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A robust adaptive neural control scheme to drive an actuated orthosis for assistance of knee movements ☆

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ABSTRACT

In this paper, we present an actuated orthosis intended to assist the subject's movements for flexion/extension of the knee. The equivalent system “subject's lower limb-actuated orthosis” is considered as black-box and is driven by a Multi-Layer Perceptron Neural Network (MLPNN) controller. This controller is adaptive, does not require the dynamic model of the system and is able to take into account all its uncertainties. The latter include the nonlinearities due to the subject's lower limb/actuated orthosis coupling, the modeling and identification errors as well as the parameter uncertainties resulting from the system's dynamics. Stability of the “subject's lower limb-actuated orthosis” system, using the proposed approach, is mathematically proved based on the Lyapunov theory. Performances of the proposed MLPNN controller are compared to those of the PID (Proportional Integrator Derivative) controller for the track of desired position and velocity trajectories. These comparisons include the trajectories errors, the capacity of each controller to assist the torque produced by the subject and the robustness of the system against external disturbances. To illustrate the efficiency of the proposed controller, real-time experiments were conducted on five voluntary subjects.

1. Introduction

Actuated orthosis/exoskeleton is a mechanical device externally worn by a subject in order to restore, augment or assist its movements. Historically, the first exoskeleton is proposed by Yagn in 1890. It consists of long springs placed in parallel to each leg of a person. The springs allow the reduction of the force due to the contact of the foot on the ground and then assist the wearer's movements for walking and jumping [1]. The first passive orthosis was proposed, by Cobb, few years later (1935). The orthosis consists of a mechanical system acting on the wearer's lower limbs and especially on its knee joint by limiting its movements [2]. In general, an exoskeleton is, an electromechanical structure, used to increase a valid human properties. An actuated orthosis is a device used to increase the capacity of an ambulatory person with a disease or physical disability [3]. Actually, exoskeletons and actuated orthosis devices are designed to be comfortable for the wearer and be able to interact efficiently with its movements through different sensors placed on the device and/or on the subject itself. Exoskeletons and actuated orthosis devices can operate on the human's upper/lower part or on all the body. Currently, these devices are used for various applications such as medical treatment, military applications, and daily task assistance [4].

In this study, we interest only on the devices acting on the human's lower limb and precisely those designed for the knee joint. The most famous exoskeletons/orthosis existing in the literature are the exoskeleton of one Degree of Freedom (DoF) developed at the University of Florid. It consists of two articulated segments based on a linear actuator compliant (Series Elastic Actuator). The system, baptized RoboKnee, is designed to assist the knee movements of dependent persons. Control scheme of this system is based on a Proportional Derivative (PD) controller. Depending on the angular position and the force of support of the leg on the floor, the controller estimates the torque necessary to the orthosis to perform the desired movement. The estimated torque is then amplified or reduced, by a factor, in order to compensate the subject's muscle weakness [5]. The orthosis of one DoF conceived at the University of Boston. It consists of two articulated segments based on an actuator with electrorheological fluid (ERF). This latter is able to provide a torque, electrically controlled. The orthosis, called AKROD (Active Knee Rehabilitation

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Orthotic Device), is designed to act on the knee joint level. For rehabilitation process, the AKROD is controlled by two control schemes. The first one is based on a Proportional Integral controller (PI) and consists of a torque tracking. The second one uses an adaptive Proportional Integral Derivative (PID) controller and is used for tracking a desired position trajectory [6]. The orthosis of five DoFs, developed at the University of Salford, is designed to assist the wearer's movements by acting on the subject's legs and hip using linear power pneumatic muscle actuators. For each articulation, the antagonistic muscle is controlled by a PID controller such that when an actuator is active on a leg, its opposite is disabled on the other leg [7]. The exoskeleton of one DoF, conceived at the University of Saitama, is designed for the rehabilitation of hemiplegia and paraplegia. The orthosis uses pseudo-bi-articular muscles, based on servo-actuators with hydraulic bilaterally transmission, and is driven by a PID controller [6]. The exoskeleton of one DoF, developed at the University of Berlin, is designed to assist the knee joint during flexion/extension, standing-up/sitting-down and climbing. It uses a linear actuator and is controlled in real time from EMG signals [8]. The exoskeleton of four DoFs, called HAL (Hybrid Assistive Limb), is developed by the University of Tsukuba and is currently commercialized by the Japanese company Cyberdyne. This exoskeleton, which consists of a bipedal locomotion device, is designed to assist the dependent persons and elderly peoples for their daily activities such as standing up/sitting down, walking, climbing stairs as well as lifting heavy loads. Reference trajectories of the HAL exoskeleton are either provided from a gait walking trajectories (cybernetic control voluntary) or by synchronizing the movement with the support of the wearer intention, estimated from electromyogram (EMG) signals (bio-control cybernetics). Notice that each joint of the HAL exoskeleton is based on the PD controller [9,10].

Regarding the rehabilitation process, active orthosis can be used to replicate desired movements imposed on deficient organs according to a given therapeutic program. Some relevant exoskeleton projects developed so far in the literature for rehabilitation purposes are the LOPES exoskeleton (LOwer-extremity Powered ExoSkeleton) [11,12], the DGO (Driven Gait Orthosis) [13], the "Lokomat- Hocoma™" [14,15], the RGT (Robotic Gait Training) [16], 4 DoF Rehabilitation Lower-Limb Exoskeleton [17,18], NaTUre-GaitS (Natural and Tunable Rehabilitation Gait System) [19], etc. Exoskeletons can also be used to assist people in their daily living activities such as standing-up, sitting-down, and walking. Some of the relevant research projects done in the literature are a standing-up robot assistive device [20], a 3 DoF walker system [21].

Comparing the control schemes used to drive the exoskeletons/ orthosis devices, in most time, they are based on the classical PID controller. However, it is commonly known that the PID controllers are weak when

1. the system dynamics vary in the time;
2. the system contains parameter uncertainties;
3. there is external disturbances.

In fact, the "subject's lower limb-actuated orthosis" system inertia, viscous/ damping coefficients and the subject's properties (e.g. mass and hight) vary in the time and from a subject to another. Parameter uncertainties such as errors occurred from parameters identification, external disturbances such as involuntary movements performed by the wearer as well as external interactions with environment, make the use of robust controller an obligation.

In the literature, different robust controllers are proposed. The most famous control schemes are the hybrid fuzzy controller, proposed by Fan et al. to drive a wearable elbow exoskeleton [17]. The hierarchical neuro-fuzzy is proposed by Kiguchi et al. to control an actuated exoskeleton [22]. The neuro-fuzzy controller is proposed by Hayashi et al. to drive an exoskeleton of three DoFs [23]. However, in these works, the rule bases are not generated in a systematic way and the system's stability is not discussed. Also, in this logic, we can find the robust control schemes based on the Sliding Mode Control (SMC) theory [24,25]. The First Order Sliding Mode Controller (FOSMC) is used by Jezernik et al. to drive the Lokomat™ system for restoration process of dependent subject's lower limbs movements [26]. The same control strategy (FOSMC) was used by Banala et al. to drive an active gait rehabilitation device of subject's lower limbs [27]. However, the main problem of the FOSMC strategy is the existence of chattering phenomenon in the control signal. The chattering phenomenon consists of abrupt and fast variations of the control signal; it can be dangerous for the orthosis actuator and for the subject safety. In our previous works [28–30], in order to restore and assist the movements of the lower limbs by an actuated orthosis, different control schemes based on the High Order Sliding Mode Control (HOSMC) strategy were developed. However, for each movement (flexion/extension of the knee in sitting position and sit/stand movement), the modeling of the equivalent system "subject's human body-actuated orthosis" is relatively complex. The identification process of the subject-orthosis parameters is very time consuming. Some parameters of the subject such as mass and length, and of the orthosis such as friction/ viscous damping coefficients, can change during the time. Consequently, in this work, we propose the use of the neural networks strategy of type MLPNN (Multi-Layer Perceptron Neural Networks) to drive the "subject's lower limb-actuated orthosis" system for flexion/extension of the knee in sitting position. The proposed MLPNN controller is able to avoid the modeling and the procedure of parameter's identification of the system. It can also guarantee high performances in term of stability of the closed-loop system, small tracking errors of the desired position and velocity trajectories, robustness of the system against external disturbances and assistance as needed of the torque generated by the subject. This study presents an extension of the paper [31] where additional descriptions and real-time validations, upon an experimental protocol, with more subjects are added.

The paper is organized as follows: Section 2 presents the "subject lower limb-actuated orthosis" system. Section 3 gives the Neural network identification procedure. Development of an adaptive neural controller and demonstration of the Subject lower limb-actuated orthosis system stability are given in Section 4. Experimental validations with several subjects and obtained results are reported and discussed in Section 5. Finally, Section 6 gives the conclusion and the future works.

2. Subject's lower limb-actuated orthosis system

The considered system represents a person in sitting position, wearing an actuated orthosis, without ground contact. The Lissi actuated orthosis is constituted by two segments, upper and lower, and is fixed with the subject's lower limb through braces in order to efficiency acts on knee joint level (Fig. 1). The subject's shank-foot combined with the actuated orthosis, considered as a single rigid segment, is moving freely around the knee joint level. The orthosis torque is generated by an actuator of type Brushless (BLDC) motor and a mechanical mechanism (Fig. 2). The total torque (τ), acting on the system "subject's lower limb-actuated orthosis" at the knee level, is constituted by two parts: the first one is the torque generated by the subject (τ_k) and the second one is those delivered by the orthosis' actuator (τ_{or}). The latter is of type Brushless (BLDC motor). Movements of the "subject's lower