Coupled Control of Human-Exoskeleton Systems: An Adaptative Process

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***Abstract* — Robotic exoskeletons are wearable robots coupled to the human body, being the human an integral part of the human-robot system. Specifically, the control plays an important role, and stability must be guarantee. Both actors form a close loop with two control systems interacting dynamically. In this regard, a relevant issue is to understand how humans and robots could physically (kinesthetically) interact and communicate better. This paper deeps in the control of systems interacting dynamically and presents an analytical discussion on the controller design for exoskeletons and the coupled stability problem. Finally, a particular study is described in order to demonstrate the human cognitive system adapting under functional compensation of tremor.**

***Keywords* — HRI, human motor control, robotic exoskeleton controller, impedance control.**

I. Introduction

A major challenge in the implementation of robotic exoskeletons that work coupled to the human body relates to the control system. Both parts behave as dynamic systems interacting each other.

There are main issues identified for a successful physical interaction, such as: the kinematics compatibility between human and robot, the application of loads on humans, and control strategies for better human physical interaction.

The role of physical interaction is quite broad and depends on wearable robot application. For instance, in a teleoperation scenario the physical interaction works as a cognitive interaction since it fed back to the human information regarding its presence in a virtual environment. In rehabilitation and assistance of disabled or elderly people, the main function of the physical interaction is to transfer mechanical power to human skeleton for function compensation or rehabilitation. Exoskeletons could also be used for power amplification, in this case the transference of mechanical power is made in order to amplify human capabilities.

In addition, during the last years there is a growing interest in the design and development of robotic devices and artificial tools in form of prosthetic and orthotic systems which functional dynamics resemble the human one in order to allow the control to be as natural as possible. Thus, sensing and actuation systems and control strategies have been inspired biologically with models that capture the main features of the person, and of the human motor control system.

This understanding about the human motor system permits to develop bio-inspired control strategies to be implemented in new devices, such as prostheses and orthoses and to explore new therapies in disabled people by pathologies and disorders affecting the motor system.

Independently from the nature of the tasks for which the wearable robot is used, the transmission of force is a main characteristic in physical human robot interaction. The physical contact between the human and the robot allows direct transfer of mechanical power and information signal, [1]. This topic must be addressed considering together the design of mechanism, sensors, actuators and control architecture in the special perspective for the interaction with humans.

This paper aims to analyze several aspects arising in the coupled control of human motor control and exoskeleton controllers. Finally, a set of experiments carry out demonstrates the human cognitive system adapting under external biomechanical loading.

Next section discusses the human and robot response in such systems. Section III discusses exoskeleton control design from the target application. Next, section IV presents experimental results regarding the human motor adaptation under the external loading, in a tremor suppression application. Finally, section V presents the main conclusions regarding the discussed coupled systems, from a control perspective.

II. Human–Robot Close Loop

As was above introduced, the coupling between a human and a wearable robot (exoskeleton) can be seen as a combination in a close loop of two dynamic control systems: the human motor control system and the robot controller. In such scenario, the human and the wearable robot interact through their sensorial and motor channels. The human receptors record the physical state of human body and its environment. The sensorial information is perceived by the Central Nervous System (CNS), in such a way that the human cognition interprets the perceived information and generates a motor action. Similarly, the sensors of the robot detect the state of the machine and their environment. The data of sensors are processed by a control scheme in order to command the actuators.

The behavior of systems interacting dynamically may be understood in terms of the properties of its impedance, [2]. Furthermore, the most important consequence of dynamic

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physical interaction between two physical systems is that one must physically complement the other. Thus, if one behaves as an impedance, the other must be an admittance and vice versa. When an exoskeleton is mechanically coupled to its environment, to ensure physical compatibility with the environment admittance, the exoskeleton should assume the behaviour of an impedance. In addition, as the human behaves as a variable impedance, the behaviour of the exoskeleton should be adaptable. Thus the controller should be capable of modulating the impedance of the robot as appropriate for a particular impedance of the human.

As a result, the wearable robot could present two behaviours when interaction with humans, [3]:

1) Admittances, which accept effort (eg. forces) inputs and yields flow (e.g., motion) outputs.
2) Impedances, which accept flow (e.g., motion) inputs and yields effort (eg. forces) outputs.

Fig. 1 represents the above concept, considering the human-exoskeleton system in term of its properties of impedance.

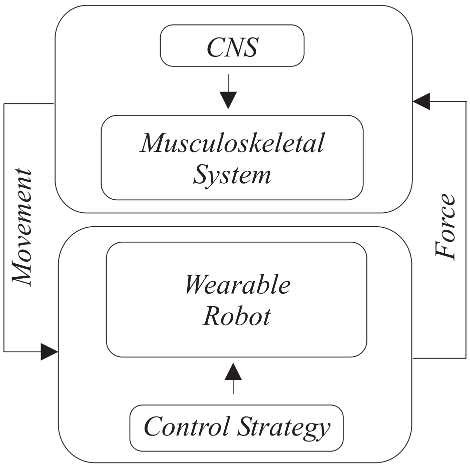

Fig. 1. Control close-loop in the interaction of human-exoskeleton systems.

Following two subsections, presents the environment perceived by the human being and robot respectively, in the interaction process of close loop system human-exoskeleton.

A. HRI: Human Behavior.

When human interact with an exoskeleton, they perceive it as an environment or external force. The CNS tries to model that force and compensate for the interaction.

In the literature, several studies on human motor control and adaptation have demonstrated that when subjects are exposed to a force field that systematically disturbs the arm motion, they are able to recover their original kinematic patterns, [4]. This is accomplished due to the fact that subjects adapt the torques generated at their joints in order to compensate the perturbing forces. When the perturbation force is abruptly removed they show an error due to adaptation. Thus, there are a basic mechanism of compensation and a learning process. The basic mechanism exploits the visco-elastic properties of the neuromuscular system. The learning process is involved in the formation of internal models in the cerebellum, [5].

Several studies have assumed a second-order mass–damping–stiffness model to describe the dynamics of the human arm (Fig. 2), [6]. These models are based on mass, *M*, damping, *C*, and stiffness, *K*, parameters which provide a direct physical interpretation.

The human limb dynamics are nonlinear and vary depending on factors such as torque bias and posture. Thus, in order to fit the data to a second-order linear model, an operating point must be specified. The equation relating the mechanical impedance is presented in (1).

$$F(t) = M \cdot \frac{\partial^2 X(t)}{\partial^2 t} + C(\delta) \cdot \frac{\partial X(t)}{\partial t} + K(\delta) \cdot X(t) \quad (1)$$

where $F(t)$ and $X(t)$ represent the force and the displacement respectively, and δ defines the operating point.

Control of the impedance of the human neuromuscular system is a form of adaptative behavior that the CNS uses to accommodate perturbations from the environment, [7].

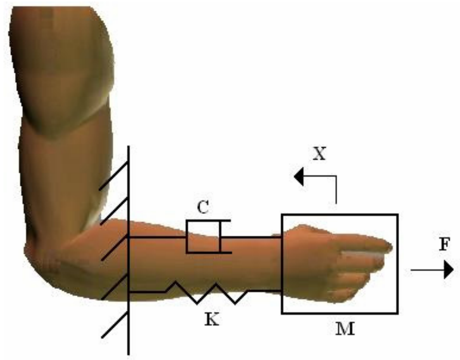

Fig. 2. Second-order model of human upper limb as a mechanical impedance.

The physical interaction in the system that forms the human and the exoskeleton generates a learning process in which human motor control is adapted. In the learning process there is a reduction of the average neural input signal. This reduction is, to a large extent, due to a decrease in the coactivation of antagonistic muscles. Therefore, in the learning process exists an adaptability of the mechanical impedance. In several scenarios of the HRI, the exoskeleton controller must consider the high variable impedance delivered by humans.

B. HRI: Robot Behavior.

In wearable robotics, the most used approach for the control of the interaction forces between the robot and the human is the impedance control, [8]. One of the main advantages of impedance control is that allows the implementation of a compliant behaviour of the wearable robot, this leads to a more natural physical interaction and reduces the risk of damage. Similarly, the capability of sensing and controlling interaction forces is relevant for cooperation between human and robots.

Impedance control allows the control of the interaction force as well as the position of the desired task. Impedance control represents a strategy for constrained motion rather than a concrete control scheme. The objective of this concept is to achieve a specific mechanical impedance at the manipulator end-effector. This objective improves the desired relationship between position error and force acting at the end-effector, [3].

The impedance of a system comprises three components, i.e. stiffness, damping and inertia. The basic idea of this approach is to have a closed loop control system whose dynamics follow a differential equation as in (2).

$$F = M \cdot (\ddot{q} - \ddot{q}_0) + B \cdot (\dot{q} - \dot{q}_0) + K \cdot (q - q_0) \quad (2)$$

where M, B, K represent the inertia, damping and stiffness of the interactive system, respectively. These variables can be adjusted by the control system according to the goals that are to be achieved by the robot in the task (impedance may vary in the various task space directions, typically in a nonlinear and coupled way).

Impedance control strategies could be classified in two categories: those performing indirect force control and those performing direct force control. The main difference between the two categories is that the former achieve force control indirectly via a motion control loop, while the latter offers the possibility of controlling the contact force to a desired value, thanks to the closure of a force feedback loop.

C. *Stability of the Overall System.*

Robotic literature typically treated the environment of a robot as a source of disturbances rather than a dynamic system. The dynamic properties of the environment have an important role in the stability of the overall dynamic system consisting of robot-dynamic environment, [8]. In wearable robotics field, the environment of the robot is the human body. As presented above, the human behavior is commonly considered passive from an energetic point of view, notwithstanding the neural feedback within the arm. This represents a fundamental implication for the stability of robot. If the human behavior can be regarded as passive, it is sufficient to guarantee that the robot behaves in a passive way, to guarantee the passivity of the overall system. In control theory, passivity is a more restrictive condition than stability, and usually a passive system behaves also as a stable one under proper conditions.

In several studies in literature has been defined the term coupled stability as the stability of the system composed of the robot and the environment, mechanically coupled together. A system is said to have the coupled stability property if:

- The system is stable when isolated.
- The system remains stable when coupled to any passive environment which is also stable when isolated.

III. Exoskeleton Controller Design

The problem of designing controllers for such systems, formed by dynamic interacting systems (human and robotic exoskeleton) has been formulated as follows, [9]:

$$\left\| Z_c(j\omega) - Z_t(j\omega) \right\| < \varepsilon \quad \text{for } \omega<\omega_b \qquad (3)$$

where $Z_c(j\omega)$ is the close loop impedance, $Z_t(j\omega)$ is the target impedance, ε is an arbitrarily small number, and ω_b is the desired bandwidth over which $Z_c(j\omega)$ and $Z_t(j\omega)$ should match.

Fig. 3 represents all of several dynamic systems involved in the human-exoskeleton interaction, since a control perspective.

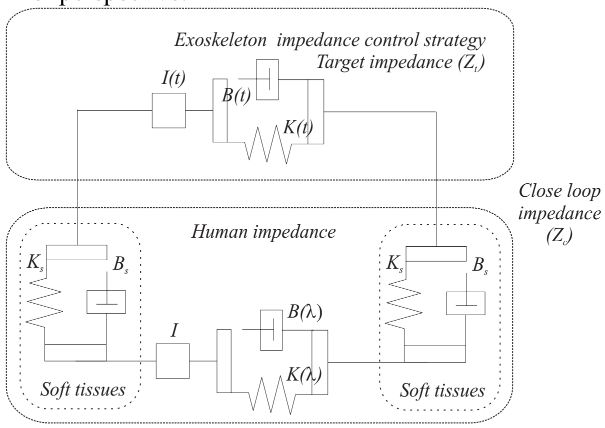

Fig. 3. Coupled control of human-exoskeleton systems understood in terms of the properties of their impedance.

Taking into account the target application, controller requirements vary in a wide spectrum. Thus, in next subsections is discussed the control requirements for the main applications of robotic exoskeleton, when work with the human being.

A. *Empowering.*

The main purpose of a robotic exoskeleton in this application is to amplify the physical capacities of a human. As a result, the person provides control signals to the exoskeleton, while the device delivers mechanical power in order to accomplish a particular task. In this application, the target impedance is calculated in order to minimize the interaction force between the human and the exoskeleton. The simplest strategy to achieve this goal is a zero interaction force controller, in which a sensor measures the forces involved in the physical human-machine interface.

B. *Telemanipulation.*

This application comprises the set of technologies that enable tasks to be executed remotely. A robotic exoskeleton acts as a master device in a teleoperation system. In bilateral control mode, it allows the operator to control a remote robotic arm (slave). Interaction forces between the remote robot arm and its environment are fed back to the master and applied by the exoskeleton to the human arm.

Classic architectures in telemanipulation are the position-position and the position-force approach. The control information flows bidirectionally between master and slave.

C. *Rehabilitation and Motor Training.*

For rehabilitation applications, the exoskeleton permits to assist in several therapies both actives and passives. Thus, the device emulates and replicates movements and exercises that a physiotherapist executes when work with a patient. The exoskeleton should be able to replicate with a patient the movements performed with a therapist during the treatment. Several control algorithms have been developed in literature that automatically adapt the reference trajectory of different reference-based controllers and/or the impedance magnitude of an impedance controller to the desired motion of the individual patient. Hereby, the human represents a component of the entire control system, which influences the overall system behavior (i.e., motion).

D. Functional Compensation.

In this context, the controller must meet special requirements such as robustness, reliability and safety taking into account that the device must identify the user's intention, analyze the information in real-time and compute the mechanical power to release in the right instant. An illustrative example of a control strategy for functional compensation is the one developed for active tremor suppression by means robotic exoskeletons. This strategy is based on a feedforward controller. It drives the exoskeleton to generate a motion equal but opposite to the tremor, based on real time estimation of the involuntary component of motion.

E. Human Motor Control Research.

There are a variety of experimental and theoretical techniques developed to model the human motor system and to infer the mechanism and strategies used by CNS to generate and modulate the movement. A classic way to characterize a system is done by perturbation analysis, through applying an external perturbation and the observation of changes in the dynamic of system being characterized.

In this ambit of application, robotic exoskeletons can apply programmed force fields. The exoskeleton control strategies should try to minimize the interference effects of the following effects:

- Gravitational compensation.
- Compensation of centrifugal torques.
- Compensation of Coriolis torques.

In literature, have been reported several studies that have implemented and configured robotic exoskeleton for researching, [10].

IV. An Experimental Study: Human Response Under Functional Compensation of Tremor

In order to illustrate the aspects discussed above, an experimental study was carry out, regarding the motor control adaptation under functional compensation of pathologic tremor by means of a robotic exoskeleton for the human upper limb.

In general, physical Human-Robot interaction will trigger cognitive processes on either side of the Human-Robot interface. This adaptation mechanism has not been clearly formalized in the literature, most probably due to the complexity of the CNS. Nevertheless, physically triggered cognitive interactions can be illustrated through the example of a wearable robot interacting physically with a human in order to suppress dynamically pathological tremor.

A. Control Close-Loop Strategy.

When a robotic exoskeleton is aimed to functional compensation, the robot must identify the user's intention, analyse the information in real time and compute control actions according to the appropriate functional compensation strategy. One application is the functional compensation of pathologic tremor. Fig. 4 presents the control strategy.

This strategy is based on a feedforward controller. It drives the exoskeleton to generate a motion equal but opposite to the tremor, based on a real-time estimation of the involuntary component of motion.

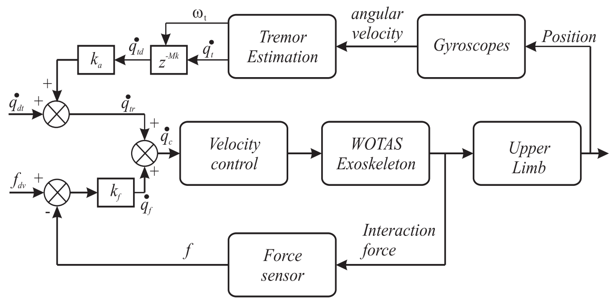

Fig. 4. Tremor suppression control strategy.

This control strategy is based on a dual control loop. The upper control loop is responsible for tremor suppression while the lower control loop is meant to minimize the influence of the control strategy on voluntary movement by means of zero interaction force control, [11].

B. Experimental Protocol.

In Reference [11], a specific protocol was developed to evaluate the control suppression strategies. In these experiments, a set of 10 patients suffering tremor-related diseases participated in trials. The subjects wore a robotic exoskeleton on its right arm allowing execute several tasks. Shaft joint on the device was aligned with subject joints.

A set of 4 tasks was selected for the evaluation trials, based on medical considerations. The tasks selected were:

1) Keeping the arms outstretched,
2) touching the nose with the finger,
3) keeping the upper limb in a resting position and,
4) drawing a spiral.

All tasks performed by the patients were clinical and functional tasks that neurologists use to diagnose tremor-related diseases.

C. Results and Discussion.

In addition to the positive quantitative information regarding the effectiveness of the tremor suppression algorithms, several others qualitative effects were observed, in the process of interaction between the robotic exoskeleton and subjects. When tremor is counteracted by the interaction between the human and robot, the following phenomena were observed:

- The visual feedback of a limb with a reduced tremor amplitude has a positive impact on the human control system. The human motor control is reinforced (a sort of positive gain feedback) and residual tremor is further reduced as a result.

- The reduction of tremor in one joint following interaction with the robot results in perturbed human motor control, possibly leading to increased tremor intensity at the adjacent proximal joints. This phenomenon is called the distal to proximal tremor shift (DPTS), [11].

According to these results, the control strategies in an exoskeleton controller must exhibit an adaptative behaviour, in order to be effective. Thus, two adaptative control strategies, impedance control and model-based repetitive control, were used to drive the robotic exoskeleton suppressing tremorous movement.

Above results reflect the modification in the human control system in response to an external force (functional compensation), trying to cancel an involuntary movement. In general, physical Human-Robot interaction such as the resultant in hybrid human-exoskeleton systems, will trigger cognitive processes on either side of the HR interface. These cognitive processes will in turn affect motor control both in the human and in the robot, all in a context of mutual adaptation during interaction.

V. CONCLUSIONS

The human motor system compensates the variations in a dynamic environment modulating the generated torque by the muscle-skeletal system in order to maintain the original movement. In such system, the dynamic characteristics of human limbs may be approximated by a variable impedance model. Thus, in literature the design of robot controllers that operate coupled to human body have been tackled as an impedance control.

As was presented, the robotic systems (such as exoskeletons) based on impedance model control can be grouped into two types: the first is a power-assist system which executes a task through the amplified human force; the second is a cooperation system in which robots supplement the human operator with an assistive force. In either case, two dynamic systems coexist, and the modulation of impedance properties of each system guarantees proper adaptation under internal and external changes.

During the trials several users spontaneously reported that they felt a decrease in the amplitude of their tremorous movement and consequently they felt more confident about the execution of the task. This indicates that the visual feedback of a smooth movement has a positive impact in the user.

Results obtained in the set of experiments illustrated the human motor control behaviour in the interaction with external devices applying some specific forces on human body. Forces in experiments carry out aimed to cancel the tremor in the upper limb level.

Actually, a lot of studies try to design controllers based on the human properties, aimed to Human-Robot control systems, [12]-[13], to find out control variables in order to allow the control to be as natural as possible, [14], and to improve the kinematics compatibility between human body and exoskeletons, [15].

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