Assisted Rehabilitation by Robotic Orthosis of Spinal Cord and Back Injuries

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Abstract— **This study addressed the design, construction and control of a prototype of active orthosis focused on assisting the rehabilitation of patients with spinal cord or/and back illnesses. The prototype was actuated with a collection of direct current motor commanded by distributed control strategy based on the so-called Twisting controller. This control action used a Super-Twisting algorithm as robust differentiator to supply the time derivative of the tracking error. A graphic user interface (GUI) was implemented to enforce the application of different therapies accordingly to the most common strategies used in clinical rehabilitation. The orthosis was implemented and the proposed controller forced the tracking of the reference trajectories supplied by the GUI. The orthosis was evaluated in simulation to adjust the controllers and differentiators gains. A real orthosis was constructed and controlled using the gains obtained at the simulation stage. The actual orthosis was evaluated to check the ability of the controller to track the reference trajectory despite the resistance of the patient that was simulated by different dummies devices.**

Keywords— **Active orthosis, spinal cord injuries, sliding mode control, Twisting controller, Super-Twisting algorithm.**

I. Introduction

Spinal Cord Injury (SCI) is a damage or trauma to the spinal cord that yields to loss of function, mobility and sensation below the level at which the spinal cord has been affected. This disorder is characterized according to the amount of functional or sensation loss and inability of an SCI individual to stand and walk. One possible and very traumatic consequence of SCI is the paralysis, whether partial or complete, may provoke complications in other parts of the body (respiratory disorder, gastrointestinal and cardiovascular disorders, skin and muscle-skeletal problems and psychological disorders). The better solution to this SCI is a very traumatic surgery, that demands long periods of rehabilitation. During this time, the patient suffers several episodes of pain [1].

On the other hand, back illnesses are classified into lumbar and thoracic back pain. Both type of sicknesses appear commonly in persons that have bad posture, remains seated for long periods, etc. Initial treatment of these illnesses require muscle relaxants or non-inflammatory medicaments. When the pharmacological treatment is not enough, muscular massages and physiotherapy are needed. If the illnesses became chronic, long term treatments included bed rest, vertebral traction, termotherapy, electrotherapy and wearing passive orthosis. This last option only provides a permanent posture control but it does not bring assisted therapy [2].

SCI and back illnesses are the major factor that motivates the back assisted therapy. Physiotherapy associated to back pain rehabilitation is an important part of helping patients get the most accelerated and complete recovery of their health. This work is regularly performed by specialized physiotherapists. However, this is very hard task and requires a lot of financial and human resources. One option to reduce the demand of resources is using active orthosis (AO) .

AO is a class of assisting robot which is designed to help patients to recover function without substituting structure. There are many examples of AO in real clinical situations and scientific literature. The majority of them were focused on assisting the movement of legs and arms. However, there are just a few of solutions regarding the active therapy for rehabilitating back pain caused by either, SCI and back illnesses [3].

AO design demands the solution of two relevant issues: 1) the controller proposed to regulate the movement of the device and 2) the reference trajectories used to force the accurate application of an automatic therapy. The first of the aforementioned stages must be solved with an automatic controller. Traditional control schemes based on classical PD controllers and Computed Torque control [4] have been successfully implemented in many AO. However, to obtain good performance in regulation and trajectory tracking applications, these controllers need the complete knowledge of the robot dynamics, which may be sensitive to problems in the presence of uncertainties, disturbance inputs, or non-modelled dynamics. Moreover, this schemes normally require high processing capacities in the control hardware [5]. The uncertainties introduced by the interaction between the orthosis and the patient must be tackled with a type of robust controller that can ensure the tracking of the reference trajectory.

In automatic control theory, exist several examples of robust control theories that can be used to solve the AO trajectory tracking problem. One of the most successfully the-

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ory of robust control is the so-called sliding modes (SM). SM and their variations have shown to be robust with respect to parametric uncertainties, presence of external perturbations and high degree of vagueness on the mathematical model of the system to be controlled or estimated (parameters or/and states). Twisting and Super-Twisting Algorithms (TA and STA) are two well known SM methods that have been used as controller and robust differentiator respectively. Recently, some results appeared where they both were used together to solve the problem of output based robust controller for second order system. This result presented the first version of Lyapunov functions that served to prove the stability of the closed-loop controller. This study used this result but in a distributed framework. Each articulation in the AO system was independently controlled based only on the reference trajectory provided by the physiotherapist. The robustness of the proposed controller was adequate to solve the tracking trajectory problem despite the global configuration of the AO back assisted therapy [6].

The aspect of designing reference trajectories in AO back assisted therapy plays a relevant role. A regular strategy for designing reference trajectories is based on the so-called Bezier curves. These curves must fulfil simple requirements including smoothness and zero derivatives in their extremal sections. The so-called Bezier polynomials have been the most popular way to get the reference trajectory curves. However they demand the estimation of many parameters for designing each polynomial.

In summary, this article deals with the problem of output base sliding mode control for a back therapy AO robotic system. The control problem was to solve the trajectory tracking task, based on the on-line reconstruction of the articulation velocity using a robust STA differentiator. The estimated states were used to design the closed-loop control based on the Twisting scheme. This combination of two different sliding mode methods was used at each articulation of the AO used in back assisted therapy.

II. Orthosis design

The orthosis for active back assisted therapy emulated the concept of multi-legged robots. The idea was to design a fixed body with six independent manipulator with three degree-of-freedom attached to a central column. The whole robotic system can be fixed to the patient's back. The fixing process is proposed to be automatic using a pressure sensors in the distal part of each arm.

This design followed the regular mechanism used to track and move the back of injured patients. The dimensions and mechanical design were adjusted to standard anthropomorphic measures for Mexican people. The orthosis was constructed using a 3D printer. The material selected for building was the ABS polymer. Figure (1) depicts the mechanical design of the orthosis which has been built. The motors were located at the each arm of orthosis and they were instrumented with the corresponding sensors (electrical goniometer devices) and actuators (DC motors). All the electronic boards used to control and monitor the coordinates of the orthosis were placed in a central power device.

Fig. 1: Mechanical design of the active orthosis and the distribution of actuators and sensors

The position of each articulation was measured using a variable resistance placed over the motor guide (goniometer). These sensors were used to recover the articulation angle and feed into the robust differentiator based on STA as well as the output feedback controller. These variables were acquired by the corresponding microcontroller device. Each of these devices implemented its own output based controller. This strategy prevent the necessity of having a master device which must calculate all the controller together. This scheme was also an innovation presented in this study.

III. Controller design to regulate the orthosis position

Using the Euler-Lagrange modelling process, the dynamic equations for the active hand orthosis can be derived. These equation can be represented as:

$$M(q)\,\ddot{q}(t) = b(q(t),\dot{q}(t),t) + u(t) \tag{1}$$