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# The Neuro-Robotics Paradigm: NEURARM, NEUROExos, HANDEXOS

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*Abstract*—**This work describes the neuro-robotics paradigm: the fusion of neuroscience and robotics. The fusion of neuroscience and robotics, called neuro-robotics, is fundamental to develop robotic systems to be used in functional support, personal assistance and neuro-rehabilitation. While usually the robotic device is considered as a "tool" for neuroscientific studies, a breakthrough is obtained if the two scientific competences and methodologies converge to develop innovative platforms to go beyond robotics by including novel models to design better robots. This paper describes three robotic platforms developed at the ARTS lab of Scuola Superiore Sant'Anna, implementing neuro-robotic design paradigm.**

*Keywords*: **Neuro-robotics, robotic model, upper limb exoskeleton, anthropomorphic robotic arm.**

## I. INTRODUCTION

The neuro-robotics paradigm is a novel design approach, mainly aimed at the fusion of neuroscience and robotic competences and methods to design better robots that can be used in rehabilitation and functional support. The ultimate objective of the neuro-robotics paradigm is very ambitious: to introduce a discontinuity in the robot design, thus going literally 'beyond robotics'.

In the last decades neuroscientists obtained important results in using different robotic platforms as a *tool* for their investigations. More precisely, the robotic device has been used as a reliable and accurate instrument to develop behavioral experiments as illustrated in the following:

- to measure and record specific parameters of neuroscientific interest (e.g. the position and velocity of the human hand [1][2], the impendence of the human arm during quick movement tasks [3]);
- to interact with a subject to analyze his/her responses to a specific external stimulus (e.g. the response to a tactile stimulus on the finger tip [4], the effect of a given force disturbance on the hand trajectory [5]).

In any case, the object of the neuroscientific investigation is the behaviour of the human subject, while the robotic device acts just as a support to measure the relevant parameters.

- This is only the simplest way in which neuroscience and robotics can interact. Indeed two more possible approaches of neuro-robotics are: development of *robotic models* (physical platforms) for the investigation of neuroscience theories; in this case, the robot is the object itself of the neuroscientific investigation;
- neuroscientific theories can be applied to design and develop novel robotic systems. The bio-inspiration of such devices will push forward the usual morphological bio-inspiration by implementing human motion-control strategies to control the device.

Our research laboratory recently focused on the development of a number of robotic systems following the innovative approaches of neuro-robotics. In particular this paper presents three robots: the NEURARM, a robotic model of the human upper limb designed to study neuroscientific motion control theories; the NEUROExos and HANDEXOS, the elbow and hand modules of an upper limb rehabilitation exoskeleton, designed in collaboration with neuroscientists to allow physiological motion of the user's elbow and hand during functional support and rehabilitation tasks.

## II. ROBOT AS A MODEL: NEURARM

Neuroscience investigations are still ongoing and conducted by a variety of means in human and animal subjects. Among others, several methods based on the recording of mechanical and neural data are commonly used. However, there is an increasing need to test different neuroscientific hypotheses by implementing them on a model system that is under full control of the experimenter. This way, results obtained by 'standard' neuroscience methods can be compared with those obtained from the model system. While this can be achieved to some extent through numerical simulation, these results are only as good as the accuracy of the numerical model conceived by the investigators. As a supporting tool to these mathematical analyses, the implementation of a specific hypothesis on a real mechanical system can reveal the effects of unmodeled dynamics and provide critical insight into how the human system works in a real environment. In order to address the need of a real mechanical model, and to support the investigation of neuroscientific hypotheses, the functionally bio-inspired NEURARM platform was developed (see **Figure 2**).

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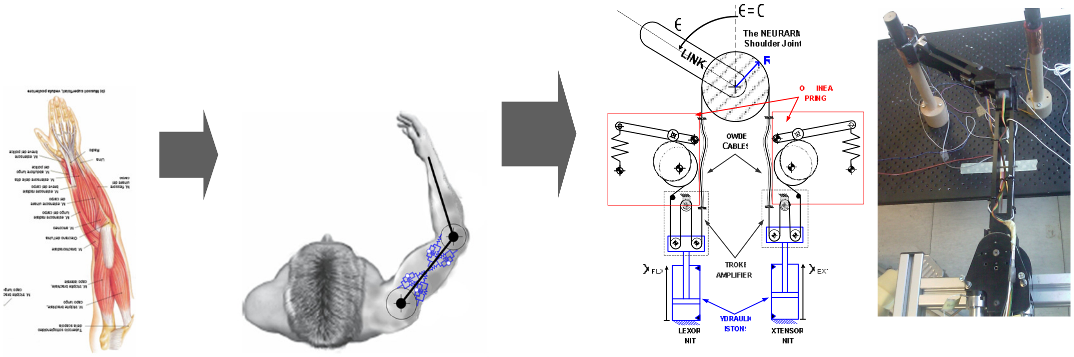

**Biological model** **Cybernetic model** **Bio-inspired robotic artifact: the Neurarm platform**

Figure 2 The neuro-robotics design paradigm: from the biological model a simplified cybernetic model, of both the mechanics and the neural control is obtained. This is the starting point for the development a bio-inspired robotic artifact, which can be used by neuroscientists as a simplified model of the human arm

The NEURARM system is a 2 link–2 degrees of freedom (DoF) planar robotic arm that replicates the main functional parameters of the human upper limb [1][7], i.e. its tendon driven agonist-antagonist actuation, mass, inertia, and dynamic performance. Clearly, this planar system is a gross simplification of the complexity of the human arm. However, the system is complex enough to address essential questions about human behavior. The two-joint linkage provides significant non-linear kinematics, statics and dynamics while the actuator system provides both redundancies in terms of force and torque production. Indeed, considerable coming into human motor behavior has been gathered from focused experiments by restricting human movements to the horizontal plane.

The functionally bio-inspired actuation system permits to implement motion control algorithms which resemble that of the human arm. A pair of muscles powering the human joint in antagonistic configuration provides the peculiar characteristics of the equilibrium point hypothesis (EPH) for human motor control. Since muscles have a natural stiffness and viscosity that varies with the muscle activation level, the central nervous system (CNS) can generate stable equilibrium postures, towards which the arm is attracted, by properly regulating the activation levels of antagonistic muscles. Moreover, the CNS can generate stable posture and even movements in absence of sensory feedback, by shifting the equilibrium point. By co-activating antagonistic muscle in parallel, the mechanical impedance (i.e. stiffness) can also be regulated. The resulting system is intrinsically stable and robust with respect to the neural transmission delays and has the capability to control on demand the impedance at the hand.

The NEURARM platform emulates the antagonist tendon driven actuation system of the human arm. Moreover, it replicates the non linear force elongation characteristic of the muscle-tendon complex, by means of a contractile element (hydraulic piston) in series with a non-linear elastic element. By properly adjusting the piston positions the control system can specify in an open-loop fashion both the joint equilibrium position and mechanical stiffness. Using this device we can test neuroscientific hypotheses about how the CNS controls movement in free space and the interaction with environment.

## III. NEUROSCIENCE IN ROBOTICS: NEUROEXOS AND HANDEXOS

### A. *NEUROExos*

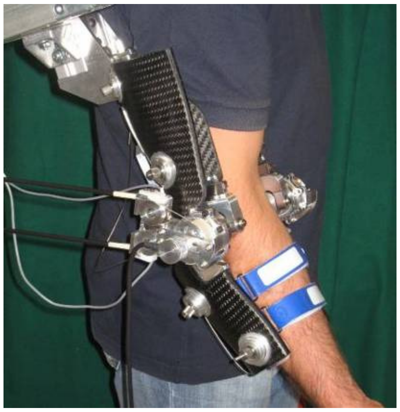

Figure 1 Overview of the NEUROExos.

Other than traditional rehabilitation techniques, in the last decades a great deal of effort and attention were concentrated to develop several robotic platforms aimed at the post stroke rehabilitation or as assistive devices of the upper limb of disabled people. While some robotics research groups focused the attention on "operative machines" rehabilitating the user upper limb by guiding solely his/her hand motion, such as the MIT Manus [1], the MIME [9], the MEMOS [10], the ARM-guide [11], other research groups focused the attention on wearable devices, acting like an upper limb exoskeleton. State of the art is represented by several examples of upper limb exoskeletons. Perry and Rosen [12] designed and developed a multipurpose 7 degrees of freedom (dof) upper-limb exoskeleton. Carignan and colleagues[15] designed and developed a 5-dof arm exoskeleton with passive adjustable linkages. Kiguchi and colleagues [16] built a 3-dof exoskeleton for physically assisting disabled, injured and/or elderly persons. Kousidou, Caldwell and colleagues [17] used the Salford Rehabilitation Exoskeleton (7-dof), for investigating physiotherapy in three dimensional space. Nef and colleagues presented ARMin [18], a 7-dof robot for the rehabilitation of the upper limb.

Critical analysis of the state of the art and the close interaction with neuroscientists showed that the crucial aspects in designing an exoskeleton are the localization and distribution of the physical interaction point between the user and the robot and their kinematic coupling. The absence of a perfect kinematic compatibility has two critical drawbacks: the subject's arm joints can be overloaded and it is impossible to provide any assistive strategy or rehabilitative treatment aimed at supporting singularly each user arm joint.

The second key issue is that of the actuation system. A rigid transmission permits to easily control the robot in terms of joint or end-effector positions as well as to provide an appropriate torque/force field. However, in order to obtain a backdrivabile system, ensuring a safe interaction between the exoskeleton and the user, a muscle like actuation system could be implemented. Thanks to the muscles-tendon visco-elastic properties human joints, are intrinsically stable and have an actively adjustable passive compliance [12]. These properties are desirable even in robots interacting with humans, especially when operating with disabled people and spastic events could happen [13].

The NEUROExos elbow module was developed with the following three main requirements:

- each link is composed by a double shell structure with an inner layer perfectly fitting the user arm and forearm anatomy;
- a 4-dof lightweight, compact, low friction passive mechanism was designed to allow the alignment between the actuated joint axis rotation and that of the user elbow articulation;
- a remotely located muscle-like powering unit, consisting of two antagonist actuators, each composed by a contractile element (hydraulic piston) in series with a non-linear elastic element;

The bio-inspired actuation system allows to control the joint position and hardware stiffness by means of an EPH based controller.

The NEUROExos elbow module (see **Figure 1**) is a mechatronic platform constituted by the following subsystems:

- an adaptive mechanical structure, including the double shell structured links and the 4-dof passive mechanism;
- two remote antagonist muscle-like actuators, powering the elbow module joint by means of steel wire ropes and Bowden cables based transmission;
- the sensory apparatus, including custom driving cables force sensors;
- the EPH based controller, acting on the piston position as explained in Section II;

The NEUROExos platform is a neuro-robot because it has bio-inspired morphological characteristics (e.g. antagonist muscle-like actuators), and it exploits motion control strategies that are taken from neuroscientific motion control hypothesis (i.e. EPH based control).

### *B. Handexos*

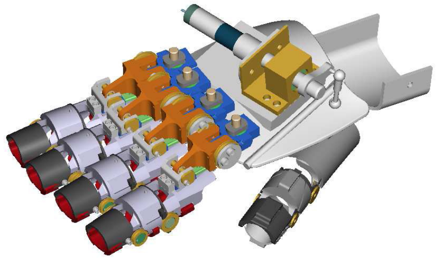

Figure 3 HANDEXOS concept.

To design a wearable mechanism compliant to the human hand movement is a great challenge because of the complexity of the hand structure. This is the reason why one of the main limits of hand exoskeletons is the high level of complexity of the structure and mechanism that often cause low aesthetic acceptability, large overall size and large weight of the device as we can see in [19][20][21]. Analyzing state of the art of recently developed exoskeletons such as [22] and [23], we can notice a clear trend in trying to overcome the complexity, but as a consequence of this, the number of the controllable DoFs decreases. The design goal of the hand exoskeleton that we are developing (HANDEXOS) is to match the two opposing requirements of allowing free hand motion but keeping low the complexity of the mechanism. The mechanical design of HANDEXOS (patent pending [24]) follows some important criteria:

- 5 independent finger modules (see Figure 3 and Figure 4);
- full mobility of the hand with a natural range of motion;
- axes of rotation of the exoskeleton joints being constantly aligned with that of the finger
- passive and adjustable mechanism on the intermediate phalanx to fit as much as possible over hands of different sizes;
- compact, lightweight and low inertia both on the lateral side of the fingers and on the upper and lower side of the hand to allow easy wearability;
- remote actuation system in order to obtain lightweight mechanism;
- palm area and each fingertip free in order to enable the subject to interact with objects during rehabilitative practice as required when therapy exploits tactile feedback.

In particular, the *Distal Interphalangeal* and the *Proximal interphalangeal* joints are coupled with a coincident revolute joint on the robot, while the *Metacarpophalangeal* joint was coupled with a 2 DoF mechanism, consisting of a prismatic and a revolute joint, allowing the constant alignment.

HANDEXOS has been designed in order to implement different actuation/transmission solutions:

- underactuation with linear springs;
- underactuation with non-linear springs;
- independent actuation with non linear springs for each joint.

Both underactuation and non linear springs are concepts derived from bio-inspired design. The first one mimics the configuration of the *Extensor Digitorum Profundus* in the human hand allowing to have lower number of actuators than DoFs, so that the need of full mobility of the wearer's hand can match the requirements of low size and weight. As a drawback, it is not possible to independently control the stiffness and position of each joint.

The non linear springs allow to mimic the force elongation characteristic of the human muscle-tendon complex. This, along with an antagonistic configuration, allows to simultaneously and independently control the joint angular position and stiffness. On the other side, this approach requires a high number of actuators (two for each joint), increasing the overall size and weight of the actuation block, which represents a great drawback in a portable system. At the moment the first two actuation strategies have been explored [25], and planned work will be to study the underactuation with non linear springs configuration in order to exploit the advantages coming from both the actuation strategies.

## IV. CONCLUSIONS

Three innovative neuro—robots were presented in this paper as case studies of novel design approach to go beyond limitations of state of the art robotsThe NEURARM, NEUROExos, and HANDEXOS are presented and analysed in order to show ongoing effort in developing novel bio-inspired control strategies and actutator systems that can be exploited in wearable robots.

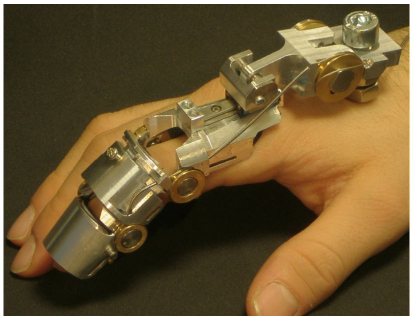

Figure 4 Overview of the HANDEXOS index finger module

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