Human-based Lower Limb Movement Assistance and Rehabilitation through an Actuated Orthosis

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Abstract: In this paper, an overview of the project EICOSI (Exoskeleton Intelligently COmmunicating and Sensitive to Intention) conducted at the LISSI/UPEC Lab will be presented. This work aims to control a knee joint actuated orthosis while tracking a desired trajectory or following the wearer's intention. The proposed control strategies ensure satisfactory performances in terms of trajectory tracking, intention detection and torque generation during rehabilitation tasks and assistive movements of the wearer's lower limbs.

1 INTRODUCTION

The last decade has shown great advances in the development of robots that interact closely with human. The sensor and actuator technologies have also shown great evolution particularly in terms of energy, portability and miniaturization. The related applications concern chiefly the assistance and rehabilitation of dependent/elderly people. In 2000, more than 60 million people in Europe were aged 65 or over. The rise in life expectancy, set to continue, combined with falling birth rates, will accelerate the ageing of the population (Mohammed et al., 2012). This will certainly have a great impact on the development of assisting robotic devices. An exoskeleton is a mechanical actuated structure with several degrees of freedom enabling the assistance or rehabilitation at multiple joint levels such as the robot suit HAL (Tsukahara et al., 2010). Particularly, the knee orthoses have been developed to tackle musculoskeletal impairments at the knee joint level. The main pointed purposes are the rehabilitation and the assistance. To ensure the first purpose, passive or active rehabilitation can be ensured. A patient-directed orthosis is used after total knee arthroplasty for knee stiffness reduction and range of motion increase by executing static progressive stretches in (Bonutti et al., 2010). The rehabilitation has also been addressed in (Schmitt et al., 2004) using the hybrid orthosis cyberthosis, activated by a functional electrical stimulation of the muscles and controlled using a proportional, integral, derivative (PID) controller in order to train the knee joint and the muscles actuating it, for flexion/extension movements. On the other hand, the TUPLEE orthosis (Fleischer and Hommel, 2008) aims to assist the wearer during various activities like standing, sitting and climbing. The user's intention is determined using Electromyogram (EMG) electrodes placed at the thigh and the control torque behaves as an amplifier of the knee torque. An elastic knee brace has been designed in (Cherry et al., 2006) to add a parallel stiffness to the knee allowing to compensate the increase of the knee joint's stiffness during running. Impedance control has been addressed in (Aguirre-Ollinger et al., 2007) to change the damping parameter and in (Aguirre-Ollinger et al., 2010) to change the inertia in order facilitate the flexion/extension movements.

The present paper deals with the control of a lower limb orthosis applied at the knee joint level. Knee joint has a great importance in maintaining the human stability during the different daily living activities. Two case studies are proposed: the first one deals with the passive rehabilitation process. A desired knee joint angle is needed and is supposed delivered by the rehabilitation doctor. The wearer's contribution is considered active if it acts in the desired position direction and is considered as external perturbation if it acts in the opposite direction. In this case the priority is given to the desired task completion independently from the human contribution (Rifai et al., 2011). The second case study concerns the human based control and lies within the assistive strategy. Muscular activities of the muscles spanning the knee joint are measured and the resulting knee joint torque is amplified through the use of the or-

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thosis to ensure a desired movement initiated by the wearer (Hassani et al., 2013). Asymptotic stability of the knee joint orthosis is guaranteed in both cases. Control law should take into consideration constraints related to the safety of the mechanism since it is in direct relation with the human body. In both case studies, the effectiveness of the proposed control strategy is tested in real-time with a healthy subject.

The rest of the paper is organized as follows: Section 2 shows the system modeling and parameters identification. Section 3 presents the passive rehabilitation control strategy while section 4 presents the subject centered control strategy case study. Section 5 shows the results in both cases and section 6 concludes the paper.

2 SHANK-ORTHOSIS MODELING AND PARAMETERS IDENTIFICATION

In the project EICOSI, the orthosis has a simple design, easy to don and doff, and match the lower limb geometry which makes it very practical to use by elderly and dependent people. The orthosis is one structure having two segments related along a rotational axis. The first segment embodies the thigh while the second one embodies the shank and are fixed to the wearer by means of straps (Figure 1). The orthosis and the human leg have, then, the same rotational degree of freedom at the knee joint level. The shank/orthosis parameters are identified using the weighted least square optimization method. The mass of the shank and the position of its center of gravity are determined based on (Winter, 2009) given the height and weight of the subject. The other parameters are identified using the passive pendulum test. To identify the orthosis' parameters, an excitation sequence describing the trajectory of the angle is predefined as well as the angular velocity and acceleration (Swevers et al., 1997). The torque developed by the actuator during the tracking of the excitation trajectory is computed using a current sensor.

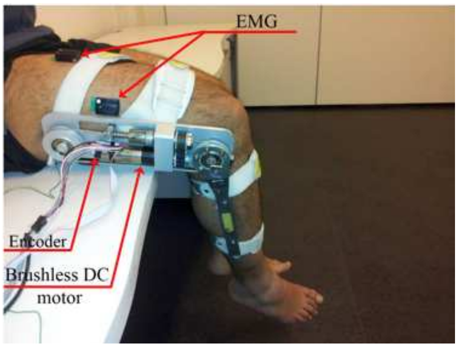

Figure 1: EICOSI knee-joint orthosis.

3 PASSIVE REHABILITATION CONTROL STRATEGY

The passive rehabilitation is performed after surgical operations of articular tissues as well as rehabilitation of spinal cord injured patients (Jansen et al., 1996) (Rudhe et al., 2012) (Chang et al., 2013). In this case study, the wearer is considered either completely passive, therefore, the wearer does not develop any human control torque or paritally passive where the wearer is developing an assistive but not sufficient torque. If the wearer develops resistive torque, this movement will be considered as perturbing movement and will be rejected by the controller. In this case study, the control law is based on a gravity compensation and ensures the tracking of a desired trajectory. The proposed strategy ensures the asymptotic stability of the orthosis/wearer for flexion-extension movements. The stance phase of locomotion has not been taken into account. The control is guaranteed to be bounded in order to take into account limited power support. Also the saturation of the actuator is used explicitly in the control law in order to prevent problems related to nonlinearities of the shank-foot orthosis. Quick friction variations induced by unpredictable movements may cause unacceptable behavior of the orthosis, also high value of the control torque necessitates high power to ensure it, which cannot be achieved in wearable robots because it affects the safety of the wearer. The saturation based control law can take into account these limitations. Consequently, the actuator magnitude limitation is taken into consideration in the design of the control torque in order to avoid irreversible damages. The proposed control law is robust with respect to external perturbations. Indeed, a misstep can be caused by a wrong movement at the knee level, it can cause instability or even falling down. Therefore, one main property of the control law is to regain the intended position whenever an unpredictable flexion occurs. Experiments that consist on blocking the shank for a short period by an external operator have been conducted and shown satisfactory results in terms of quickly regaining the desired position. The magnitude of the resulted perturbation remains within the saturation limits imposed by the controller.

4 SUBJECT CENTERED CONTROL STRATEGY

An ”Assistance as Needed” approach is developed to allow a flexible and smooth orthosis/wearer interaction. In this case study, a realistic bio-inspired musculoskeletal model is used to control the orthosis movements (Hassani et al., 2013) . Parameters such as muscle length variations, activation and contraction dynamics and moment arms are taken into account. This will allow a better estimation of the wearer's intention. The identification of the above parameters was made through an unconstrained optimization problem formulation. Secondly, a control law strategy is developed to guarantee asymptotic stability of the knee joint orthosis as well as flexible interaction between human and exoskeleton. This control law has also shown its robustness with respect to external disturbances. In this case study, the wearer is supposed to developing a torque to move his/her leg. The orthosis is assisting the wearer by delivering the complementary torque, necessary to achieve a given desired task. The subject's intention is taken into account through the human developed torque while the controller's parameters are adapted automatically with respect to the wearer's changing human contribution during the completion of the task. This approach can be used particularly during a rehabilitation process as the contribution of the orthosis torque decreases with the improvement in the performance of the wearer. Indeed, the controller continuously attempt to reduce its assistance ratio when the wearer develops an effort to accomplish a given task. On the other side, when the user moves largely away of the desired joint trajectory, the controller develops a counter-torque to bring the wearer limb back to the desired trajectory or to its vicinity.

5 RESULTS

The control law is tested in real-time using the EICOSI orthosis of the Laboratory of Images, Signals and Intelligent Systems (LISSI) of the University of Paris-Est Crteil (UPEC). The mechanical structure of the orthosis consists of two segments attached to the thigh and shank respectively by means of straps, with a rotation axis at the knee level. The orthosis is actuated using a brushless DC motor (BLDC) chosen because it delivers a relatively high torque and runs smoothly at low speeds. The maximal torque that can be delivered by the actuator is equal to 25 N.m. The orthosis is also equipped with an incremental encoder that delivers the angle of the shank segment relative to the thigh one. The control torque is computed using a controller board (dSPACE-DS1103) equipped with an IBM processor running at 400Mhz. The controller takes the measurement of the angle delivered by the EICOSI's sensor and the angular velocity obtained by a simple derivation as well as the desired angle and velocity. The controller board delivers the pulse width modulation (PWM) level to control the actuator's velocity. The control loop runs at 1 kHz, fixed due to current and position sensors constraints. The experiments are conducted on a healthy subject having 35 years old, weighing 94Kg and measuring 1.82m.

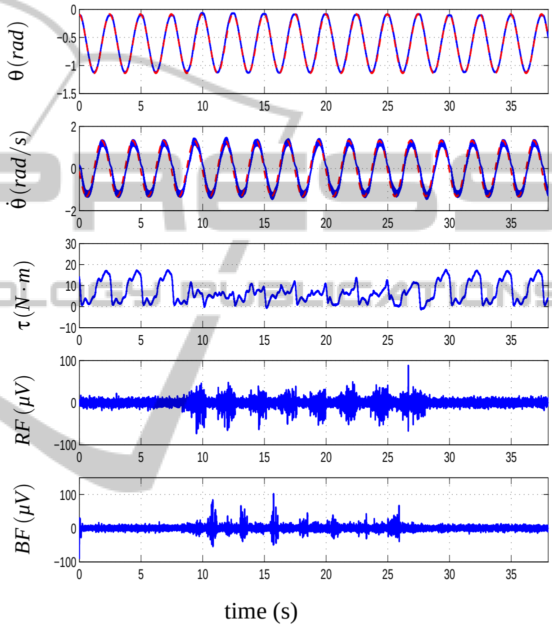

Figure 2: Sine reference trajectory with assisting human effort in the time interval $[8.5, 28.5]\,s$: The first two plots represent a good tracking between the current and desired knee-joint angles and angular velocities, the current values are plotted with continuous blue line and the desired ones with red dashed lines. The control torque τ has lower values during the assistance phase detected by the RF and BF muscles activities.

In figure 2, the subject is able to move his leg but does not have sufficient power to achieve a movement. In other words, the subject delivers a part of the torque necessary for the movement and the exoskeleton is supposed to help him ensuring the desired movement by delivering the complementary torque. This strategy is known as the assistance-as-needed. The subject is delivering an effort in the time interval $[8.5, 28.5]\,s$ that goes in the same direction as the desired trajectory. It can be seen that the Rectus Femoris (RF) muscle is active during the extension (sine with positive slope) while the Biceps Femoris (BF) during the flexion (sine with negative slope) in the last two plots of Figure 2. However, this effort is not sufficient to ensure the tracking of the desired trajectory. The control is therefore only assisting the subject during this interval. One can notice that the magnitude of the control torque is lower than that delivered outside the assistance phase, *i.e.* in the time intervals $[0, 8.5[s$ and $]28.5, 38]s$. The control law ensures a good adaptation and trajectory tracking (first two plots of Figure 2) during the assistance and non-assistance phases which guarantees the safety of the wearer.

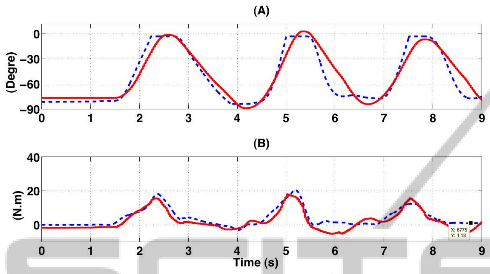

Figure 3: Assistance results (A): Desired position (dashed blue) and current position (red), (B): Human torque (dashed blue) and exoskeleton torque (red).

In figure 3, the control is based on the wearer's intention. The wearer's torque is estimated using the lower limb anatomical model based on the use of the modified hill-type muscle model. The raw EMG signals are measured from the quadriceps and hamstrings muscles. During this experiment, the wearer is asked to produce free flexion / extension movements of the knee joint. The advantage of the proposed approach consists in its nature which is subject centered where no predefined position trajectory is imposed to the wearer.

6 CONCLUSIONS

This paper treated the control of a knee-joint orthosis. A model, of the shank and orthosis, is proposed and its parameters has been identified. Two control strategies were proposed, the first one deals with the passive rehabilitation process. A desired knee joint angle is needed and is supposed delivered by the rehabilitation doctor. In this case the priority is given to the desired task completion independently from the human contribution. The second case study concerns the human based control and lies within the assistive strategy. Muscular activities of the muscles spanning the knee joint are measured and the resulting knee joint torque is amplified through the use of the orthosis to ensure a desired movement initiated by the wearer. Experimental validations of the proposed strategies were conducted in real-time with a young healthy subject using the EICOSI orthosis of the LISSI Lab.

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