Adaptive Control System for Ankle Orthosis T-Flex

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***Abstract*— Cerebrovascular disease (stroke) is the third cause of mortality in Colombia, and this index has been rising in last years. Stroke can result, as one of its events, in a total or partial loss of gait and, in several cases, this type of consequence is susceptible to rehabilitation. T-Flex is an ankle orthosis based on bioinspired tendons of variable stiffness, which is used to help and rehabilitate patients with gait disturbances. Its function is to provide specialized assistance during the different phases of the walk. Systems such as T-Flex require a control mechanism that allows to adjust the type and level of assistance according to the performance of the movement in each of these phases. In this paper, we propose to implement an adaptive control system for T-Flex that actively assists dorsiflexion and plantar flexion of the foot during gait phases. The proposed control system makes the ankle to follow a pre-defined trajectory using clinical tests, adjusting the controller parameters based on the performance evaluation of the previous step and the reference trajectory, to update the orthosis assistance. This approach allows the conditions of the ankle/orthosis system, and the specific parameters of each patient, don't to drastically affect the correct operation of the orthosis, and optimal support can be achieved for patients with gait disorders.**

I. Introduction

In recent years, cerebrovascular disease (stroke) has been the third cause of mortality in Colombia, and this index has been rising [1]. Currently, more than 60.000 people in Colombia suffer from a Stroke. The most frequent and severe consequences of stroke are locomotor and coordination disorders which generate gait alterations and higher costs for health systems and their families [2]. The stroke results in a total or partial loss of gait, and in several cases these disorders can be rehabilitated. It has been shown that repetitive training and stimulation can produce a cortical reorganization in the brain and consequently restore motor functions. There is increasing interest in using robotic devices to help provide rehabilitation therapy following neurologic injuries such as stroke [3]. Some robots have acquired sophisticated bioinspired designs that adapt anatomically to the extremities of people. They are called wearable robots [4]. A wearable robot is an electromechanic system that is designed around the shape and function of the human body, with segments and joints corresponding to those of the person it is externally coupled with [4]. Wearable robots are worn such that the physical interface permits a direct transfer of mechanical power and exchange of information [5]. Carlos Cifuentes et.al [6], have developed an ankle orthosis based on bioinspired tendons of variable stiffness, which is used to assist and rehabilitate the pathological gait of patients [6]. This robotic orthosis attaches to the lower joint and allows active assistance during the rehabilitation process. This mechanism allows to recover the deficient movement of the lower joints due to the effect of paralysis or muscular paresis. This wearable robotic system is called T-Flex [6]. In order to provide specialized assistance during the different phases or the gait, systems like T-Flex require a control system that allows to adjust the type and level of assistance according to each of these phases. Several control algorithms have been developed and applied to robotic ankle orthosis, during rehabilitation processes [7]. The most developed paradigm is the assistive one. Assistive controllers help participants to move their weakened limbs in desired patterns during the gait [3]. Active controlled assist exercise interleaves effort by the participant with stretching of the muscles and connective tissue. Effort is thought to be essential for provoking motor plasticity [8], and stretching can help prevent stiffening of soft tissue and reduce spasticity, at least temporarily [9].

Several control schemes developed for active ankle devices rely on the fact that gait is essentially a periodic motion [10]. Kim et al. [11] present an openloop-state-machine control applied to an actuated robotic ankle orthosis to induce plantarflexion or dorsiflexion movements to the foot after detecting the gait phase. Also a proportional controller using myoelectric signals to control the ankle orthosis has been proposed by Ferris et al. [12].

On the other hand, preprogrammed patterns, that may be adjusted as a function of the stride time and information about the current kinematic and kinetic state, have been proposed to simulate the ankle behavior [10]. J.Hitt et al.[13] purpose the use of a trajectory tracking controller for an active orthosis actuated by a motor with an element of elasticiy in series [13]. This is a low power controller that has a proportional derivative structure (PD) and uses an adjustable (adaptive) running pattern as a reference for the motor position. The reference pattern is generated by a polynomial adjustment of a normal walking pattern and is a function of stride time [13] [14] [15].

Adapting control parameters is a fundamental part inside patient-cooperative training strategies for rehabilitation. This kind of strategies were developed first for the Lokomat, where the robot adaptively takes into account the subject's intention rather than enforcing a repetitive control strategy [3] [16]. It is also a key part of performance-based progressive robot-assisted therapy control strategy developed by H.I Krebs for the MIT-MANUS robot [17]. These, and other,

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adaptive strategies have been proposed of the form:

$$P_i + 1 = f * P_i - g * e_i \quad (1)$$

Where,P_i is the control parameter that is adapted (e.g. the gain of robot assistance force), i refers to the i^th movement, and e_i is a performance error (measure of participant movement or participant's performance). The constants f and g are the forgetting and gain factors respectively [3].

This adaptive expression is an error-based strategy that adjusts a control parameter from trial to trial based on measured participant performance [3] [17].

The objective of this study is to evaluate the available control mechanisms for robotic ankle orthoses and to propose an efficient control strategy that allows the T-Flex orthosis to be modulated in terms of actuation and assistance, depending on the patient's performance during gait.

II. Methodology

The T-Flex system consists of a support system, which allows an adjustment of the upper body, as shown in figure 1 . The T-Flex orthosis is a wearable robotic system that adapts to the ankle joint. It consists of a system of inertial sensors (IMU), two electromechanical actuators and a group of bio-inspired tendons of variable rigidity, which form a 4-bar mechanism. The tendons are attached at the ends of the motors.

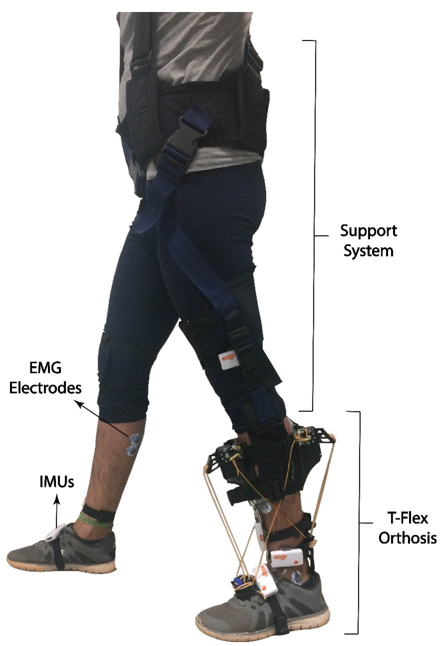

Fig. 1. Robotic ankle orthosis system for gait assistance [6].

This mechanical system (agonist-antagonist) allows (depending on the direction of rotation of the electromechanical motors) assistance in the joint, in both dorsiflexion and plantar foot flexion, in the sagittal plane. The material of the tendons is a combination of an elastic filament, called FilaFlex (thermoplastic elastomer), and a type of rigid polymer fiber, widely used in fishing. This configuration allows the elasticity of the human tendons to be closely simulated, while providing the necessary rigidity to assist movement correctly after 15% elongation of the tendons. From this characterization of the material, it is possible to define the kinetic and kinematic models of the system, which will allow to establish the parameters of the controller to define the actuation of the electromechanical motors.

A. Detection of gait phases

The detection of the running phases is fundamental for the design of the control algorithm. Depending on the stage of the gait the participant is in, the system must be able to emit an electrical response on the motors immediately, to actively assist the ankle during dorsiflexion and plant flexion. Initially, experimental tests were carried out on healthy patients with the IMU inertial sensor system (without assistance) to validate the correct detection of the gait phases. The IMU was calibrated before each experimental session. Before each gear test, the inclination angle of the IMU was checked, and the sensitive axes of the accelerometer were checked to ensure that they were approximately parallel to the sagittal plane. The sensor data were acquired and the IMU quaternions were obtained. The quaternions were processed and the angular velocity curve was obtained, on the Y axis. This was done to detect significant movements of the IMU relative to the foot throughout the experimental session.

B. ON-OFF Control Algorithm and Review of alternative control Strategies

Subsequently, a control algorithm with an ON-OFF system was designed to verify the performance of the motors and validate the detection of the running phases in conjunction with the ankle orthosis actuation system. This control algorithm makes it possible to modulate the direction of rotation of the motors to assist the movement during dorsiflexion or plantar flexion of the foot, depending on each of the phases of the gait. As soon as the gear cycle starts, with the heel strike, the motors actuate to allow the foot to slowly approach a stable position during the full stance phase. Later, when heel lift occurs (terminal stance), the direction of rotation of the motors changes to assist planting foot flexion. Finally, in the swing phase, the direction of rotation of the motors changes to assist the dorsiflexion of the foot and restart the gait cycle.

As a next step it was decided to evaluate the different control strategies used so far for the control of robotic ankle orthoses.

III. Results

The ON-OFF control system provides dorsiflexion and plantar flexion support during the different gait phases, however, studies have concluded that excessive support from the orthosis may not contribute to appropriate muscle rehabilitation[10]. In control mechanisms like this, the amount of assistance provided by the orthosis is calculated from the parameters of the ankle/orthotic system, and from an empirical determination of the magnitude of the assistance.

For this reason, it is proposed to implement a control system that does not require any prior estimation of the ankle/orthosis system parameters and where the amount of motor assistance can be adjusted depending on the dynamics of the system, and a continuous comparison with a desired trajectory compatible with the patient's condition.

The assistive control algorithms presented in [11], [12] are static mechanisms in the sense that they don't adapt controller parameters based on online measurement of the participant's performance.

As mentioned in[13], [14], [16] and [17] , designing a control system whose parameters can be adapted according to the subject's intention and performance during the gait, is a fundamental approach to development in this area.

It is proposed to implement an adaptive control system for the T-Flex ankle orthosis, as shown in Figure 2. System inputs are reference parameters (Ref) obtained from experimental tests specific to the patient's condition. The variables to be controlled are the angular position (qt) and the angular velocity (wt). These variables are monitored by means of an encoder and an IMU inertial unit, respectively (observer). With this reading, a continuous comparison is made with the reference values, and the controller parameters are adjusted according to the difference found in that comparison (Fig. 2).

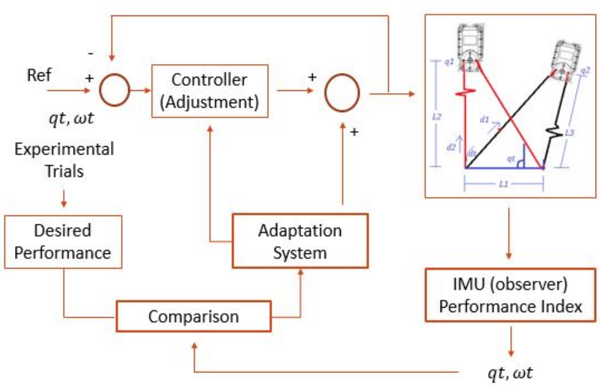

Fig. 2. Proposed adaptive control system.

IV. Conclusions

Adapting control parameters has the potential advantage that the assistance can be automatically tuned to the participant's individual changing needs, both throughout the movement and over the course of rehabilitation [3] [7]. In this paper, we propose a adaptive control system for T-Flex orthosis. This control system makes the ankle to follow a pre-defined trajectory using clinical tests, adjusting the controller parameters based on the performance evaluation of the previous step and the reference trajectory, to update the orthosis assistance. This approach allows the conditions of the ankle/orthosis system, and the specific parameters of each patient, don't to drastically affect the correct operation of the orthosis, and optimal support can be achieved for patients with gait disorders.

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