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Nonlinear disturbance observer based sliding mode control of a human-driven knee joint orthosis

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HIGHLIGHTS

- This paper deals with the control of a knee joint exoskeleton for rehabilitation purposes.
- An observer is proposed to estimate the muscular torque developed by the wearer.
- A robust terminal sliding mode control method combined with the observer is presented.
- Asymptotic stability is proved by means of a Lyapunov analysis.
- Experiment tests were conducted with three subjects.

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ABSTRACT

The present paper deals with the control of a knee joint orthosis intended to be used for rehabilitation and assistive purposes. A model, integrating human shank and orthosis, is presented. To reduce the influence of the uncertainties in muscular torque modeling on the system control, a nonlinear observer is proposed to estimate the muscular torque developed by the wearer. Additionally, a robust terminal sliding mode control approach combined with the nonlinear observer is presented. To illustrate the effectiveness of the proposed control method, a comparison with two control methods, basic sliding mode and sliding mode with nonlinear observer, are also given. The asymptotic stability of the presented approaches and observer convergence are proved by means of a Lyapunov analysis. Furthermore, the proof of advantage of the robust terminal sliding mode control method with the nonlinear observer (improving the tracking precision and reducing the required time for eliminating external disturbances) is proposed as well. The experiment results show that the robust terminal sliding mode control approach combined with the nonlinear observer has a significant advantage with respect to the position tracking and robustness regarding the modeling identification errors and external disturbances.

1. Introduction

Wearable robots are mechatronic devices that are embodied by the human upper and/or lower limbs to enhance the ability to achieve a given task. Their structure should suit perfectly the embodying limbs such that the set moves synchronously and can be considered as one unit. These exoskeletons, also called orthoses, have drawn a large amount of interest related to the increase of the elderly and dependent populations. The domains of application concern the assistance of the user during daily activities, the rehabilitation of the impaired joints or limbs and the muscles strengthening.

Lower limb exoskeletons act at the hip, knee and/or ankle joint levels. They are equipped with sensors gathering information about the orientation of the joints, position of the limbs, ground reaction force, muscular activities, etc. as well as actuators delivering the necessary power to drive the exoskeletons and contribute to, or even induce, the movement of the limbs. The amount of power that should be provided to ensure a given task is determined by means of an appropriate control law. The task can be characterized by a desired trajectory, determined by a therapist in post-operation for rehabilitation cases, or following the intention of the user to improve his/her performance. This intention is estimated relying on data issued from on-board sensors, detecting the brain or muscle activities, posture, etc.

Exoskeletons, having several degrees of freedom, allow to tackle deficiencies in multiple joints such as the robot suit HAL [1] and ensure gait restoration using some treadmill-based devices as the

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Lokomat [2] and LOPES [3]. Knee orthoses are mainly used to treat musculoskeletal impairments at the knee joint level. Two main purposes are targeted: the rehabilitation and assistance, to strengthen or aid damaged limb functions. For example, they are used by osteoarthritis patients, whose ligaments or cartilage are affected, to strengthen the muscles, reduce the stiffness and provide joint stabilization. A patient-directed orthosis is used after total knee arthroplasty to reduce the knee stiffness and increase its range of motion by performing a static progressive stretch in [4]. They are equally used by patients who have been subject to a stroke, spinal cord or traumatic injuries to help them regain control of their limbs and ensure daily activities. A study has shown that the use of an untethered knee joint orthosis has enhanced the gait speed of post stroke patients; the level of patient intervention during training is fixed by a physical therapist [5,6].

So far, many researches on the control strategies of the wearable exoskeletons have been presented [7]. Some works dealing with the control of knee joint orthoses will be presented in the following. Roboknee aims to enhance the wearer performance by assisting the thigh muscles during flexion and extension of the knee joint using a proportional controller [8]. The user's contribution is evaluated by measuring the ground vertical reaction force using two load cells placed in the shoes. The user's effort is determined in [9] using Electromyogram (EMG) electrodes placed at the thigh and linked to the knee joint torque through the muscle model. Proportional control of the orthosis linear DC motor is also used to amplify the weak torque generated by the knee joint. Adaptability of the exoskeleton's parameters has been used to define a desired behavior of the system composed of the lower limb and the exoskeleton. The system's stiffness is reduced by adding, in parallel to the knee joint, an elastic brace aiming to increase running abilities [10]. Damping and inertia parameters of the system has been modulated in [11–13] with respect to the wearer's intention. PID and Linear Quadratic (LQ) controllers have been used respectively to track the desired trajectory. Previous works of the authors [14,15] have considered the orthosis EICOSI (Exoskeleton Intelligently COmmunicating and Sensitive to Intention) with a full motor actuation for knee joint passive rehabilitation purposes. For very weak muscles, hybrid exoskeletons associated to functional electrical stimulation of the muscles can be used [16]. For example, the cyberthosis is dedicated for muscle training and knee joint flexion/extension movement execution by means of a proportional, integral, derivative (PID) controller [17].

The present paper deals with the control of the orthosis EICOSI (Exoskeleton Intelligently COmmunicating and Sensitive to Intention), which has one revolute joint degree of freedom at the knee joint level. EICOSI has a simple structure, easy to don and doff and practical for people suffering from knee joint impairments. In this paper, the EICOSI is mainly considered to assist patients to strengthen theirs muscles in a sitting position. A model integrating the human lower-limb and orthosis is proposed. Considering the different characteristics of the joints, the human muscular effort is taken into account in the control strategy. To obtain satisfied control performances, a nonlinear observer is presented for estimating the muscular torque developed by the wearer, and the uncertainty in muscular torques estimation is considered as an external disturbance. Furthermore, a robust terminal sliding mode control method combined (RTSMC) with a nonlinear disturbance observer (NDO) is presented. Compared with the basic sliding mode, NDO based sliding mode control (SMC) can enhance the tracking precision, estimate the external disturbance and extend the control bandwidth, which is a major disadvantage of the basic sliding mode. Furthermore, since the terminal sliding mode control can guarantee the tracking error to converge to zero in finite time [18], a NDO based RTSMC is proposed to reduce the required time for eliminating external disturbances and improve the robustness at the same time. The asymptotic analysis of the NDO based SMC and NDO based RTSMC are given in this paper. The advantage of NDO based RTSMC with respect to the convergence time is analyzed as well. For comparison, experiments conducted with different subjects within three control methods (basic SMC, NDO based SMC and NDO based RTSMC) have been performed respectively to show the efficiency and advantages of the NDO based RTSMC in terms of tracking precision, required time for eliminating disturbances and robustness to external disturbances.

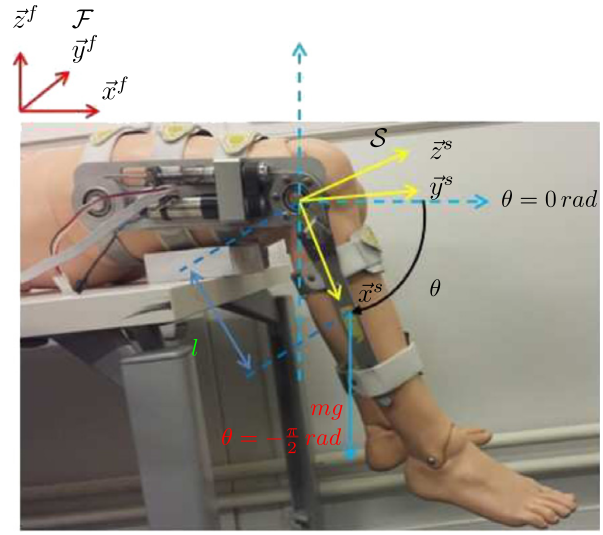

Fig. 1. A subject wearing the robotics orthosis ($\mathcal{F}$: Base Frame; $\mathcal{S}$: Coordinate System of Shank).

The paper is organized as follows. The shank–orthosis model is presented in Section 2. The NDO based SMC and NDO based RTSMC approaches and analysis of their stability by means of Lyapunov analysis are presented in Section 3. Experimental setup and the parametric identification of the shank–orthosis system are addressed in Section 4. Experimental results are presented in Section 5. Finally, conclusions and future works are outlined in Section 6.

2. System modeling

A subject wearing the robotic orthosis with the shank freely moving around the knee joint is illustrated in Fig. 1. This system is designed to carry out the flexion-extension movement of human knee joint. The robotic orthosis consists of two segments attached to the thigh and shank separately. It is fixed to the wearer leg by appropriate braces. The robotic orthosis has one DOF at the knee joint, which is driven by both the actuator and human thigh muscles.

According to the Lagrange formulation, the dynamic model of the shank–orthosis system can be written as:

$$J\ddot{\theta} = -\tau_g \cos\theta - A\text{sign}\dot{\theta} - B\dot{\theta} - K(\theta - \theta_r) + \tau + \tau_h \qquad (1)$$

with:

- $J = J_s + J_o$: the sum of inertia of shank and orthosis,
- $\tau_g = m_s l_s g + m_o l_o g$: the gravitational term in which m_s and $l_i\ (i \in \{s, o\})$ are the masses and lengths of the shank and orthosis respectively,
- $A = A_s + A_o, B = B_s + B_o$: the solid and viscous friction parameters of shank and orthosis,
- K: the stiffness of the knee joint,
- θ_r: the rest position of the knee joint,
- $\tau,\ \tau_h$: the input torques of the actuator and human effort respectively.