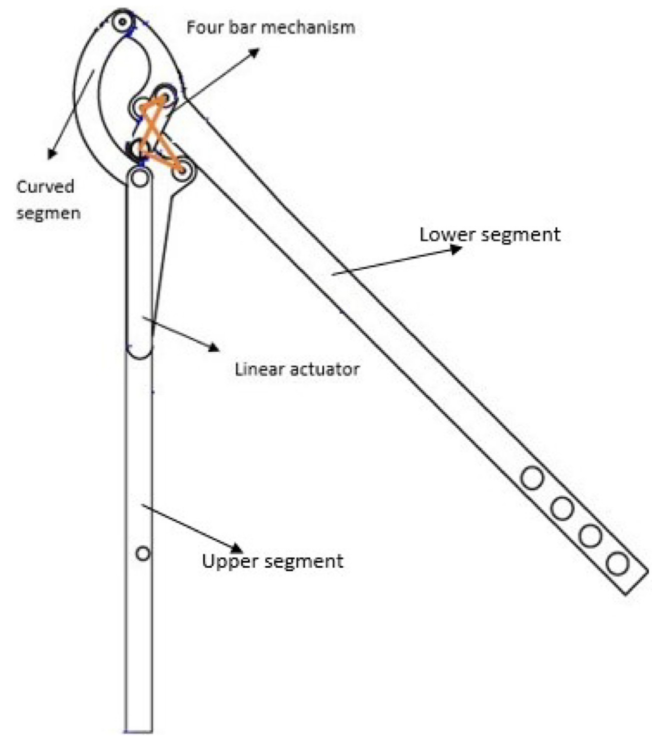

Fig. 1. Knee exoskeleton segments.

The four-bar linkage can maximize kinematic compatibility and limit the migration of the knee brace relative to the knee. A sitting advantage of the four bar knee linkage is the effective shortening of the shin as it passes into flexion. This advantage also gives the unilateral above knee amputee the visual appearance of legs with matching knee heights when sitting. For tall amputees with an excessively long shin, it can cause clearance problems in cases such as sitting at desks or tables. Furthermore, the tall amputee is forced into an uncomfortable position of excessive hip flexion, when sitting on low chairs. By the shortening action of the shank in the sitting position, the four- bar linkage can reduce both of these problems [21].

2.1. Mechanical structure

Utilizing the four-bar linkage, the torque and rotation speed of the whole system can be controlled through the operation of the motor attached to the crank [10]. In Fig. 2, the four bar linkage used in the knee exoskeleton is shown along with the angle and length of eachlink. The loop closure Eq. (1) simply sums the position vectors around the complete four-bar linkage, and in vector form it is given as:

$$L_1 e^{j\theta_1} + L_2 e^{j\theta_2} + L_3 e^{j\theta_3} + L_4 e^{j\theta_4} = 0 \quad (1)$$

There are four variables in Eq. (1) and the link lengths are all constant. The value of the angle of the link L_1 is θ_1 is assumed fixed and similar to the ground link. The independent variable is θ_2 which is controlled by a motor. The following algebraic expressions define θ_3 and θ_4 as the functions of the constant link length and the input angle.

$$\theta_3 = f_1(L_1, L_2, L_3, L_4, \theta_2) \quad (2)$$