NEUROExos elbow module:
a new exoskeleton for elbow rehabilitation

E. Cattin, S. Roccella, N. Vitiello, F. Vecchi., and M.C. Carrozza

Abstract— **The development of innovative exoskeletons for the upper limb requires a strong collaboration between robotics and neuroscience. The robotic system will be deeply coupled to the human user and the exoskeleton design should be based on the human model in terms of biomechanics, and control and learning strategies. This paper presents the results of the design process of the NEUROExos exoskeleton. The catching of a moving object has been chosen as reference task from a neuroscience point of view and an ad-hoc setup has been designed and realized. Experiments has been performed and the obtained results has been used to design and develop a bioinspired two joints-two links robotic arm: the NEURArm platform. It has been developed for implementing bioinspired control strategies and for obtaining a human-like robotic arm to be used for assessing active exoskeletons in fully safe conditions. The main features of the NEUROExos elbow module platform and the on going activities related to human/machine interface are presented.**

I. INTRODUCTION

Different research groups have developed a number of robotic solutions for supporting the motor activities of the upper limb focusing on different aspects of the system. For example, D.A. Caldwell and H. Kobayashi use McKibben actuators as actuators for their prototypes. D.A. Caldwell proposed an upper limb rehabilitation exoskeleton with a rigid link structure [1] while Kobayashi group integrates McKibben actuators into a power suit in a configuration similar to the natural muscles [2]. Other research groups focus on the control strategy. K. Kiguchi proposed a cable-driven exoskeleton actuated by DC motors and using neuro-fuzzy logic to control and to predict the arm movements [3],[4]. Genetic algorithm based on the Hill-type muscle model has been developed by J. Rosen (2005) and implemented on a new arm exoskeleton with 7 dof. using EMG, position and force interface information the control system predicts the motions and the torques of the shoulder and of the elbow [5]. The Maryland-Georgetown Army (MGA) Exoskeleton faces up the problem of kinematics coupling between the exoskeleton structure and the human shoulder [6]. NEUROExos upper limb exoskeleton aims to provide an effective kinematic coupling with the upper limb implementing an agonist-antagonist bio-inspired scheme for actuation of the system.

II. METHOD

The main requirements of a robotic exoskeleton have been summarised as follows:

- kinematic coupling of the mechanical structure with the human arm;
- mechanical structure able to support the arm and to transmit force at the arm/exoskeleton interface;
- actuation system able to generate the required torques at the joints;
- high wearability, comfort and safety;
- control system able to predict/drive human arm motion with support/augmentation functions.

Considering that the wearable robotic systems are physically coupled with the human arm, the exoskeleton design should be based on the human model in terms of biomechanics, and control and learning strategies, hence the development of innovative exoskeletons for the upper limb requires a strong collaboration between robotics and neuroscience. The development of this new robotic platform named NEUROExos takes place in the framework of the NEUROBOTICS Integrated Project (The fusion of NEUROscience and roBOTICS, IST-FET Project #2003-001917).

The design and the development of NEUROExos will fuse Neuroscience and robotics:

- to investigate how humans can control the robotic system with non invasive interface and fast intention decoder. The objective is to obtain a “natural” control interface based on the natural user behavior;
- to investigate how to couple the exoskeleton to the human arm by monitoring the mechanical interface between them (inner exos surface vs. human skin) and the forces;
- to control the external artificial actuator system acting in parallel to the internal natural muscoskeletal system. The human control strategy will be investigated and replied in the external actuator system. The natural movement of the user will be enhanced (and not hampered) by the external actuated system;
- to continuously match the exoskeleton impedance to the human arm impedance by means of a agonist/antagonist control of the NEUROExos joints;

The methodology adopted in the NEUROExos design is summarized in the following steps.

A. Reference task experimental setup and biomechanical model implementation

Definition and development of an experimental set-up to carry out reference experiments. The catching of a moving object has been selected as a benchmarking task because it is a well known task in neuroscience and it is challenging

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in terms of kinematics and dynamics. An ad-hoc catching apparatus has been developed for carrying out experiments with human subjects. Fastrack Polhemus Motion Capture System has been used in order to acquire the human arm movement during the catching task. Four markers have been placed on the right shoulder, elbow, wrist, and hand. The acquisition sample rate is 30 Hz. An EMG acquisition system and a National Instrument DAQ have been used to register the activities of the following muscles: Anterior Deltoid, Posterior Deltoid, Biceps, Triceps, Wrist flexor, Wrist extensor. The acquisition sample rate is 1500 Hz. The Catching setup has been designed and manufactured ad hoc to provide an object moving straight at different velocities (0.5, 1.0, and 1.5 m/sec) on a horizontal plane. A 2D load cell (Fx and Fy components, 1000 N max load on each channel) has been integrated into the handle to measure the catching force between handle and tester hand. Starting from the rest position, subject has to stop the slider moving at different velocities, grasping the cylindrical handle. The arm movement has to be planar and parallel to the table surface.

Fig. 1. Ad hoc catching platform during tests on a subject. On the right side of the figure the handle (target) is placed on a slider. The slider runs on two bars by means of two linear bearings. A spring mechanism push the slider that is release unexpectedly by the tester.

Experimental and analytical definition of human arm’s biomechanical model for obtaining the assessment of the cinematic and dynamic performance of human arm during the execution of the reference task. ADAMS® software (LIFEMOD plug-in) has been used to obtain the analytical model of human arm starting from the experimental cinematic data acquired using the specific experimental set-up (see Step 1). The biomechanical model of the arm has been obtained. It is usable to estimate: the cinematic and dynamic parameters of each joint and body segment of the upper limb, the synergies of all the muscle activations, the mechanical impedance of the arm joints. Some examples of application of the obtained biomechanical model are depicted in figure 2 and 3.

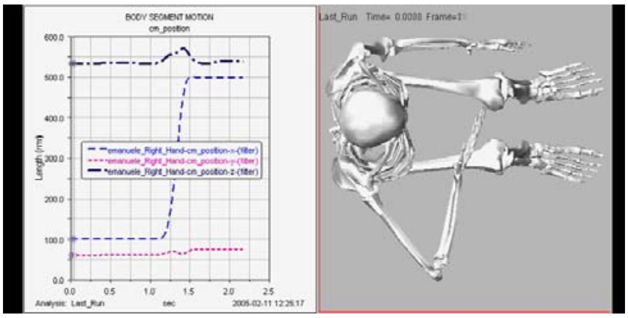

Fig. 2. The biomechanical model used to estimate the kinematics of the joints. The motion data acquired by the reference task are the inputs of the ADAMS® biomechanical model.

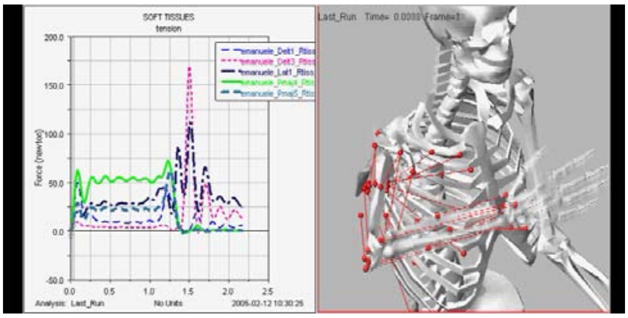

Fig. 3. The biomechanical model used to estimate the muscle activation during the task execution. These figures depict the shoulder agonistic/antagonistic muscles activations. On the right muscle layout can be observed.

The results of the numerical analysis performed using the biomechanical model of the human arm allow to define the technical specification of the actuation system. Two actuators will act on each joint using two cables in order to implement a bio-inspired agonist/antagonist configuration. The joint stiffness will be controlled using the co-activation of two actuators, the cable transmission and two non linear springs. A critical aspect of the actuation design is just the design of the non linear springs that have to be coupled to each actuator.

B. NEURARM anthropomorphic two link planar robotic platform

Design and development of a two links-two joints robotic arm, actuated with four actuators in agonist/antagonist configuration (two actuators for each joint) has been performed. Figure 4 depicts the NEURARM that replicates the human arm in term of:

- physical constrains (ranges of motion, mass, inertia, stiffness, weight);
- agonist/antagonist scheme of actuation system;
- high planar motion performance during the reference task;
- sensory functions.

The impedance control and other control strategies of the robotic platform will be implemented to replicate the cinematic and dynamic performance of the human arm during the same task. It is important to use the dynamic model of the human arm to estimate the range of the human arm stiffness during the execution of the catching task.

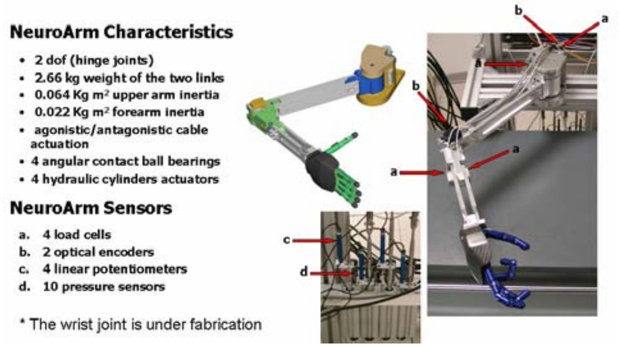

Fig. 4. The complete configuration of the NEURARM planar robot arm.

The NEURARM will be able to mimic the human arm during the execution of reaching and manipulation tasks.

C. NEUROExos elbow module rehabilitation exoskeleton

The technical solutions provided on NEURArm platform will be implemented in NEUROExos platform expecially regarding the actuation strategy and transmission system.

The NEUROExos system has been designed as a wearable robotic system able to self-adapt its kinematic to the variable kinematic of the human upper limb joints. This solution allows a correct coupling between the human and the robotic system. Design has been focused on elbow joint to verify the working principle of this new type of joint.

The elbow anatomical axes moves during flexion-extension movement changing orientation respect to the humerus and ulna-radio bones. The mechanism comprises two universal joint, a rocker arm mechanism and circular slider assembled in order to passively follow the anatomical axis of the elbow.

In order to obtain a comfortable coupling of the system with the upper limb a double shell structure has been provided. The external shell is responsible for supporting all the joint and actuation system, while the inner shell provides the support of the limbs, the comfort and size compatibility.

Fig. 5. Rapid prototyping mock-up of the NEUROExos elbow module.

The external and internal shells have been shaped around the user arm in order to reduce the bulk of the structure. Carbon fiber material has been used for the external shells to ensure stiffness and lightness of the structure. Orthopedic thermo-forming materials has been adopted to develop the internal shells. The use of a cable transmission solution to act the elbow joint maintains the lightness of the structure placing in a remote position the actuators.

Sensors are integrated in the structure in order to measure angular position, applied torque and force at interface.

A concept of the mechanical structure of the NEUROExos has been realized using rapid prototype technology to verify the bulk of the system. Afterwards the first prototype of the elbow module of NEUROExos platform has been manufactured. Figures 5 and 6 show the mock-up and the first prototype.

Fig. 6. NEUROExos elbow module first prototype.

At the same time, a number of experimental activities will be carried out in order to:

1) evaluate sensory fusion and real time control. A number of sensory information will be real-time processing and a number of control signals will be real-time generated by the NEUROExos controller. These processing should not be noted by the NEUROExos user: the robot will be physically coupled with the user’s arm and should adapt in real-time to its movements, to gravity, to external events;
2) investigate human/robot force/torque/equilibrium position interaction. The human will physically interact with NeuroExos. Three models of interaction will be investigated using the NEURARM. The shared control of the robot’s end point stiffness will be investigated. Strategies for planning the NeuroExos end point stiffness will be also investigated;
3) investigate the EMG interfaces to control the force and movement/equilibrium position of the end point of the robotic arms. The sEMG signals could be used in conjunction with kinematics signals for estimating the kinematics and torques of the joints, or for predicting the joint torque and stiffness, or for predicting the kinematics of a joint using the kinematics of another joint (e.g., the prediction of elbow kinematics by the shoulder kinematics);
4) investigate the hybrid mechatronic-EMG approach to control the exoskeleton. The sEMG signals could be also used in conjunction with the other sensory information of the mechatronic system for anticipatory triggering between pre-selected trajectories or for implementing more complex

algorithms that combine EMG-Kinematics information for transforming EMG-based force fields into the joint space;

5) develop mechatronic sensory skin that will be applied onto the internal surface of the exoskeleton and that will be used as control interface. The mechatronic sensory provided with contact and proximity sensors will be also applied on the external surface of the exoskeleton for implementing automatic obstacle avoidance behaviors. Fig. 7 shows an example of the mechatronic sensory skin under development at SSSA [7], [8].

Fig. 7. Three prototypes of the Soft Compliant Tactile Microsensor.

6) develop of novel wearable control and cognitive feedback interfaces. The ACHILLE interface is a wireless sensory insole that has been developed at ARTS Lab and that has been used for controlling multi-joints hand prostheses and for controlling the PC pointer (see Fig. 8) [9]. The same concept could be used for controlling some features of the NEUROExos and for feeding back cognitive information to the user.

Fig. 8. The ACHILLE interface is a wireless control interface that can be inserted inside the shoe and can be used to control external devices.

III. CONCLUSION

The biomechanical model of the human arm and the NEURARM have been developed and tested, and neuroscience experimental activities are ongoing for investigating human sensory-motor models, motor control strategies, and human machine interfaces by using the NEURARM. Specific sensory-actuated wearable interfaces are being developed for feeding back cognitive information to the user and to be used as control interfaces. One of these interfaces is based on flexible technologies and can be inserted into the user's shoe. In addition, the first concept of the NEUROExos has been developed. It has been specifically designed to be an orthotic device composed of two shells and able to passively adapt to the kinematics of the human arm, ensuring comfort and safety for the user by means of innovative kinematics and transmission solutions. The results of analysis and simulations made using ADAMS® software of this new system show the ability of the system to maintain the alignment with the anatomical axis of the elbow. Hence the acting torque can be transmitted without any additional force or torque that can annoy the user. The final prototype, in this moment under manufacturing, will be assembled and will be coupled with NEURArm platform in order to test the coupled control system in total safe conditions, as shown in figure 9.

Applications of NEUROExos elbow module for elbow rehabilitation protocols will be evaluated focusing on possible rehabilitation scenarios.

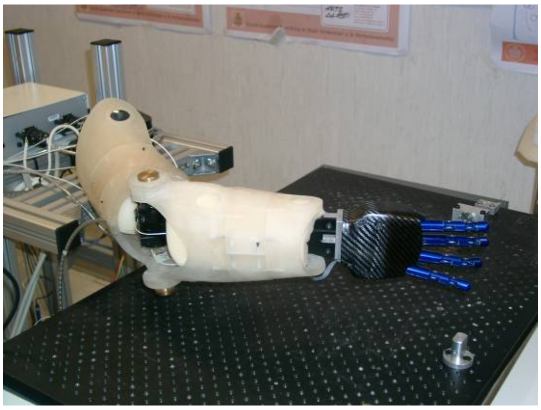

Fig. 9. NEUROExos elbow module worn by NEURArm robotic arm.

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