Development of a hand neuroprosthesis for grasp rehabilitation after stroke: state of art and perspectives

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Abstract— **Stroke disrupts motor and sensory pathways, affects the ability to sense without distorsions body and peripersonal space, to decide to act, and to control efficiently the body. This paper describes the contextual requirements for the design of a grasp rehabilitation system for goal directed exercises. An implementation of a compatible system is shown.**

I. INTRODUCTION

Grasping an object, although apparently a simple and natural action, is a highly specialized set of tasks involving the ability to stabilize the shoulder, perform counter-gravity movements, stabilize arm and wrist during reaching and grasping, preshape the hand as desired, and grasp with the desired strength. The altered skeletal muscle performance is a multi-segmental combination of paralysis, increased tendon reflex activity and hypertonia.

The search for an effective rehabilitation lies on the rebalancing motor, sensory, and cognitive skills in a coherent and contextual fashion. However, the development of a grasp rehabilitation system general enough is still a matter of investigation. The reasons of such complexity depend on the variability of the cortical damage, and the variability of its impact on the person's motor and sensory function.

Neuro Muscular Electrical Stimulation (NMES) is one of the treatments proven to recover the use of paretic limb after a stroke and improve grasp capability [3], [4]. If compared to passive splinting or active robotic solutions, NMES evokes sensory rich afferent informations, and is a means of active muscle reconditioning in patients with partial or absent volitional recruitment. NMES can be combined with splints and exoskeletons as means of mechanically stabilizing weak or poorly responding segments while providing goal-directed contextual training. For neuroprostheses using robotics and NMES, the discriminants for effective clinical use can be summarized in portability, weight, fast calibration procedures, range of motion achievable with limited anti-gravitary muscle strength, comfort, and practicality for usage and cleaning. Active glove solutions such as the GloReha (Idrogenet s.r.l.) satisfy those requirements [5] from a mechanical perspective. Within this line of thought, we designed a goal-directed grasp rehabilitation system which includes multi-electrode NMES, a novel grasp orthosis, and a rehabilitation protocol with interactive objects for contextual grasp assistance.

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II. MATERIALS AND METHODS

The system described in this paper aims at recovering and supporting person's ability to perform Activities of Daily Living (ADL) in subjects with upper limb impairment due to a stroke at the sub-acute or early chronic stage. A set of passive wearables are used for selectively constrain wrist and finger motion, while electrode arrays target selectively hand opening and closing without the need of complex agonist-antagonist stimulation tuning.

A. User-centered design

The collection of requirements for the design of the orthoses proceeded over multiple meetings with prototypes look-like, and orthoses aimed at assisting power grasp. Focus groups with patients, physicians and neurologists, and on-field tests with prosthetists and therapists aimed at determining the number of necessary sizes, the amount of mechanical support needed for patients with limited spasticity (Modified Ashworth Scale $\leq$ 2), and with the need to sustain the wrist in subjects with null stabilization capability. Differently from the conventional splinting solutions, the hand palm was minimally covered with cloth-like material to allow the hand to conform to the objects used for the exercises, and to avoid any reduction on afferent tactile information. If not designed properly, rigid wrist locking can cause high pressures in localized areas. Goodness of fit and comfort of use were addressed by conforming the orthosis to common variability of hand and wrist; areas associated to potentially prominent exostoses were shaped to minimize the risk of direct contact. The material was chosen to allow, if needed, a quick reshaping of the wrist compensation angle and of the degree of opposition of the thumb. Selectively constraining of fingers is obtained with custom rubber-like clasps; a first clasp constrains proximal phalanges to move planar along the MCP joint, a second clasp joins the middle phalanges.

B. Active Modules

Topographically mapped multiple electrode arrays (Fig. 1) allow to provide dynamically reconfigurable stimulation maps. The device is designed to provide electrical stimulation on extrinsic hand flexors and extensors with independent sets of electrode arrays. The RehaMove Pro (Hasomed) [6] is used to deliver stimulation through custom produced 3 electrode arrays, each with 16 independent active sites. In this implementation Virtual Electrodes (VEs) are implemented through the synchronous activation of single or multiple active sites each with sizes ranging from 1x1 to 2x2 electrodes. The VE centroid on the grid determines electrode

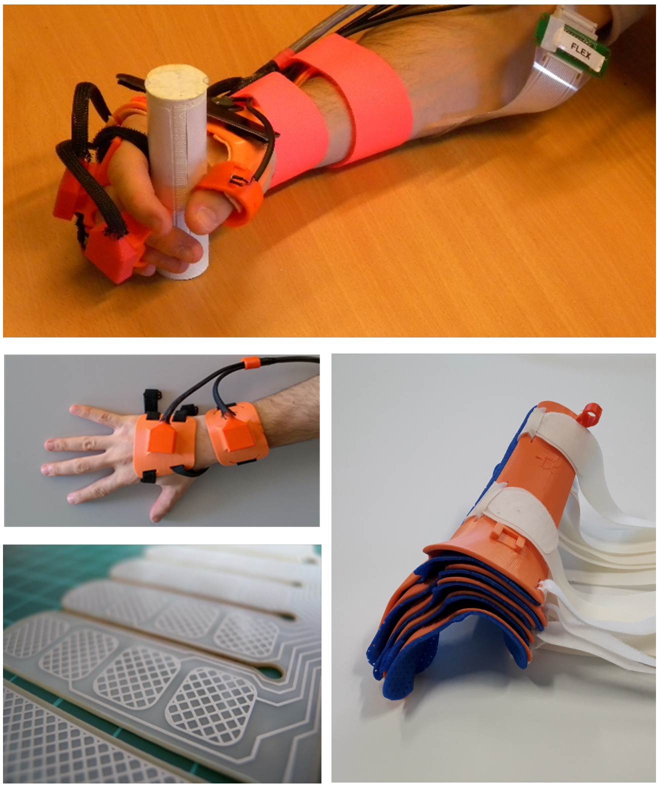

Fig. 1. For exercises requiring to grasp objects, the wearable is designed to lock the wrist at standard extension angles, and to monitor the opening and closing of the hand. Top: the worn system with the orthosis used to perform the grasp exercises. Bottom: details of the orthosis for wrist exercises, of the electrode array, and of the variability of fitting covered with the different size.

size, direction, and location thus providing a set of positions and a varying depth encoding of the field of activation as a consequence of the dynamically changeable electrode size. The maximal stimulation intensity is limited for each VE to 30mA and 300 μs. The VEs positions are personalized through a reactive GUI [7] to elicit functional grasp, to obtain whole muscle conditioning, and to produce open-loop or closed-loop grasp control. This approach diverges from the auto-tuning procedures proposed by other authors because it implicitly includes stimulation acceptance information. Moreover, stimulation maps deriving from previous sessions or other users can be transferred to the current session, reducing the manual search to 2-3 minutes. An anti-windup PID controller, fed with the desired metacarpal joint angle or grasp force, implements a simple anti-slacking stimulation scheme. Clasps contain force sensors and inertial sensors to estimate grasp force and hand kinematics. Objects, used for mimicking daily life tools, weight up to 600g, and the force sensors measure up to 15N. The objects are labelled with Radio-Frequency IDentification (RFID) tags, a reader filters by proximity the selected objects among several ones. The robotic system is fed with information on the objects proximal to the hand (e.g. physical characteristics, expected sequence of use) to drive exercises execution and stimulation activation.

III. Results and Discussions

The hand neuroprosthesis described in this paper is able to recover and support person's ability to perform exercises based on ADL in subjects with upper limb impairment due to stroke at the sub-acute and at the early chronic stage. Pilot tests with with previous embodiments of the device [8] proved to be insightful in defining anthropometric requirements and practicality requirements usually not needed in healthy populations. The current set of wearables allows to fit the target population, and to functionally constrain the movement for the exercises as needed. The functional constraining implemented in the orthosis is fit with the execution of the exercises and allows to host the electrode arrays for targeted NMES. A Randomized Controlled Trial (RCT) aimed at evaluating the effectiveness of the system in recovering of hand function is registered (Clinicaltrials.org, NCT03199833) and currently ongoing.

IV. Conclusions

The preliminary results suggest that this wearable allows performing goal-driven exercises in a population that otherwise would be targeted either with splinting, passive external mobilization, or with repetitive NMES. In the companion paper [9] are described the exercises implemented with this device and a preliminary assessment on efficacy and usability.

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