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# A Hybrid NMES-Exoskeleton for real objects interaction

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## Abstract

**Clinicians constantly face the need to rehabilitate stroke patients to re-establish coordinate reach and grasp. Rehabilitation, to be effective, requires intensive and repetitive tasks. Assist-as-needed motion control for reach and grasp assistance are usually treated separately, and mostly based on virtual reality games. To increase the clinical outcome, we designed flexible modules for a clinical platform, able to provide synchronous reach and grasp support and to interact with common objects. An upper limb exoskeleton provides the reaching support, a NMES-system based on electrode arrays provides grasp control by means of muscle contraction, and a satellite robot presents the objects to be grasped. Specific rehabilitation tasks can be implemented by taking advantage of the possibility to quantify the support needed by patients, and to modulate both the mechanical and NMES support over the reachable workspace.**

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## Introduction

Stroke, with 1.1M new cases a year in Europe, is the leading cause of permanent loss of motor function [1]. A consistent fraction of those patients suffers contralateral upper limb weakness or paresis. Shoulder strength and scapular stabilization, required for sustaining the weight of the arm, are usually missing. Forearm and hand muscles can often be either paretic or totally flaccid. In clinical practice, intensity and frequency of treatment are key elements to provide positive outcomes in the limited time-frame allowed by the hospitalization. Traditional and emerging rehabilitation techniques are often hindered by clinical conservatism, and new devices can be accepted from a clinical perspective only if economically sustainable in terms of efficacy of treatment and modularity of use. As an example, in upper limb rehabilitation, traditionally standard treatments such as physical therapy, and hand splinting are not necessarily effective. On the contrary, robotic devices therapy improves motor and functional outcomes of shoulder and elbow, and cyclic neuro-muscular electrical stimulation (NMES) therapy improves hemi-paretic upper extremity. There is no such device currently available on the market that embeds both functionalities. On the contrary, the efficacy of other technologies such as virtual reality is still debatable and far from being proven to be effective. Despite that, VR is de facto the standard visual feedback system used in robotic rehabilitation, although its ability to maintain the patient engaged and focused in games is often unclear. Effects of the rehabilitation with multiple combined technologies are still unknown, and the higher the clinical device complexity, the more unlikely will be its use in clinical practice. Upper limb Robotic Rehabilitation (RR) is known to be, at best, as efficient as an averagely skilled therapist [2] but currently less flexible in the rehabilitation treatments. Such robots are currently seen, and used, as a separate and independent entity from therapist. RR can accurately quantify the support given to patients in motion, and programmatically adapt the assistance according to data driven choices, but is currently unable to benefit from the therapist expertise, and to adapt to the subtle cues a patient could easily communicate, verbally or not, to a therapist. Most current upper limb exoskeletons focus only on reaching tasks, with one handle as interaction medium, and confine the activities to virtual reality games. The conceptual shift of changing the standard handle used for virtual reality rehabilitation to more specialized tools was implemented by [3]. Most of the commercial upper limb exoskeletons have handles and bulky parts that assist the patient in reaching, and pronation-supination movements, but prevent the free grasping of real objects [4]. Clinical concerns can rise when such exoskeletons are used in cooperation with separate robotic manipulators because of possible problems related to "last centimeter" interactions. Our aim is to break the barrier of the virtual reality rehabilitation, and to allow the rehabilitation tools to better interact with patient and therapist. We integrated an upper limb exoskeleton, and an experimental NMES system, and a custom robot. Combined reaching and grasping tools enable users to perform meaningful tasks in their reachable space, while giving the clinician quantitative evaluation of the support needed to achieve specific tasks. As impedance based control is available in the exoskeleton, parameters can be set to constrain the user’ joints within therapeutic movements, and thus avoid unwanted compensation strategies. Our system can adapt to a variety of control strategies that will purposefully require the intervention of the patient to successfully reach the object, and interact with it.

## MATERIALS AND METHODS

### PERCRO ALEx

Among the variety of UL exoskeletons, ALEx (PERCRO, Pisa) allows removing the handle, and the corresponding support structures, thus reducing the overall footprint of the end effector.

 Figure 1: ALEx upper limb exoskeleton without the standard handle.

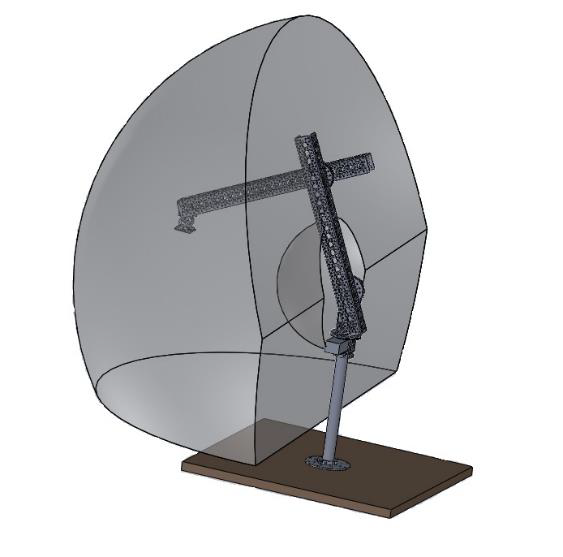
As visible in Fig. 2, the adapted device in operative conditions can provide almost unobstructed reaching of objects positioned on a table whose size is larger than 15 centimeters  Figure 2: Subject testing an early stage prototype of the rehabilitation framework (ALEx with NMES and other devices)

In the actual implementation, an object is suspended on the end-effector of the LAMP-O module, which provides to ALEx the absolute position. The exoskeleton can assist its user in the reaching phase following different strategies: - The exoskeleton can compensate its own weight as well as the weight of the patient’s arm by applying a positive and constant force on the vertical axis, without constraining the patient’s end effector movement. - The impedance control, for each joint, can be used to define the expected position, and progressive strengths can limit deviations. - Alternatively, the exoskeleton can follow, in its workspace, a succession of predefined set-points. In this case the assistance is expected to be proportional to the intensity of the impedance parameter (as presented in the Validation). Consequently one could map how difficult it is for a patient to reach a given set-point, and adapt the impedance in order to maintain challenging but feasible exercise conditions.

Besides the strategy to support the user during the task, the safety of the user was not neglected. Two protective force-fields prevent accidental collisions of the robotic arm with the user body. The first force-field protects the head and the trunk of the user with a virtual wall in the coronal plane; the second force-field, similarly,protects the legs of the user with a virtual wall in the transverse plane. Finally a couple of large and highly visible mechanical “shut-down” buttons are placed within reach of both the therapist and the user at any time to disable the motors, and to have minimum mechanical impedance.

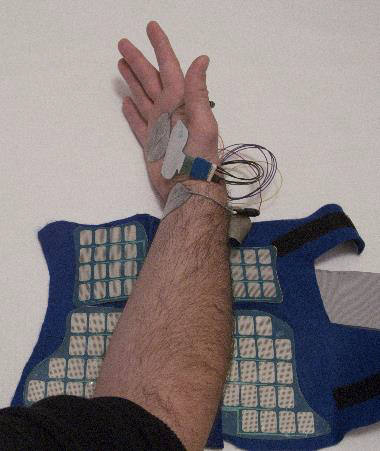
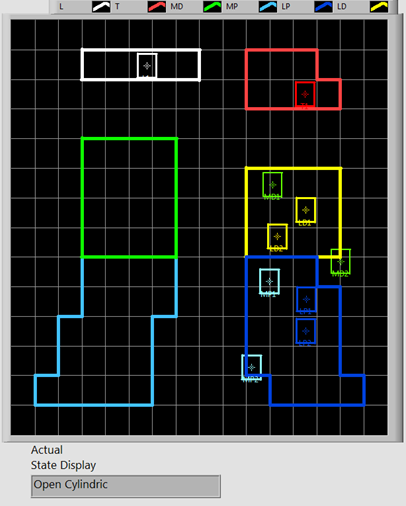
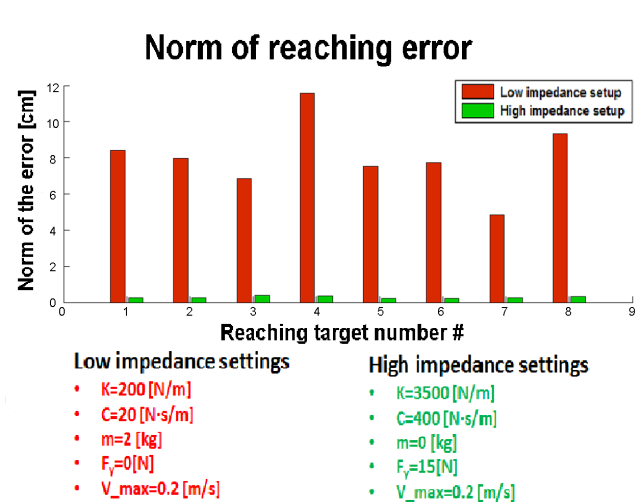
### LAMP-O

We designed a robotic arm as a serial chain of a three-links manipulator with revolute joints, and able to support objects weighting up to 1 kg. Dynamics simulation of the structure was performed in Matlab (Mathworks Inc.), and servo motors have been chosen accordingly. The end effector hosts a magnetic locking structure which keeps vertical the hung object. Position and orientation of the tool in three-dimensional space are handled by a minimum jerk trajectory planner. Solutions of the planner are constrained to maintain the end effector pointing downward. Custom objects can be easily connected to the end effector, and removed, for reach and grasp tasks. A user interface(Labview, National Instruments®) manages synchronous control of the device in the joints space with 10 Hertz update frequency. The end effector can programmatically reach a predefined set of locations within the patient workspace, or custom 3d coordinates. A WiiMote controller (Nintendo®) is interfaced with the control pc [5], and allows controlling the end-effector in free mode, or the sequential reaching of position. In the free mode state,new sets of data points can be recorded, and played back at the therapist will. Fig. 3 shows the reachable space of LAMP-O.

 Figure 3: model of the LAMP-O module, used to present objects to the patient wearing the exoskeleton. In light gray it’s represented the reachable space as a section of a sphere with 0.5m radius.

### Hand NMES

A wearable NMES system [6], able to provide multiple stimulation patterns, is used for eliciting the contraction of extrinsic and intrinsic hand muscles. Custom electrode arrays [TNE-Tecnalia, and AG 702, Axelgaard], designed to conform to the user’s forearm, can be personalized to the user’s anthropometric characteristics, and can provide electrical and mechanical skin matching. A custom stimulator, supporting channel multiplexing (Rehastim, Hasomed GmbH), delivers pulse-trains at a frame frequency of 20 Hz. Additionally, multiple spatially distributed virtual electrodes can selectively elicit different surface muscles. A simple graphical interface allows the therapist to map location and intensity of the stimulation, and to create compound muscles activation patterns, and consequently to induce different hand pre-shaping and grasping types. Each stimulation map can be activated independently, and sequential switching between sets of maps allows performing non trivial hand pre-shaping and grasping sequences. Fig. 4 and Fig. 5 show close-ups of the garment and the simplified interface.

 Figure 4: Hand NMES device  Figure 5: A simplified user interface mapping of the NMES virtual electrodes. Position and intensity of stimulation determine the actual action performed by the user. The modulable intensity of stimulation can be used to suggest what muscle the subject shall use, or to physically induce muscle contraction.  Figure 6: Effect of the impedance settings over the norm of the reaching error ##Validation Following the hypothesis that an overall higher impedance would lead to a stronger and more precise robotic support during the reaching task, in the preliminary platform testing a healthy subject was equipped with the exoskeleton and instructed to remain passive, not helping nor contrasting the exoskeleton at all during set-points reaching tasks. During the exercise, the embedded position sensors of the exoskeleton were used to record the precision of every reaching movement, and the exercise was repeated several times with varying impedance settings to empirically search for optimal control solutions and to compare the results achieved with different impedance values. As shown in Fig. 6, by switching from low to high impedance settings, the accuracy to reach a specified point in the exoskeleton’s workspaces increases. This result is consistent over points scattered all over the workspace, and suggests that impedance switching may allow to support progressively increasing task’s difficulty, as well as subjects with higher motor deficit in specific volumes of the workspaces.

## Limitations

In the actual design of the exoskeleton, the trunk of the user can be fixed properly to the seat, but shoulders are not mechanically restricted. The alignment between the user’s and the robot’s shoulders could mismatch during part or the whole task. This issue is not prominent in studies concerning healthy subjects since they tend to keep their back straight and flat on the seat. On the other hand, patients with some degree of muscular spasticity or patients being highly concentrated on the task are more likely to move on the chair, causing misalignments. Since the shoulder is expected to maintain a specific location in space, misalignments can induce difficulties in the control of the exoskeleton. Another limitation of the actual design is the ability to adapt the robot to patients with different anthropometric sizes. The length of the arm and forearm is fixed, as well as the position of the shoulder. As a consequence, the tested prototype allows properly align the robotic joints only with relatively small and thin subjects. With taller and larger subjects the mechanical mismatch would result in a poorly controlled application of the support forces. The next version of the prototype will minimize such issues. Finally, the position of both LAMP-O and ALEx end-effectors are assumed to be correct based on the machines’ own sensors, but a validation of the whole system with an independent measurement device needs to be done.

## Conclusions

This work is an early effort aiming at helping motor impaired patients to receive adequate rehabilitative support by exploiting the most promising technologies available and coordinating them into a highly modular framework that researcher and therapists can easily adapt and extend based on their own experience and ideas. The system presented in this study was designed as a combination of three main components (1) an upper limb exoskeleton (the ALEx), (2) a NeuroMuscular Electrical Stimulator [6] and (3) a robotic manipulator, respectively to support reaching movement, grasping movement and to present real objects to reach for and grasp. As previously stated, the lack of a clear proof of the efficiency of virtual reality applications within the rehabilitative framework lead the authors to design a system that could deal with completely real tasks, providing a complete sensory feedback for all the aspects of the reaching and grasping task. In the actual framework objects are presented through LampO, and the user of ALEx is helped in reaching the object from a neutral position, grasp and return the objects on the ipsilateral side. The framework is still subject to modifications and extensions and in the short term the authors plan to complete it with a more comprehensive platform for object selection and presentation, allowing to better mimic activities of daily living. Moreover, the whole framework was built with an easy-to use and versatile interface allowing high cooperation with therapists. This will allow them to perform on-line personalization of the rehabilitation process of single patients using position sensors to define where an object to reach should be, as well as a remote control to modify the settings of the exercise. In addition to the strong interaction with therapists, the system was also built on a very modular basis to allow the fast and efficient insertion of new control algorithms for the rehabilitation process. These efforts to simplify the implementation of novel control algorithms are meant to favor the interaction with other research groups toward the design of innovative and more effective control algorithms that actually are the biggest flaw of robot-assisted rehabilitation. To conclude, the actual system displayed great potential to sustain and support real reaching and grasping exercises. An extensive validation, based on a statistical study and involving several disabled patients will be carried out in the next months in order to confirm the therapeutic benefit of the framework described.

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