Wearable Systems for Grasp Rehabilitation after stroke

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PAR

Andrea CREMA

acceptée sur proposition du jury:

Dr S. Carrara, président du jury
Prof. S. Micera, Prof. J. D. R. Millán Ruiz, directeurs de thèse
Prof. F. Molteni, rapporteur
Prof. A. L. G. Pedrocchi, rapporteuse
Prof. F. Hummel, rapporteur

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE
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Abstract

Stroke is the leading cause of long term disability, causing both motor and cognitive impairments. Stroke impacts both motor and somatosensory capabilities of the individual, causing distorted perception of the environment and of the body. Consequently persons with grasp impairments are subject to activity limitations and participation restriction because of perceptive limitations and because of reduced control of the affected limb. Recent medical research has demonstrated that the contextual matching of motor intent with rehabilitation assistance is a decisive factor for success of therapies that involve functional electrical stimulation. In clinical practice therapies based on transcutaneous electrical stimulation are not efficiently integrated to provide such training in a simple fashion.

In this thesis I present the evolution of a wearable neurorehabilitation system in which a multichannel transcutaneous electrical stimulation is used for grasp rehabilitation. Different embodiments of the system are used for transitioning from research-grade prototype to devices usable in clinical trials minimal or absent engineering supervision.

Keywords

Hand; Neurorehabilitation; Stroke; Cognition; Grasp; Rehabilitation; Neuroplasticity; Motor Outcome; Treatment Outcome

Riassunto

Le vittime di stroke sono soggette a disabilita' protratte nel tempo sia di tipo motorio che percettivo. Lo stroke, causando alterazioni delle capacita' motorie e somatosensoriali individuali, induce una distorta percezione del corpo, dell'ambiente circostante e delle possibili modalita' di interazione. Conseguentemente, le persone con deficit alla mano sono soggette a limitazioni nelle attivita' quotidiane sia per cause percettive e cognitive, sia per il ridotto controllo motorio dell'arto plegico. Ricerche mediche recenti hanno dimostrato che l'assistenza riabilitativa associata contestualmente con l'intento motorio del paziente e' un fattore essenziale per il successo della riabilitazione con stimolazione elettrica funzionale. Tuttavia, nella pratica clinica non vi sono dispositivi integrati capaci di fornire questo tipo di trattamento in maniera semplice. In questa tesi presento l'evoluzione di un sistema indossabile che sfrutta la stimolazione elettrica transcutanea multicanale per la neuroriabilitazione della mano. Il sistema usato in questa tesi prende forma in diversi prototipi, mostrando la transizione da prototipo da laboratorio a dispositivo usabile in trial clinici.

Parole chiave

Mano; Neuroreabilitazione; Stroke; Ictus ; Cognizione; Afferraggio; Mano ; Riabilitazione; Neuroplasticita'; Risultato motorio; Risultato del Trattamento

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Background

This dissertation concerns the design of wearables for the rehabilitation of grasp impaired subjects. This work starts from the results of Lawrence and Kuhn [1], [2] at ETH Zurich, and proceeds in an attempt to simplify neuromuscular electrical stimulation (NMES) in functional and non-functional tasks. Whereas the work at Zurich was mostly focused on the creation of restorative neuroprosthesis (NP) for grasp assistance in SCI subjects, we focus on the design of rehabilitative tools for stroke patients.

The Article 1 of the UN Convention on the Rights of the Persons with Disabilities classifies persons as disabled if affected by any ''long-term physical, mental, intellectual or sensory impairments which in interaction with various barriers may hinder their full and effective participation in society on an equal basis with others''. Stroke is the leading cause of disability, followed by SCI injuries, traumatic nerve transections, and neurodegenerative diseases. Such global epidemic determines high human, familiar and societal costs [3]–[5]. Post-stroke sensorimotor complications can be treated with a compensatory approach or the restorative approach. While the compensatory approach aims at teaching patients new substitutive skills without the need of reducing impairments, the restorative approach aims at neuromuscular facilitation. Neuromuscular facilitation aims at improving motor recovery and maximizing brain recovery with sensorimotor stimulation, exercises and resistance training [6]. Timing of treatment and adequate predictive factors are still matter of discussion, with studies showing often contradicting or inconclusive results. Upper extremity pain and limited mobility are common in the patients after stroke [7] and regaining functional upper limb mobility is often more complex than restoring lower limbs motor independence. One of the possible reasons of this outcomes disparity lies in the functional needs for upper and lower limbs. While lower limbs have mostly postural function, human upper limbs are tools for highly specialized manipulation. Humans manipulate objects in accordance to the intended use so, rather than focusing on a standardized grasp, they consider the possibility of an action on an object or environment. The concept of affordance [8] impacts on a variety of fields including cognitive psychology, perceptual psychology, robotics, artificial intelligence, and interaction design. Healthy subjects are capable of fine manipulation control with minimal apparent effort, even though grasping requires complex coordinated action of several muscle groups. Natural human grasping is achieved by the synergistic activity of extrinsic, intrinsic, superficial, and deep muscles. The hand structure allows performing a variety of affordances or "action possibilities", mechanically compatible with the exertable forces and the necessary control. A more subtle aspect of the concept of affordance is related to the "perceived action possibilities".

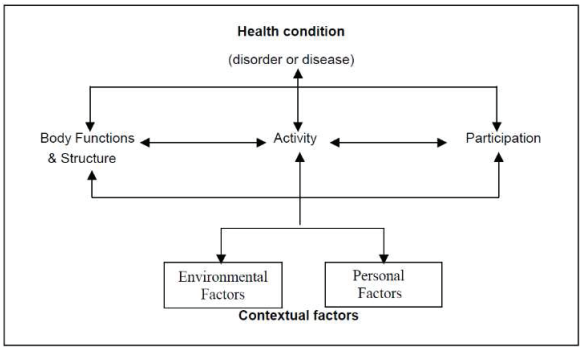


Figure 1: ICF scheme of interactions

(Interaction Model of the International Classification of Functioning, Disability and Health (ICF). Image originating from [9])

For the next few lines I take the liberty of assimilating humans to generic robotic agents. An agent, to operate in an environment, requires awareness of its body and awareness of the environment. The embodied agent interacts with the environment in accordance to the available perception modalities and its willingness to act. For healthy subjects, concepts such as embodiment and agency are trivial at the point to be ignored or forgotten. For disabled subjects and for the clinicians that daily have to deal with impaired sensory-motor integration, these concepts are definitely actual and more troublesome. The WHO translates those themes with the International Classification of Functioning, Disability and Health (ICF) ("WHO | International Classification of Functioning, Disability and Health (ICF)," 2001) framework, aimed at describing and organizing information on functioning and disability. The ICF model conceptualizes ''a person's level of functioning as a dynamic interaction between her or his health conditions, environmental factors, and personal factors'', in a ''biopsychosocial model of disability, based on an integration of the social and medical models

of disability''. Physiological and psychological body functions, as well as affected body structures, determine the kind of impairment and the general level of functionality. These elements, the participation level of the subject, and the environment can be facilitators or restrictors of the subject's activities.

Reduced hand functionality is a major post-stroke outcome, often matched with sensorimotor deficits and cognitive impairments. The effort overhead in neurorehabilitation is also biased by the timeliness of the treatment and its specificity. Residual motor abilities and body representation dynamically change at higher rates in the first weeks after the accident, and quick intervention is seen as way to compensate for motor deficit, or conversely to avoid the neuroplastic consolidation of a bad sensorimotor control. Early adoption of hand sensory-motor rehabilitation is consequently suggested for quicker regain of residual capabilities [10], [11].

The Evidence-Based Review of Stroke Rehabilitation [12] offers insight on the efficacy of the most common practices, and their usefulness in relation to the clinical picture of the patient. In an attempt of evidence-driven guidance through the most efficient techniques, neuromuscular electrical stimulation (NMES) is reported as a viable option for treating stroke-related upper-limb disabilities. NMES improves hemiparetic upper extremity function, and botulinum toxin in combination with electrical stimulation improves tone in the upper extremity. However, standard motor rehabilitation outcome is often suboptimal, because insufficient or non-specific treatment is provided. Non-specific training, due to easy to use but simplistic tools, can lead to non-sufficient quality of treatment. This limitation can be countered with tools able to provide specific training, usable and robust, that can be used to provide more patient specific treatment with less constant clinical supervision.

1.1 Neurobiological mechanisms

Muscle and nerve tissues are excitable by electrical forces. When a sensory receptor is elicited, the generator potential is graded in accordance to the stimulus intensity. If the stimulus intensity is sufficient to induce a generator potential higher than the receptor potential, an action potential (AP) propagates along the axon from the receptor to the spinal cord and from here can be relayed to the brain for the appropriate processing. Similarly an AP can be relayed to a motor neuron as a sensory reflex arc or as a cortical decision to induce localized contraction. These physiological reactions can be elicited by artificially modifying the local electrical potential with e.g. electromagnetic induction, direct current injection, or transient electrical field. The selectivity of the artificial stimulation procedure varies with the chosen methodology, with the proximity of the source and the targeted volume, and the invasiveness of the procedure. The stimulation selectivity can often be non-sufficient to target only the desired fibers and both desired and undesired AP can arise. For instance, transcutaneous NMES can induce muscle contraction and evoke painful sensations. A typical way of delivering ES stimulation is by providing one single pulse or a train of monophasic pulses over an electrode pair. Although energetically suboptimal for stimulation, rectangular pulses are used for ease of electronic implementation. Cathodic stimulation (minus polarity) is preferred to anodic stimulation because it elicits response with lower intensity pulses. Monophasic stimulation is useful when a limited number of pulses needs to be delivered; in case of prolonged stimulation, monophasic stimulation causes a constant increase of injected charge and contributes to the quick deterioration of the tissue in the proximity of the stimulating electrode. Biphasic charge balanced waveform overcomes this problem by delivering on the same stimulating electrode a cathodic pulse followed by an anodic pulse (or vice versa). Sinusoidal stimulation was used at first for simplicity of implementation, but the phase reversal can cause threshold current to increase at the cathode, and can have mixed effects on the anode threshold current. This limitation can be mitigated by using biphasic charge-compensated rectangular pulses, with the cathodic and anodic waveforms separated by an Interphase Delay of at least 50 μs. A good overview of these issues is provided by Reilly [13] and updated waveform propositions are ongoing topic of investigation [14] .

The kind of fibers that populate the area targeted by artificial stimulation play a role in defining the stimulation intensity threshold. Artificial stimulation causes inverted muscle fiber recruitment, with Type II fibers reacting at lower stimulation thresholds than Type I fibers. A twitch is represents the quantized muscle response to an incoming AP, and it appears when over-threshold stimulation pulse is provided to the innervating neural tissue. The muscle tension can be graded through the variation of AP rates. During repetitive stimulation, muscle twitches are visible as single events when low stimulation rates are applied (Figure 2). Single twitches become less visible with the increase of stimulation frequency, and the muscle tension generated by stimulation appears stable starting from 30Hz. As a side effect, because of the artificially inverted recruitment, repetitive stimulation is known to causes a quick fatigue onset [15]. Supraspinal factors are also known to affect the motor response and the perceived fatigue [16], [17].

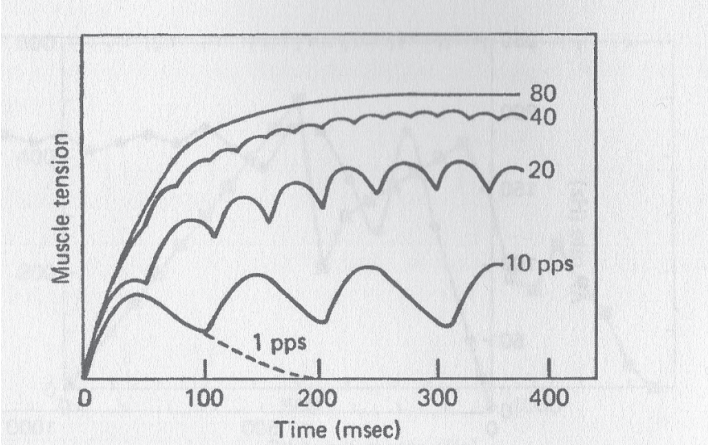


Figure 2: Effects of stimulation rate on muscle tension.

(Serialized events can be recognized at low stimulation rates. Fused twitches are still recognizable at excitations of 20 pulses per second. Higher stimulation rates provide smoother response at the expense of early fatigue onset. Figure originating from Reilly [13])

Electrodes of different invasiveness can be used for delivering electrical stimulation. Implanted multipolar, epimysial and intramuscular electrodes offer the possibility to recruit specific muscles with high selectivity and low activation currents. They also require invasive surgery for each placement, repair and substitution operation, thus making them good candidates only for long term implants for individuals with an acceptable life expectancy and good systemic health conditions.

At a lower degree of invasiveness, percutaneous electrodes are inserted with thin wires through the skin and, upon correct and stable positioning, offer selective stimulation of small muscles or specific volumes of larger muscles. However the reliability of these electrodes is in general lower than the implanted because cables inserted through the skin are prone to getting damaged by mechanical stress. Additionally, transcutaneous cables are a preferential way for propagating infections and contamination through the insertion site, making device sterilization and extreme skin care a need.

Surface electrodes are non-invasive conductive patches positioned on the skin. When compared with percutaneous and implanted electrodes, surface electrodes have low selectivity and require higher injected charges to compensate for the dispersed displacement currents, thus making the result of stimulation highly dependent on the skills of the operator, and on the properties of the tissues interposed between the electrode pair and the targeted fibers. Although implanted electrodes have clear technological advantages for long term use, surface electrodes are preferred for NMES therapy.

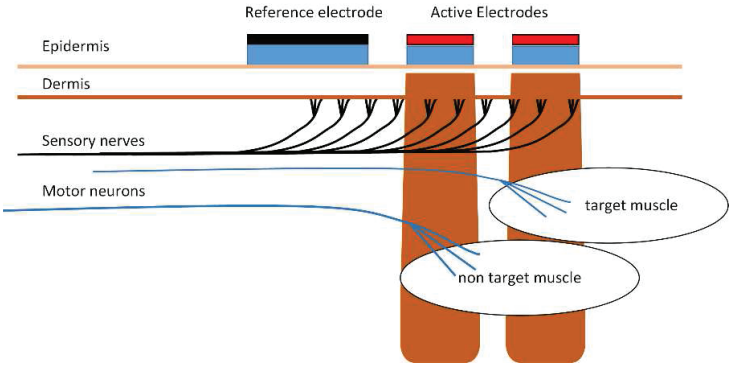


Figure 3: transcutaneous ES selectivity

(Effects of active electrode position and selectivity of superficial electrodes. The activation volume of a stimulating electrode (brown) depends on the electrode size and shape, the stimulation intensity, the local properties of the skin, and on the interposed tissues. Stimulation is in general performed on intact skin, without bruises, wounds or swelling. The presence of implants or previous surgery on the targeted area is, in general, an exclusion criterion. Deep excitable tissues such as motor neurons are shielded by the presence of more superficial tissues, and deeper tissues require more intense stimulation to be elicited. Since the injected currents follow a lowest resistance path, receptors and sensory nerves are a primary stimulus dispersion pathway, and are targeted even at low stimulation intensities. The location of the stimulating electrode and depth of field affect the ability of selectively elicit

the targeted muscle, and of avoiding undesired co-activations. The active electrode on the left would activate targeted and non targeted muscles with a high intensity stimulation, with a medium intensity stimulation only the targeted muscle would be recruited via the innervating motor neurons. The active electrode on the right would elicit only the targeted muscle, and not the deeper non-targeted muscle because of lack of innervation in the activation volume.)

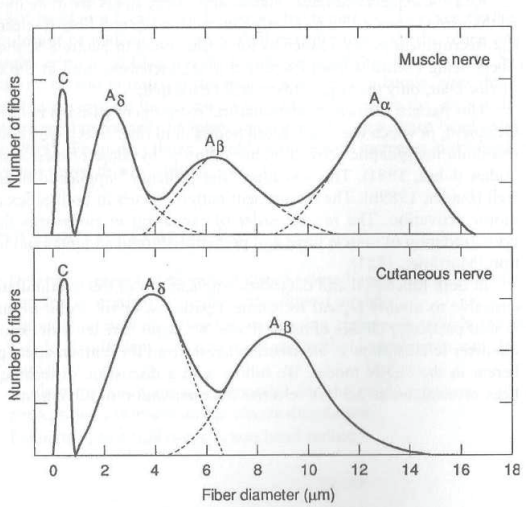


Figure 4: Distribution of peripheral nerves fibers.

(Lower: cutaneous. Upper: muscle. Figure originating from[13])

Since surface electrodes are non-invasive, affordable and easy to dispose, and allow clinical practitioners and caregivers to position and reconfigure them with ease. Different positions of an active electrode on the skin can elicit a different perceptive and motor response (Figure 3), with motor points being the best tradeoff between expected motion and acceptable sensory feedback [18]. Although of theoretical interest from an engineering modelling and design viewpoint, the models of Kuhn [2] are not used in clinical practice because intersubject variability and pronation-supination movements cause motor point variability not accounted in the model parametrization.

The working principle of transcutaneous electrical stimulation impacts on the overall clinical usability. Since NMES requires selective activation volumes, sensory fibers are also elicited by NMES and they can respond by providing afferent information about the stimulated area, nociceptive feedback, or irradiate and provide sensory information apparently originating from different locations. Physiological recruitment of motor fibers follows the size principle [19], with smaller motor fibers activated selectively at low load conditions and larger fibers progressively recruited when larger forces are needed. Electrical stimulation activates the large peripheral nerve fibers first; smaller fibers are progressively recruited with increasing electrical potential gradients. Motor and sensory fibers share similar fiber diameter sizes (Figure 4) and similar activation thresholds.

The stimulation location and pattern affect the perception threshold in electrocutaneous stimulation [20], [21], additionally there is significant inter-individual variability and intraindividual sensitivity adaptation over time [22]. The McGill Pain Questionnaire [23] and TES comfort questionnaire [1] exemplify how it's possible to assess the perceptive variability of electrodes and stimulation and associate them to the most affected layers.

At a first level of approximation, cutaneous adverse sensations are more related to poor interface behavior between electrode and skin, whereas deep sensations rely on too intense local activation fields, and more general adverse sensations seem to depend on un-even stimulation patterns. Table 1 aggregates common adverse sensations with the expected origin. The main mechanism behind stimulation discomfort is still unknown, experimental evidence suggests that the cutaneous component is mainly related to the dishomogeneity of the skin-electrode interface or due to a high surface current density.

Table 1: Categorization of TES Comfort Questionnaire descriptors and depth location

Cutaneous	Deep	General
Pricking	Cramping	Throbbing
Stabbing	Gnawing	Shooting
Sharp	Pulling	Tingling
Hot-Burning	Aching	Tender
Stinging		Splitting/cutting

(Data originating from Lawrence [1])

Table 2: nerves classified by size/conduction velocity

Nerve Fibers	Designation	Function
Large myelinated nerves	A-α, A-β	Proprioception, vibratory sensation, motor
Medium myelinated nerves	A-γ	motor
Small myelinated nerves	A-δ	Pain, temperature, autonomics
Small unmyelinated nerves	C-fibers	Pain, temperature, autonomics

NMES surface electrodes are traditionally standardized electrically-conductive skin adhesives, made of carbon impregnated rubber, vinyl chloride, or metallic foils. The aim of such electrodes is to provide homogeneous mechanical and electrical contact. More recent patents focus on plasticized films of electrically conductive organic polymers[24], engineered to provide locally bound current distribution [25], customizable in shape [26], [27], or with edge protection [28], [29].

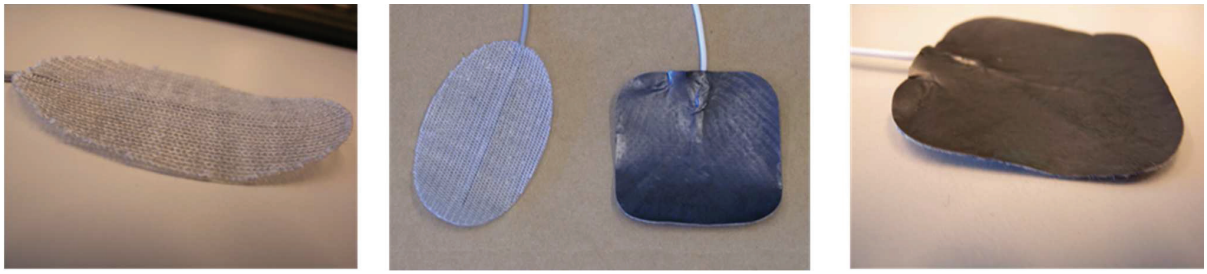


Figure 5: comparison of standard surface electrodes from Axelgaard and Axion.

(Left and center-left: Axelgaard PALS® electrodes are made with a woven conductive distribution grid aimed at dispersing current evenly across the electrode. Center-right and right: Axion TENS electrodes use a thin vinylic layer. The woven structure provides higher localized conformability than the vinylic layer. Gel was mechanically removed from both the electrodes after softening in hot water.)

Although standard surface electrodes have always been a reliable skin interface, the use of electrode pairs become a sub-optimal solution when more channels are needed because it increases the time required for accurately positioning the electrodes, for managing in a convenient way the bundle of cables connecting electrodes to the stimulation apparatus, and for correctly associating the stimulation channels to the expected elicited motor function.

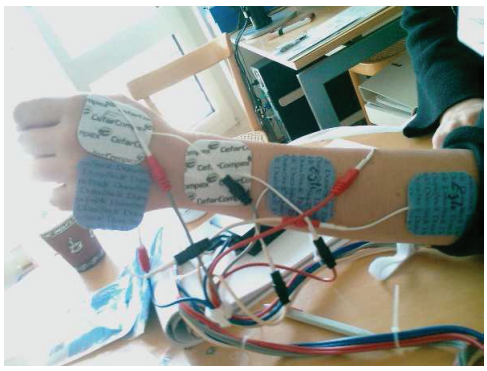


Figure 6: customization and cable handling issues in a simple task preparation.

Garments can include a wiring management solution able to reduce the spaghetti-cable issue. Correct electrode placement is anyway a limiting factor because good fit, tight adherence, simple handling and frequent cleaning are necessary. Mollii Elektrodress (Figure 7) exemplifies the use of mixed woven conductors and dry electrodes for low intensity neurostimulation. To minimize the problem of cable spaghetti, arising with the need of distributed electrodes, the woven conductors are separated from the skin with regular fabric (nylon 82%, spandex 18%). This solution assumes low levels of humidity, which may fit the intended use of this device, but would not qualify for NMES use.

Figure 7: garment with distributed dry electrodes

(Mollii Elektrodress (Inervetions AB, Solna, Sweden) is an example of full body clothing than includes conductive threads connected to dry electrodes. Conductive thread, woven on an elastic substrate, connects the low power stimulation units to the with 58 silicone rubber electrodes (40 active sites and 18 reference electrodes). The expected lifetime of the garment is of 20 wash cycles.)

While the Electrodress may fit the TENS treatment needs, NMES mediated grasp requires a denser distribution of independent electrodes, able to deliver more intense electrical stimulation, typically 40 mA and 150 V. Safe electrical isolation between conductive pathways is needed to avoid, e.g. in case of sweating, localized bursts of stimulation on unintended skin areas.

In an attempt to design textile electrodes Zhou [30] compared wet and dry electrodes, and concluded that wet textile electrodes and hydrogel electrodes can produce painless electrical stimulation, whereas dry electrodes cause painful sensations at levels of stimulation not sufficient to elicit functional movements.

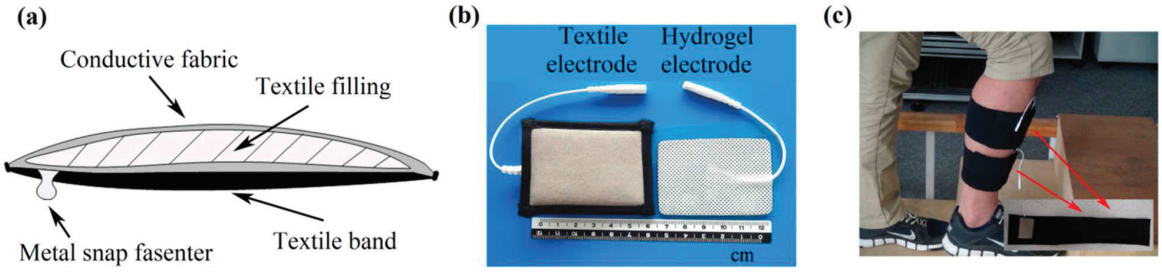


Figure 8: Textile electrodes

(A) schematic view illustrating the composition of the textile electrode. B) textile electrode compared with standard hydrogel electrodes. C) Sample placement of the textile electrode. Figure originating from [30])

As visible in Figure 8, the textile wet electrodes could be a re-usable alternative to standard hydrogel electrodes. It's still unclear the usability of such electrodes in applications where the electrode pairs have to be replaced by smaller, multiple electrodes.

Alternative solutions aiming to obtain a denser routing by using directly fabric were provided by SMARTEX s.r.l. and Bischoff Textiles AG. The SMARTEX prototype is a dense grid of electrodes; informal stimulation test in dry and wet conditions, and with the

electrode arrays covered with gel patches triggered the onset of painful sensations at any tested conditions. The main cause of such behavior was the localized contact thread hand sewn, as visible in Figure 9, on the knitted conductive layers.

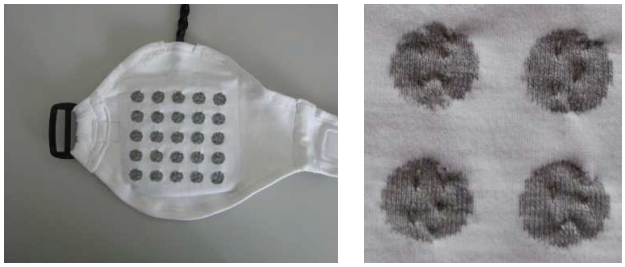


Figure 9: SMARTEX prototype tested for NMES motor recruitment and stimulation comfort.

(Left: SMARTEX testbed for NMES usability. The 5 by 5 matrix includes round electrodes. Right: the close-up on the 8mm round electrodes shows finely knitted conductors connected externally with sewn thread. The presence of sewn thread causes stimulation hotspots)

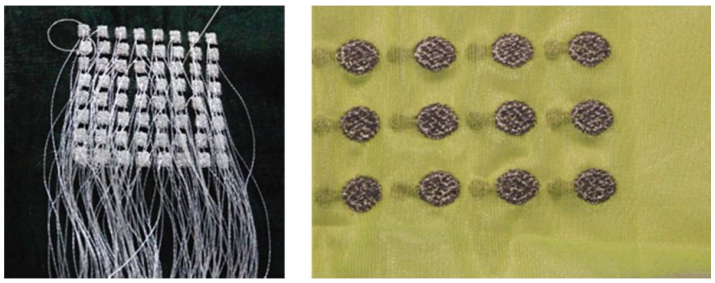


Figure 10: Bischoff prototypes for evaluating NMES motor recruitment and comfort

(The electrode arrays shown above highlight the technical potentialities and limitations of embroidered custom-shaped electrodes. Also the Bischoff prototypes, machine embroidered with conductive thread on fabric, when tested in conditions comparable to the SmarTex array, caused pain, thus confirming that the inhomogeneity of the stimulation surface and of the electrical properties are a major factor on the stimulation comfort. No electrical isolation mechanism is included in these electrode arrays to prevent short circuits; any excessive moisture or local shift of the fabric and wires can cause unintended contact of independent conductive lines with consequent accidental diversion of the current from the expected spot.)

When using embroidered electrode technology, at the cost of higher stiffness, the conductive lines can be isolated as shown in Figure 11. The use of intermediate hydrophobic membranes is a means of reducing problems of short circuits as a consequence of machine washing of the wearable or of excessive sweating of the subject. The additional fabric layers, needed to improve the electrical isolation, increase the stiffness of the fabric thus reducing the global foldability and adaptability to the skin surface.

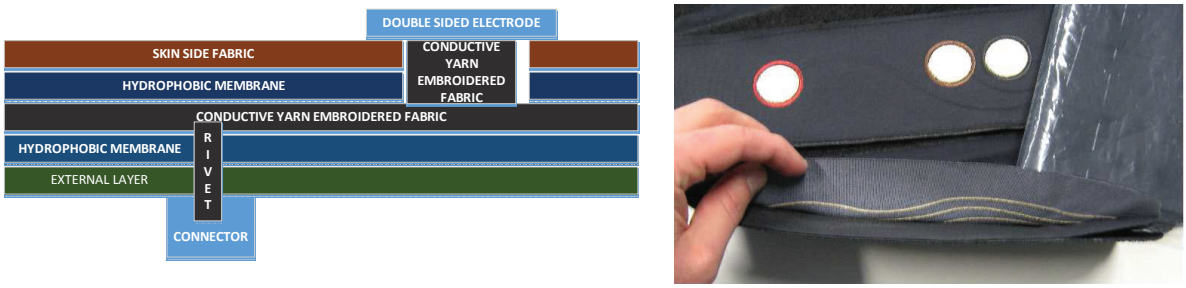


Figure 11: Embroidered electrode technology, sample electrical isolation layers

(Left: sample structure of multi-layer fabric with isolated electrodes. Right: details of the embroidered prototypes. Embroidered fabric, thermal gluing and membrane details.)

A larger improvement in the quality of stimulation, the consistently achievable density of independent electrodes, the wiring and isolation of electrodes, and the usability in clinical context derives from the use of plastic substrates with screen printed conductive tracks. Sample production of this technology is shown by Malesevic [31].

Natural human grasping is achieved by the synergistic activity of extrinsic, intrinsic, superficial, and deep muscles subjected to volitional control. Causes affecting grasp capabilities can vary, but as long as motor units are responsive to electrical stimulation, grasp assistance can be externally triggered. In particular, transcutaneous neuromuscular electrical stimulation (NMES) can be used to recruit different muscles in a coordinated way to restore grasping functions. However, NMES is not able to restore fine manipulation because it can selectively elicit only a limited and variable subset of muscles through the corresponding innervation points.

The variety of grasps used in Activities of Daily Living (ADL) in healthy subjects [32] is not currently replicable with the aforementioned wearable technologies focused on practicality [33]–[36], but limited by the low number of independent stimulation channels.

Table 3: percentage of activities of daily living versus grasp type

Grasp Type	Name			Example
	Vergara	Sollerman	Light	The palm is involved. The thumb is in direct opposition to the
Cylindrical grasp	12.3	14	25	fingers (in abduction or neutral)
Oblique palmar grasp	5.9	15		Variation of the Cylindrical grasp. The palm is involved, but
Hook grasp	2.9			the thumb is adducted
Lumbrical grasp	9.7	15		Palm and thumb are not involved. The object's weight is borne by fingers
Intermediate power-precision grasp	3.3	4	10	Thumb and proximal part of the fingers are involved, but the
Pinch grasp	38.3	20		palm is not involved
Lateral pinch	8.8	20	20	The palm is somewhat involved but both the thumb and index stabilize the grasp
Special pinch	2.8	10	10	Thumb and fingertips (one or more) are used
Non-prehensile grasp	12.7	2	10	The lateral part of the fingers (one or more) are used, and
Other /not analyzed	3.3			

(Table data extracted with adaptation from [32], [35], [36])

First-generation NMES-based grasp assistive devices [37], [38] were able to achieve grasping by recruiting mostly extrinsic flexors and extensors; in some cases, the stimulation of the thenar eminence was also used. These devices were characterized by very good usability, design simplicity, and mechanical robustness. Because of the use of large, non-selective electrodes and limited independent stimulation channels, these devices were able to induce coarse grasp patterns [39].

To increase the usability of this approach, stimulation has to be more selective and easier to personalize; therefore, the number of independent stimulation channels must increase. Such changes require a trade-off between effectiveness, technological complexity, and setup time. First-generation NMES systems, used in parallel to achieve such functionality, are prone to "spaghetti-cable" problems and are difficult to calibrate.

For these reasons, many groups have recently pursued new approaches (second-generation devices) to address the previously mentioned limiting factors, in particular, donning, tuning time, and limited functionality [31], [40]–[43]. Lawrence and colleagues[1] developed an e-textile solution to improve wearability. Conductive threads, embroidered in the fabric, provide connectivity between skin electrodes and the stimulator. However, limitations apply to this design as conductive yarns are prone to wear and failure; redundant embroidery is needed to reduce the failure risk, and an isolating membrane coating is needed for electrical safety. To address this issue, Popović and colleagues[44] designed a general-purpose thin electrode array (EA) using silver ink as a conductive medium. This technology grants better stability of the conductive lines while maintaining low linear impedance and thinner isolated lines, thus allowing for denser routing on flexible dielectric substrates.

Single channel NMES is known to be suboptimal and prone to fatigue [45] compared to physiological muscle recruitment. The use of EAs allows exploitation of spatial and temporal summation effects on the targeted anatomical structures. The studies of Nguyen and Malešević suggest the possibility of mitigating the exponential performance decay over time using distributed electrical stimulation sources [46]–[50].

Causes affecting grasp capabilities can vary, but as long as motor units are responsive to electrical stimulation, grasp assistance can be externally triggered. In particular, transcutaneous neuromuscular electrical stimulation (NMES) can be used to recruit different muscles in a coordinated way to restore grasping functions. However, NMES is not able to restore fine manipulation because it can selectively elicit only a limited and variable subset of muscles through the corresponding innervation points. To overcome this limitation, electrodes providing optimized shape and depth of the activation volume[2], [51] could be used to achieve better selectivity.

1.2 Commercial NMES devices for rehabilitation and home use

Despite upper limb impairments being among the most disabling impairments, commercial solutions able to providing a structured home assistance or rehabilitative training are limited. Practitioners have options for at home treatment that are often geograph-

ically limited by local laws and certification requirements, approved reimbursement schemes of the local national health systems and insurance companies. For such reasons devices for home use tend to be affordable, simplified versions of the clinical tools used for physical medicine. Splinting solutions, custom made by clinical specialists or adapted from commercial devices often have the purely mechanical function of maintaining extended as needed the hand as a whole [52], [53] or specific segments [54]–[56]. As this set of options is conservative with respect to the actual patient conditions, no improvement is expected in muscle tone or hand preshaping capabilities. These splinting solutions can also be used to constrain movements, while therapy is delivered through standard NMES stimulators, but the combined use is deemed to the user. Effective transcutaneous NMES requires good mechanical and electrical contact between electrodes and skin. Reliable wearables in general offer a limited number of independent channels, large electrodes, and tightening devices used to mechanically compress the electrode against the skin of the affected part. Arthur Prochazka went through extended clinical testing and technology transfer for the Bionic Glove [37], a non-invasive FES device that restored hand opening and pinch-grip in the paralyzed hands of SCI patients, but commercial success was not achieved.

Based on the same concept of the Bionic Glove, the Bioness H200 [38] is an arm neuroprosthesis targeting extrinsic and intrinsic hand muscles. The clam-like orthosis embraces the forearm, and allows simple adaptation of the electrodes location. Large non-selective electrodes allow stimulation five muscle groups (Extensor Digitorum, Extensor Pollicis Brevis, Flexor Digitorum Superficialis, Flexor Pollicis Longus, and thenars) to achieve fingers extension and grasping. Despite the limited functionality, and the lack of true interactivity, the H200 is commercialized as an assistive device for hand function. However, considering these devices from the simpler rehabilitative perspective, several elements are anyway missing that would allow better clinical and at home treatments. First, the limitations on the stimulation selectivity are reflected in the possibility to elicit only broad hand motion, and thus restrict the possibility of training specific hand grasping and preshaping patterns. Second, the lack of intuitive interactivity schemes with the environment can hinder the potential neuroplastic effects. Any commercial device aiming at providing a significant improvement in the rehabilitative process is required to comply with three major factors to deliver significant results: task specificity, adapted intensity of treatment, and high dose of treatment. These requirements are, at the moment, not fulfilled by commercial devices due to technological limitations of the wearables, limited possibilities for programming in a general purpose framework the interactivity with the environment, and because of limited integration and ease of use for non-trivial tasks.

Chapter 2 Design of a Wearable Platform for GRASP assistance

2.1 DESCRIPTION OF CONTEXT

We started designing wearables for hand rehabilitation within various projects. In one of them we tried combining the garment wearable technology (Bischoff Textil AG, Sankt Gallen, Switzerland) with a passive exoskeleton (Armeo Spring, Hocoma AG, Volketswil, Switzerland) [57]. Among several limitations of that setup, one was due to sub-optimal fitting of the textile garment for NMES due to the restriction of producing only one size. Not having the possibility of producing a reliable garment with multiple electrodes densely packed, due to embroidering issues and unpredictable yarn damage, a technology shift was required. We started designing the Helping Hand system, and deciding to adopt the new electrode array technology (Fatronik Serbia, now part of Tecnalia, Spain). The aim was to design the Helping Hand Exo, a specialized NMES wearable for grasp rehabilitation usable in conjunction with a supporting exoskeleton.

The preliminary prototypes of that technology were used first within a project aimed at designing a multimodal neuroprosthesis for upper limb support of severely motor impaired patients, able to provide contextual control of arm reaching and hand grasping. The expected population included cognitively intact patients, affected by neurodegenerative disease such as Amyotrophic Lateral Sclerosis (ALS), Friedreich Ataxia (FRDA), Multiple Sclerosis (MS) or high level Spinal Cord Injury (SCI). The hypothesized outcome was that, by providing a different set of task-initiating triggers and modular assistance to reaching and grasping, patients with progressive degenerative diseases could learn to use the system when minimally compromised from a motor perspective, and later be assisted during the progression of the disease. The MUNDUS project [58] consisted of 3 technological challenges: (1) design working prototypes for the multimodal motor support of reaching and grasping, (2) reliably detecting intention, (3) providing a clinically usable integrated system for extended exploratory testing on patients.

The design of a wearable platform for grasp assistance, usable in a clinical context, relied on a set of hypotheses requiring usability validation. This chapter includes the first design of the HelpingHand Exo platform.

Object manipulation is a contextual task depending on the discrimination of objects of interest (perception), the understanding of the actions that can be performed with a set of objects (self-embodiment and agency), and the likely object-enabled actions (intention). These decisions and the consequent actions (reaching and grasping), were split in multiple independent modules that needed interdependent coordination to succeed. In the project's assistive perspective, the decision of specific grasp actions was deemed to a central controller that, triggered by specific Human-Machine-Interfaces (BCI, Eye Tracker, volitional EMG, and RFID sensors) substituted this cognitive layer with simpler preset commands.

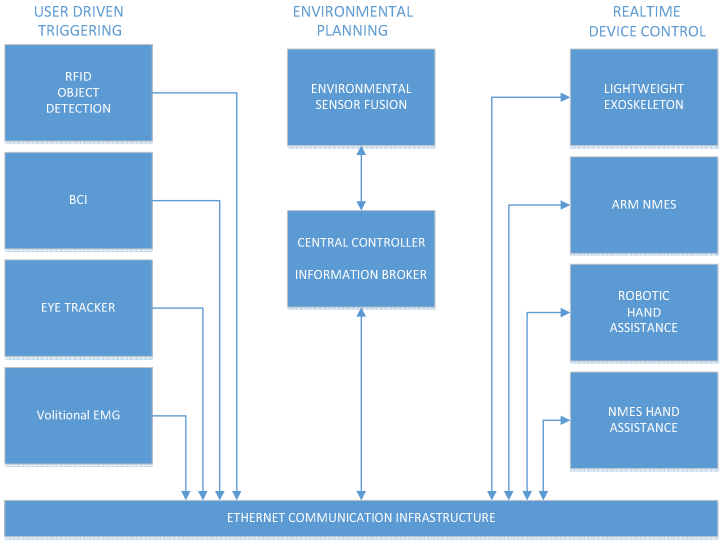


Figure 12: MUNDUS network infrastructure

(General architecture implemented in MUNDUS. Each sub-module was connected to the same Ethernet with a switch, with information TCP broadcasting as a standard communication method for each device)

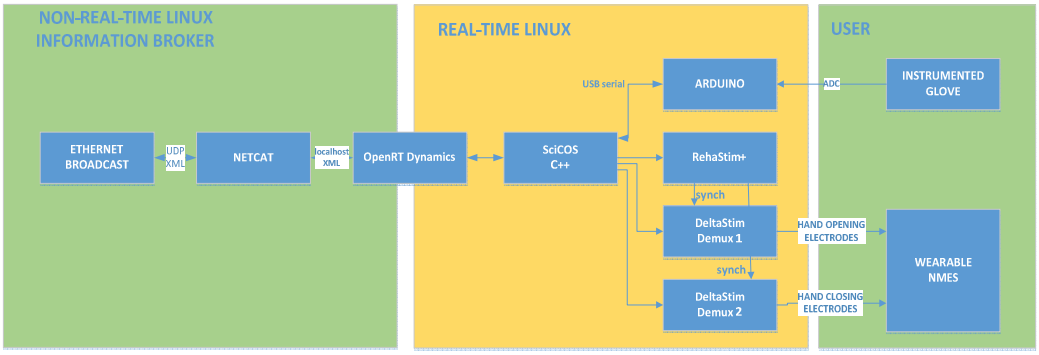


Figure 13: HelpingHand MUNDUS real-time implementation

(Breakdown of the software components in the MUNDUS HelpingHand module. Left: non real-time communication with the whole MUNDUS infrastructure described in Figure 12. Center: real-time control logic. Right: wearable stimulation apparatus as visible in Figure 14 and Figure 15)

Aim of the Lightweight exoskeleton was to assist the user in reaching task by providing gravity compensation by locking with brakes the motion within predefined kinematic planes. Assistance to the hand opening and grasping was deemed to two inter-changeable modules, Manovo and HelpingHand. The Manovo module (Hocoma AG) was a 1 DoF hand orthosis used to induce passive hand opening and closing, with the hand tightly fixed to the structure, and with stepper motors included in the dorsal mechanical enclosure. Complementarily to the Manovo module, the HelpingHand module was required to actively assist the user in simplified grasping tasks by means of selective NMES, without mechanical constraining of the hand and fingers. However it was unclear how to effectively transfer the use of printed flexible electronics into clinically usable prototypes for NMES applications. Previous screen printed electrode arrays produced for hand grasping tasks relied on the stimulation of extrinsic extensors and extrinsic flexors of the hand, but the degree of usefulness of EAs for the stimulation of intrinsic hand muscles was not reported. Printed electrode arrays were using single gel patches on each active site of stimulation, with the patches largely distanced to prevent unexpected lateral contact from neighboring elements [59]. Additionally the electrode arrays design was limited, for simplicity purposes both on the stimulator electronics and on the substrate manufacturing, to four by four grids of elements, with the elements positioned ad hoc on the targeted muscles.

2.2 HelpingHand characterization

2.2.1 Device design rationale

The HelpingHand Exo module was designed to deliver electrical stimulation to extrinsic and intrinsic hand muscles. Using an improved version of the technology presented by Popović [60], low cost electrode arrays were designed with improved routing density and more uniform electrical isolation. Six EAs were included in the device (Figure 14): two were dedicated to activating intrinsic hand muscles (array L for lumbricals/palmar interossei and T for thenar eminence), two were for the extrinsic flexors (medial proximal MP and medial distal MD), and two were for the extrinsic extensors (lateral proximal LP and lateral distal LD). Three electrodes (PALS Oval 40 mm x 64 mm, Axelgaard Manufacturing Co., LTD.) were used as anodes. The first was positioned on the anterior aspect of the wrist and coupled in combination with the MP, MD and T to elicit extrinsic grasp muscle responses and thenar muscle contractions. The second was located on the posterior aspect of the wrist and coupled with the LP and LD to elicit extrinsic muscles for finger openings. The third anode was positioned on the hand palm and coupled with the array L, positioned on the dorsal aspect of the hand, to elicit the contraction of intrinsic grasp muscles such as palmar interossei and lumbricals. A central rigid PCB, hosted under the subject's forearm, provided connectivity between the EAs and the electrical stimulator and limited the overall number of cables needed. The LD, LP, MP and MD arrays provided the butterfly-like shape to the forearm garment. Plastic screws secured each array-PCB gate, providing mechanical stability against pulling and torsion. 150 µm thick polyester substrates isolated the conductive lines of the EAs; the substrate allowed the overall structure to be flexible (but not stretchable), to conform to nearly flat or conical surfaces, and to offer a paper-like touch and feel. The EAs contained a layer of glue to allow the fabric to adhere. The prototypes used either fake-leather fabric or felt fabric for hosting the PCB and the flexible EAs. Velcro hooks and straps tightened the device on the forearm. A removable gel patch placed on the EAs moderately increased the overall EA flexion stiffness. The gel patch contained AG702/735 gel (AmGel Technologies, Axelgaard Manufacturing) and was used to ensure good skin contact and for impedance matching. For simplified clinical usage and replacement of the disposable elements, gel patches were cut to match the shape of each EA. The gel patches provided higher adhesion on the EA side than on the skin side to allow complete and easy removal of the EAs from the skin.

A customized version of the RehaStim stimulator with two DeltaStim demultiplexer units (Hasomed GmbH, Magdeburg, Germany), was connected to the HelpingHand system. Stimulation was provided in time-frames of 50 ms, each consisting of a volley of 10 independent pulses. Each pulse of the frame could be adapted in terms of intensity of stimulation, pulse width (PW), active electrode and counter electrode. The network of dedicated real-time Linux systems (Figure 12) communicating with the local node (Figure 13) to provide environmental triggering.

Arnet [61] reports that from a purely biomechanical perspective, to enable patients to grasp objects of varying sizes, a functional grasp is required that has a larger excursion of fingertip-to-palm distance than can be supplied without intrinsic function. In physiological conditions the simultaneous activation of the FDP and the intrinsic muscles results in a more functional hand closing compared to FDP activation alone because of altered kinematics and larger fingertip-to-palm distances. In general, NMES responses exhibited significant inter-subject and intra-subject variability from intrinsic not-controllable parameters, such as different physiological conditions, electrode selectivity, skin stimulation filtering effects, tissue impedances and day-to-day variability, and different alignments between motor points and stimulation fields. In these experiments, we considered the size, shape, and position of the electrodes, as well as stimulation intensity and timing as design parameters that were tuned to optimize usability and the effectiveness of the system. To be able to target superficial muscles while maintaining comfort, we sized the active electrodes according to Kuhn and Lawrence [51]. Elongated electrodes are prone to forcing the injected charge distributions on the extremes of the main length axis; electrodes with sharp corners suffer the same problem and can produce a needle-like stimulation feeling. Round electrodes avoid this risk but when shaped in arrays do not efficiently cover the skin surface; they also pose the risk of not eliciting extremely selective and localized motor points (e.g., with extremely slender subjects). Larger electrodes mitigate the risk of high current densities and require a lower number of independent stimulation channels at the cost of reduced EA selectivity. In contrast, smaller electrodes increase the selectivity, the stimulator complexity, and the risk of higher current densities. To balance selectivity and electronic complexity, we chose to use two electrode sizes: 12 mm by 16 mm and 14 mm by 18 mm. We arranged the electrodes in the array to fit subjects with large forearms and to be adaptable for fitting smaller subjects. The device was designed to fit a forearm length of up to 330 mm and a circumference in the proximal part of the forearm of up to 400 mm.

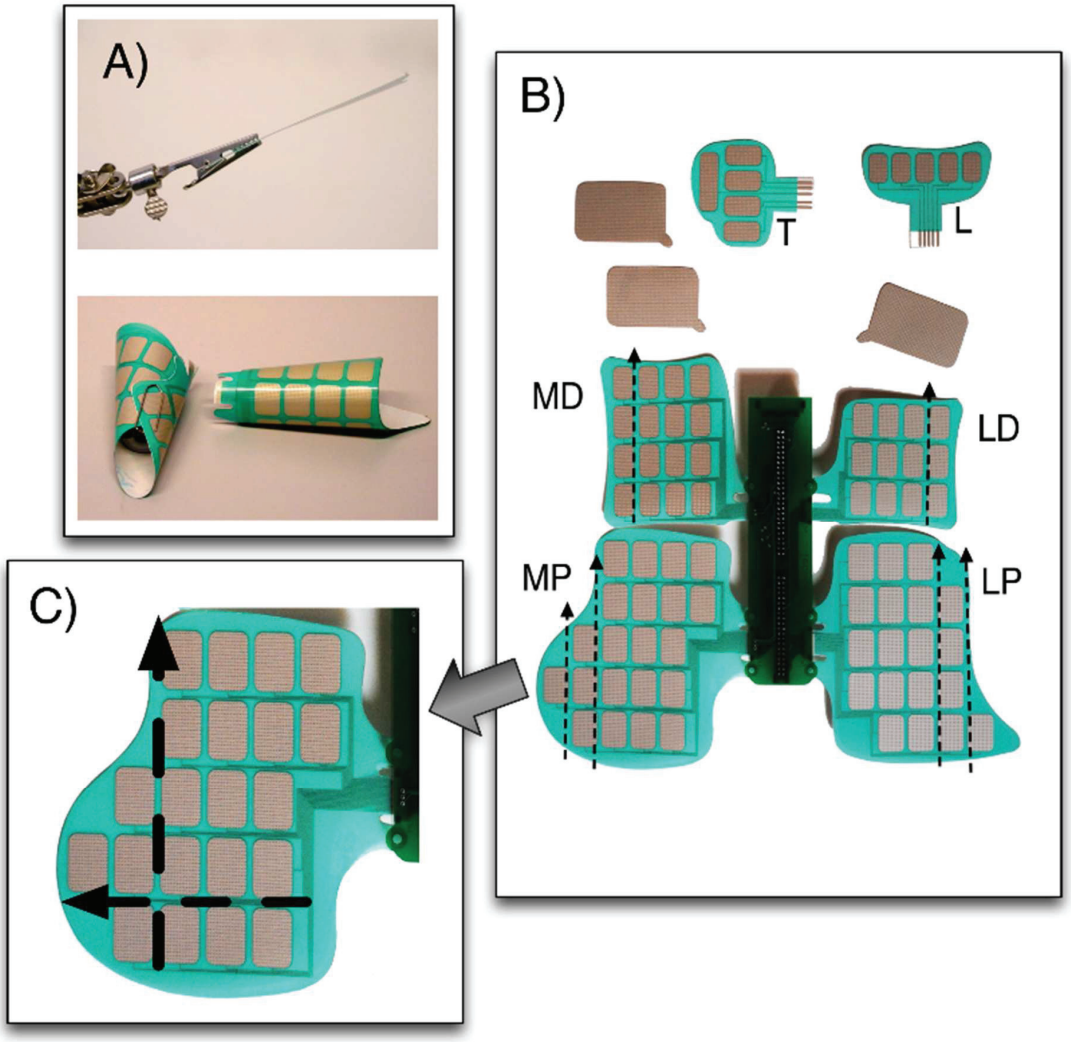


Figure 14: The HelpingHand MUNDUS system.

(A: Flexible electrode arrays have a paper-like touch and feel; the thickness, which does not exceed 150 µm, can be seen in the top image. In the same image block below are depicted two rolled electrode arrays fixed with a paperclip; the array on the right has a superimposed layer of gel (AG702, AmGel Technologies ®). The overall thickness of the matrices, gel included, is approximately 1 mm. B: Of the six electrode arrays connected to the central PCB, four of them constitute the butterfly-like body for extrinsic muscle stimulation. The electrode arrays are routed to allow trimming both in width and in length. This design allows reduction of the electrode arrays to fit subjects smaller than the maximum estimated size. C: Details of the routing can be seen in the bottom left callout box. All the arrays connected directly to the PCB are routed to allow external element trimming (top and lateral for top electrode arrays, bottom and lateral for bottom arrays). Hand electrode arrays, being mostly linear, do not require special routing to comply with functionality and adaptability)

To customize the length and width of the device for various normotypes, the arrays were individually trimmed. The conductive paths routing from the connectors to the electrodes allowed the removal of unneeded electrodes without compromising the functionality of the internal electrodes.

In previous approaches [31], [44], EAs were positioned on the skin on the approximate motor point position. Single patches were positioned using a garment, with anatomical landmarks used as absolute references. Figure 2 shows the alignment process of the forearm and the garment. A cotton glove was used to secure electrode contact with the skin during object manipulation. Force-sensing resistors (FSRs, A201, A401, Tekscan Inc.) hosted in sleeves in the internal side of the glove detected grasp intensity information for the force feedback protocols.

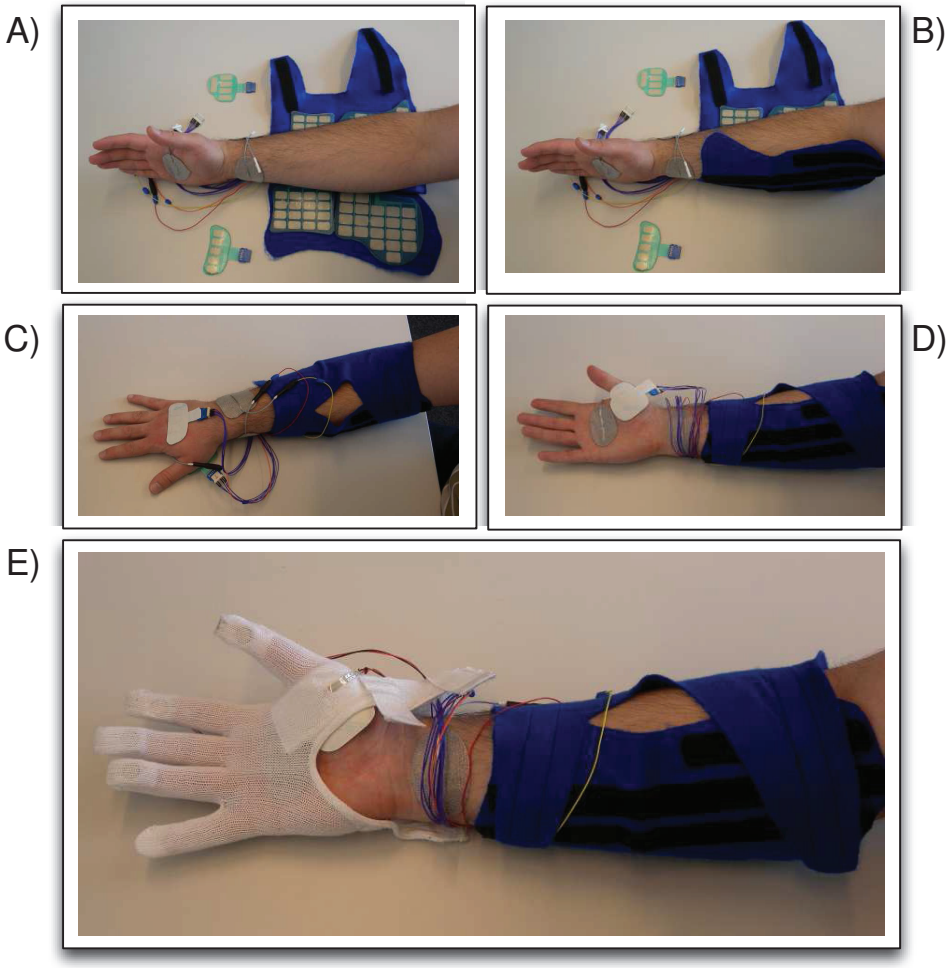


Figure 15: Donnign of the HH system

(A) Oval ground electrodes (Pals Clinical, Axelgaard Manufacturing Co., Ltd.) are positioned on the hand palm, on the anterior aspect of the wrist and on the posterior aspect of the wrist. B) The forearm, once aligned with the PCB, has the most distal electrodes of the MD and LD arrays not closer than 2 cm from the corresponding counter electrodes. Each electrode array, which can be glued on the fabric to provide additional mechanical stability, is separately stuck on the subject's skin, and the garment is tightened with Velcro. C) and D) The small electrode arrays, stuck on the dorsal aspect of the hand and on the thenars, provide stimulation for intrinsic hand muscles. E) A cotton glove is used to protect the ground and hand electrodes during object manipulation. FSRs are hosted in sleeves to detect grasp and to provide grasp intensity information.)

Finding effective NMES parameters is primarily a tuning process. In this experiment, we considered three criteria to classify a stimulation configuration as valid: 1) induced finger movements have to be compatible with a chosen action or affordance without causing spasms in other districts, 2) wrist movements have to be compatible with a chosen action and should not deviate significantly from expected angles, and 3) stimulation should not cause adverse sensations. To be able to modulate grasp strength, we proceeded in two steps. First, the optimal parameters of stimulation in terms of location and current intensity were determined in the open loop. Second, we fixed the stimulation location and current intensity and closed the control loop by force feedback while using PW modulation to match the desired grasp intensity.

The CNP-EPFL Ethical Committee approved the experiments on healthy subjects within the EPFL premises. The Italian Ministry of Health, and the local ethical committee of Clinica Villa Beretta, Ospedale Valduce, provided the approval for the clinical testing.

To assess comfort we performed two kinds of tests on healthy subjects: the first was aimed at verifying selectivity and acceptability of stimulation, whereas the second verified the controllability of the grasp through the wearable. To preliminarily verify the efficacy and usability of the HelpingHand, the device was tested with healthy subjects in two experiments. The EPFL local ethical committee approved the experiment. Each subject provided informed consent before proceeding with the tests. Nine healthy subjects (8 males, 1 female), aged between 23 years and 34 years, and homogeneous in forearm length, performed the tests. The garment was shortened to the chosen length by trimming the excessive electrodes. All the subjects used the same custom garment. To reduce

the influence of gel degradation, new gel patches were used for every subject. Of the nine subjects, three were previously accustomed to NMES, and six subjects did not previously experience NMES and could thus be considered naïve to such sensation.

2.2.2 Quality of stimulation

To characterize the selectivity that different electrodes can provide in terms of elicited kinematic responses, we stimulated one electrode at a time in each EA. In these tests, we targeted muscles with fine control and low innervation ratio. Stimulation was set at 20 Hz, with 250 µs PW on extrinsic muscles. The PW was reduced to 150 µs on hand intrinsic muscles because of better sensory tolerability of shorter pulses in these areas.

In these experiments, we performed full sequential mapping by evaluating the local usefulness of stimulation. On each pin, we divided the task into three phases: A) stimulation that lasted 2 seconds; B) rest that lasted 2 seconds, during which the stimulation was off and the subject was asked to provide sensory feedback; and C) return that lasted 1 second, which was used to remind the subject to return to the initial task condition. When the task required stimulation of extensors, the initial condition was a relaxed closed hand. In contrast, when flexors were elicited, the hand had to be open in a relaxed state. The starting current intensity was set to 2 mA, and the "stimulation", "rest" and "return" phases were iterated for all the pins in the chosen array. Once the sequential pin scan was completed, the current intensity was increased and the process was repeated. The current was increased in steps of 2 mA for matrices L, T, MP and MD and 4 mA for matrices LP and LD. The topological and intensity mapping was terminated when the stimulation was perceived by the subject as consistently annoying or painful, or when the task performance was expected not to improve because of an increase in the stimulation intensity.

Open loop identification data were ranked to find suitable stimulation locations and intensities to match the induced movements with a library of desired movements. Moreover, a set of stimulation parameters was considered valid if the stimulation did not cause discomfort. Ranking was calculated as the compound effect of the following criteria: limited wrist motion, effective grasping kinematics, and comfort of stimulation. It is possible to formalize this method as:

$$J_{global}(i,k) = J_w(i,k)J_f(i,k)J_s(i,k\ )$$

where i represents the current intensity, k represents the pin number of the tested electrode array, J_w represents the wrist motion score, J_f represents the finger joint movement score, J_s is the sensory acceptability score, and J_{global} is a measure of the performance of a stimulation pattern of the selected pin location and current intensity. All the parameters were normalized with "1" corresponding to an optimal response. When J_{global} exceeded an arbitrarily chosen threshold, we considered the stimulation pattern to be acceptable. As a fictitious example, let us assume a grasping stimulation with $J_{global} = 0.6$ with, $J_s = 1$, $J_w = 1$, and $J_f = 0.6$. In this scenario, the stimulation was either not perceived or just above the perceptive threshold, the stimulation did not deviate the wrist from the neutral position, and at least one finger was flexing in a balanced way so that the MCP and the PIP joints were more than 50° each. Score values of 0.6 were heuristically considered acceptable for arrays triggering extrinsic finger movements. Concerning L and T arrays, because of the higher hand sensitivity to stimulation and the fact that intrinsic hand muscles trigger mostly the MCP joints, a score of 0.3 was taken as a reasonable approximation. For each array, we considered the two best scores exceeding the threshold values to be the optimal parameter sets. Further criteria for finger movements, wrist movements, and sensory acceptability are reported below. We assumed that the hand of the end-user was not constrained to make undesirable compensation schemes or mis-stimulation apparent. In such conditions, we wanted to avoid excessive wrist flexion-extension (ϑ_{FE}) and ulnar-radial (ϑ_{UR}) deviation. Therefore, we defined the maximum safety subspace as shown in Table 4.

Table 4: Selected wrist ranges of motion for flexion-extension and ulnar-radial deviation

Action	Ulnar-radial deviation ϑ_{UR}		Flex-extension deviation ϑ_{FE}	
	min [°]	max[°]	min[°]	max[°]
Open	-30	30	0	60
Close	-30	30	-20	40

The wrist motion criterion was then defined as

$$J(i,k)_w = I\left[\left(\vartheta_{FE}^{min} \le \vartheta_{FE}(i,k) \le \vartheta_{FE}^{max}\right)\left(\vartheta_{UR}^{min} \le \vartheta_{UR}(i,k) \le \vartheta_{UR}^{max}\right)\right] * \left(1 - \frac{1}{K_{\sigma 1}^2}\left(\vartheta_{FE}(i,k) - K_{\mu 1}\right)^2\right) * \left(1 - \frac{1}{K_{\sigma 2}^2}\left(\vartheta_{UR}(i,k) - K_{\mu 2}\right)^2\right)$$

where $K_{\mu 1} = \frac{\vartheta_{FE}^{max} + \vartheta_{FE}^{min}}{2}$, $K_{\mu 2} = \frac{\vartheta_{UR}^{max} + \vartheta_{UR}^{min}}{2}$, $K_{\sigma 1} = \frac{\vartheta_{FE}^{max} - \vartheta_{FE}^{min}}{2}$, $K_{\sigma 2} = \frac{\vartheta_{UR}^{max} - \vartheta_{UR}^{min}}{2}$, with I representing the indicator function. Angular deviations that exceeded the above described safety subspace were not allowed.

The fingers criterion was defined as $J_f(i,k) = 1 - \min_{i,M} \sum_s w_{Ms}\left(\vartheta_{iks}^m - \vartheta_{iks}^d\right)$ with w representing a weight function for expected set M of fingers movements on the finger segment s, ϑ_{iks}^m the measured flexion-extension angle, and ϑ_{iks}^d the desired flexion-extension angle. The masked M motions set the desired angles ϑ_{iks}^d to the corresponding supremum value for finger extension. Optimality conditions are mirrored for finger flexion.

Finally, the sensory acceptability was determined as $J_s(i,k) = I(S(i,k) \leq 0.5) + (1 - S(i,k))I(S(i,k) > 0.5)$.

Keyboard buttons were encoded with a set of emoticons, arranged to express a Likert scale. The emoticon coded sensory feedback was assigned to the S null value if no sensation was perceived, 0.25 if the subject perceived a light stimulation sensation, 0.5 if the sensation was clearly noticeable, 0.75 if the stimulation was annoying, and 1 when a painful sensation was elicited. The sensor acceptability criterion was designed to consider valid "light sensation" and "perceivable stimulation", to highly penalize "annoying feeling" reports, and to exclude any worse condition. The wrist motion was considered acceptable for opening and closing movements if the wrist motion was within a predefined flex-extension range with no significant deviation on the ulnar or radial side. For hand opening, two possible conditions were considered valid: 1) fully extended digits from the index to little finger, or 2) the fully extended thumb. For hand closing, the possible conditions could be expressed as the opposite of the hand opening conditions. In such a way, because the motor point for thumb extension and the motor point for the extension of all the other digits were separated, superposition of stimulation effects could be taken as a simple approximation. For completeness, stimulation of the thumb extension could also trigger the index extension, which was remarkably less elicited by the activation of extrinsic extensors in general. The stimulation of extrinsic extensors, conversely, mostly affected motion of the ring, middle and little fingers. For hand closing movements obtained with the L, T, MP and MD arrays, a valid grasp was obtained if at least one finger was completely flexed on the MCP and PIP joints. The stimulation of intrinsic flexors could trigger complex behaviors of all the digits, but the effect consisted primarily of the simple flexion of the MCP joints close to the active pin, with no action of the corresponding PIP joints. Conversely, the stimulation of extrinsic flexors, depending on the depth of selective stimulation, could elicit either flexion or deviation of the wrist (superficial); or induce the flexion of the PIP joints and assist flexion of the MCP joints and the wrist flexion (intermediate); or induce flexion of the DIP joints while assisting PIP and MCP joint flexion. In all these cases, the predominant effect on the PIP and MCP was on the ring and middle fingers.

Nine subjects that volunteered in this study found the stimulation acceptable during the preliminary stimulation phase and became accustomed to the stimulation sensation. Figure 16 depicts the effects of selectivity from adaptable locations of stimulation and indicates that small location changes can provide current spreading effects, causing coarse stimulation. It is worth noting that finger movements were coupled, and consequently single finger movements could usually not be achieved with single motor point stimulation, whereas adjacent joints could passively follow the triggered finger movements.

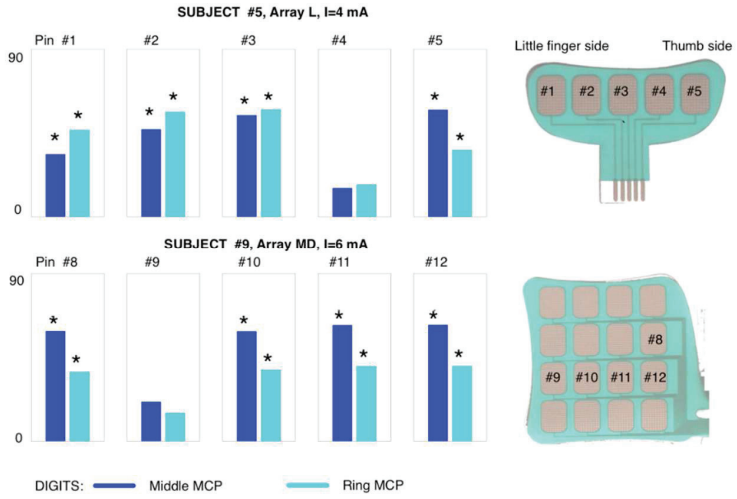


Figure 16: Stimulation examples of two different arrays and detail of sequential scans on five pins

(The metacarpal flexion of the middle finger (blue) and the ring finger (teal) are shown. During one pin stimulation cycle, variations of at least 10° from the start angle to the end angle are used to discriminate induced motion from random passive motion; induced motion, active or passive, is marked with an asterisk. Top: the L array induces direct contraction of lumbrical and palmar interossei

muscles. Stimulation on pin #1 and #2, close to the little finger side, mostly induces ring finger flexion, with the middle finger passively following, thus suggesting mostly ulnar nerve elicitation. As the stimulation location moves toward the center of the hand palm, on pin #3, the middle and ring fingers are more elicited, and the flexion is higher and more balanced and suggests a purely median nerve stimulation. Pin #4 stimulation does not induce motion, and the MCP joints stay in rest conditions. Pin #5 causes a dominant flexion of the middle finger with passive flexion of the ring finger as a result of more medial branches of the median nerve. Bottom: the MD array induces contraction of the Flexor Digitorum Superficialis of the Flexor Digitorum Profundus. The sweep on the forearm produces a fast response to stimulation of the median nerve on pin 12, which is able to effectively target the middle and ring fingers. The same selective motor response, but kinematically slower (not shown), is also clearly visible on pins 8, 10, and 11 where motor responses are suboptimal because of the distance from the motor point.)

Figure 18 shows the global expectations for functional stimulation. For each array, we choose the best three stimulations on for each subject, described as stimulation's pin, depending on the value J_{global}. The resulting matrix was normalized for all the subjects, providing a probability of useful motor point locations. It should be noted that intra-subject results can vary significantly, as shown in Figure 17. Several causes in particular could account for this variability; e.g., variability among the subjects in terms of forearm circumference, different positions of the electrode array and physiological conditions during stimulation. Despite the homogeneity in terms of forearm length, subject #4 on the left and subject #6 on the right exhibited substantial differences in stimulation location, intensity of optimal currents, and acceptability of stimulation. With hand intrinsic muscles, current intensity effects were more noticeable, including lower relative current thresholds for subject #4. This observation was generally consistent across the tests, with subject #4 on average requiring lower stimulation than subject #6 to obtain similar effects. The optimal stimulation locations produced detectable and partially overlapping patterns, as well as moderately different optimal locations, thus suggesting that a partial information transfer of stimulation maps from subject to subject; it is also possible (but not necessarily optimal) that such transfer occurs within the same subject but in different sessions. As an example, for array LP, subjects #4 and #6 exhibited similar J scores of 0.87 and 0.91, respectively, but the optimal locations of the two electrodes were axially shifted (by approximately 40 mm). Within the same set of experiments, perceptive results of subjects #2 and #3 appear in generally darker shades than the ones observable with subjects #4 and #6. The 2 mA increase step of stimulation intensity in these subjects was relatively high for fine tuning of an acceptable motor response and for an acceptable global response. The optimal scores in this case also depended highly on the overall acceptability of the stimulation, which could easily disqualify topologically close locations. As an example, subject #3 obtained low optimal scores on array MP with an optimal J=0.45.

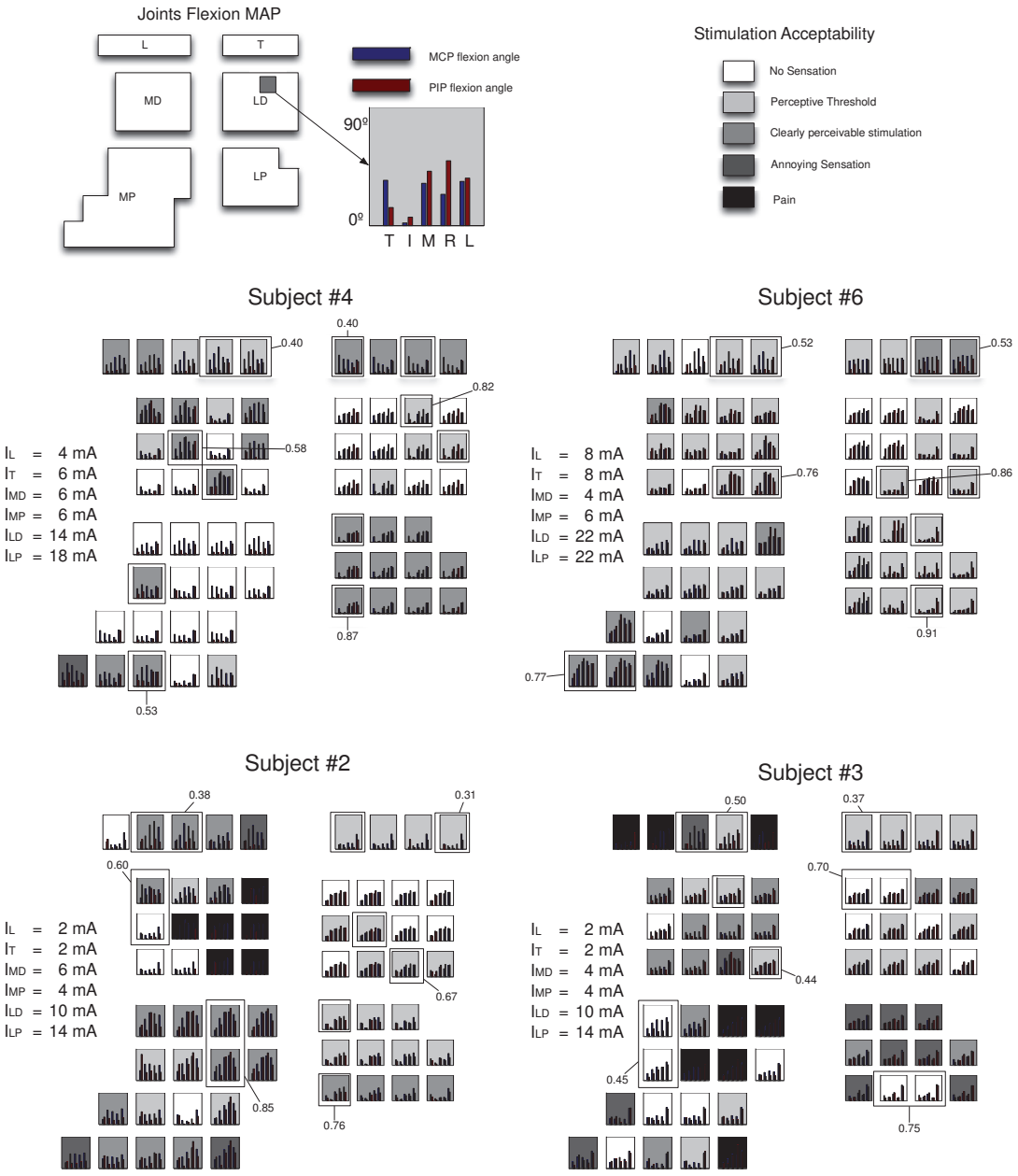


Figure 17: inter-personal motor and perceptive variability affects optimal pattern distribution.

(The inter-personal response variability to NMES can lead to dissimilar stimulation patterns. Top left: The six matrices in the lower panels are sorted, as schematically shown in the legend. For each pin location, the response to stimulation is shown for each finger as a set of histograms representing the flexion MCP joints (blue) and PIP joints (dark red). Fingers, thumb to little finger, are shown within each square from left to right. For all the arrays, the height of the bar represents the induced flexion of the fingers. Because L, T, MP and MD arrays are expected to induce flexion, higher bars represent broader motion. For arrays LP and LD, the lower the bar, the more the opening is induced by the stimulation. For sake of simplicity, the wrist deviation graphs and the overall scores J_{global} are not shown. For each subject, the optimal pins are indicated with a surrounding rectangle and the best J score is indicated. Top right: The stimulation acceptability is shown for each pin as a background shade. Darker shades represent a higher nociceptive sensation and brighter shades represent negligible or absent sensation. Center: Subject 4 and subject 6 show good acceptability of electrical stimulation, and good modular character of evoked motor responses. Partial information transfer of optimal maps is possible from one subject to another. Bottom: Responses from subjects #2 and #3 are shown in darker shades than those observable in subjects #4 and #6, and proper tuning of a sensory acceptable motor response seems harder to achieve, with more sparse and globally lower optimal responses.)

2.2.3 Grasp force controllability.

The stimulation apparatus (RehaStim Delta, Hasomed GmbH, Magdeburg, Germany) allowed current intensity increments of 2 mA from 0 mA to 110 mA and PW increments of 1 µs from 50 µs to 500 µs. The experimental current values usually ranged from 4 mA to 30 mA, whereas the effective PW ranged from 100 µs to 500 µs. The optimal current intensity and location of stimulation were taken from the ranking results of the open loop identification. The grasp force was controlled by PW modulation. The force sensor positioned in the thenar eminence of the glove (Figure 15E) measured the grasp intensity with a 50 ms impulse response delay and long-term drift. The NMES muscle response finite delay was estimated to be approximately 200 ms. When the absolute error $|e(t)|$ between the desired force $F_d(t)$ and the measured force $F_m(t)$ was larger than 2 N, a purely proportional control scheme $u(t) = K_p e(t)$ was used. Otherwise, when the absolute error was lower than 2 N, a proportional integral control $u(t) = K_p e(t) + K_i \int e(t)\, dt$ was applied. An anti-wind-up component was added to prevent excessive error ramping.

The stimulation setting procedure could result in different selections of pins and different values of NMES parameters; despite these differences, however, the technology achieved a functionally efficient and effective stimulation capable of properly controlling the grasping action. However the grasping of real objects is not purely a kinematic challenge, as it also depends on the chosen affordance for the specific object; for this reason, proper force feedback is needed. In our experiments, the optimal location and current intensity remained constant once they were set, whereas stimulation was adapted by modulating the pulse width. Figure 19 shows a sequence with successively higher requirements for grasp force.

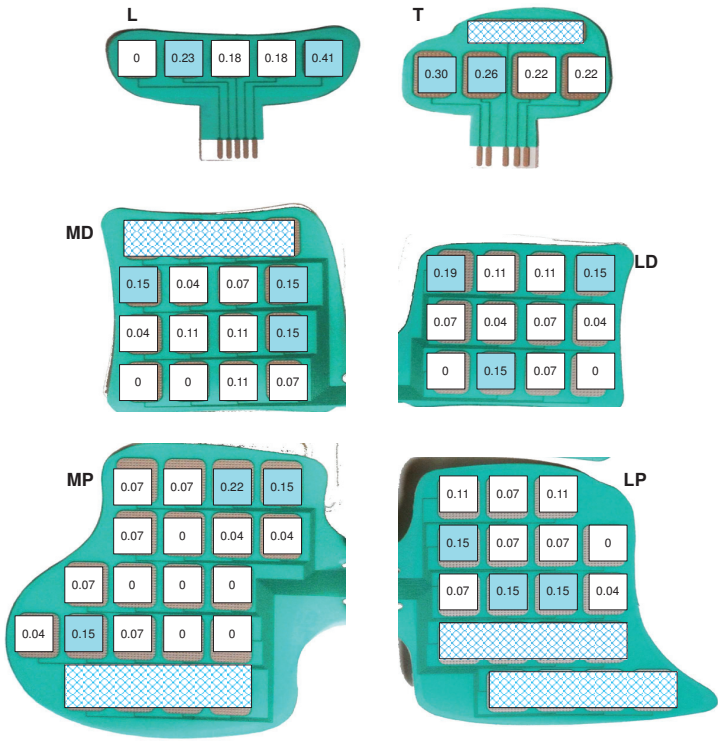


Figure 18: Statistically probable location of useful motor points, normalized for each array

(In each array, blue spots represent the ranked points that are optimal candidates for stimulation of the average subject. Such blue points are consequently the first points to be tested when calibrating the simulation for a new subject. The trimmed electrodes are represented as white rectangles with a teal grid.)

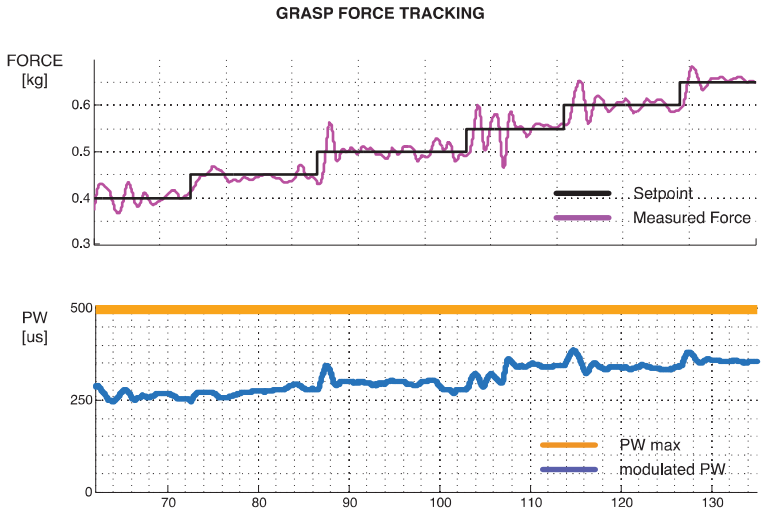


Figure 19: Force tracking though PW modulation

(Sample stimulation session. The overall stimulation lasts for more than 70 seconds and is aimed at testing the muscle in fatigued conditions. Top panel: the desired force is increased stepwise to verify the ability of the controller to compensate for unexpected changes. Bottom panel: the pulsewith is modulated to match the desired grasp force and to compensate fatigue.)

2.3 Interactivity with extended ecosystems

The original HelpingHand system was tested on an extremely limited number patients that allowed highlighting the potentialities and the technical and technological limitations of the system. The Helping Hand system was designed to operate in conjunction with an exoskeleton aimed at supporting the user in reaching the desired target and at providing the environmental information used for triggering the hand opening, preshaping and grasping. The exoskeleton was also needed to support the ribbon cables connecting the wearable with the stimulation apparatus, and at preventing cable pulls or contacts with the wearable PCB that could cause misconfiguration and miscontact; the whole system was deployed in one hospital and used for the main usability tests of MUNDUS.

To further the testing of HelpingHand Exo in an environment functionally similar to the one of the MUNDUS experiment, we readapted some functional components. The use of RTAI and of the associated toolchain were dropped in favour of tools able to increase the usability of the whole platform. The original communication protocol of the stimulator was ported to Labview (Labview 2013, National Instruments, Austin, Texas); the new toolchain allowed simplified implementation of the low level device control, interfacing with external hardware, and design of custom graphical user interfaces without the unnecessarily complicated architecture of Figure 12 and Figure 13.

Consequently we interfaced the HelpingHand with a different exoskeleton (ALEX, Percro, Italy) as described in [62], included in the same platform a GUI aimed at defining stimulation patterns. Two interaction modalities were implemented: in the first a custom designed robot was aimed at presenting objects in different locations of the workspace (Figure 20), in the second an IR vision system allowed to detect objects with predefined patterns. The IR-tracking system, arm-mounted on the first iterations, was moved on the 'head' of the exoskeleton for improved position tracking.

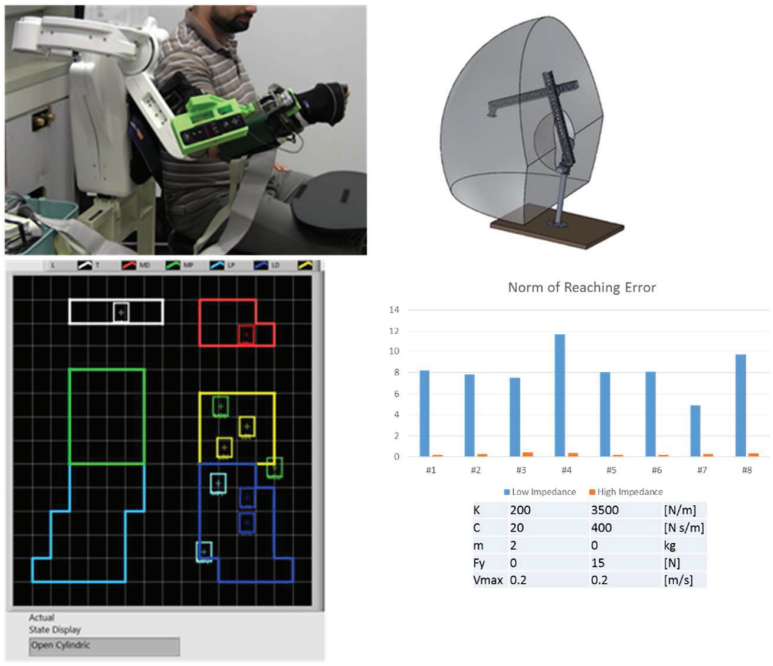


Figure 20: HelpingHand -ALEX implementation

(Top left: the ALEX exoskeleton with the HelpingHand system and one implementation of the IR detection system. Top right: model of the Lamp-O robot used for moving objects in the workspace. Bottom left: a calibration map used for preshaping the hand in grasping tasks. Bottom right: assisted reaching accuracy at different levels of impedance.)

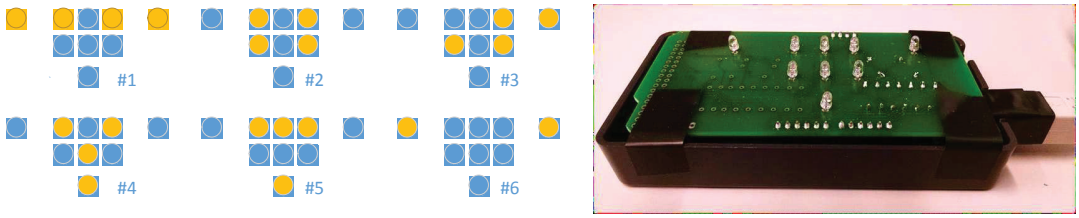


Figure 21: IR-patterned object and glyphs

(Left: six different glyphs were used as patterns recognizable through the WiiMote (Nintendo). Each pattern was associated to a desired affordance. Right: the prototype object used for IR stereo-tracking; buttons and remote control allowed to switch the displayed glyphs in accordance to the necessity of the operator.)

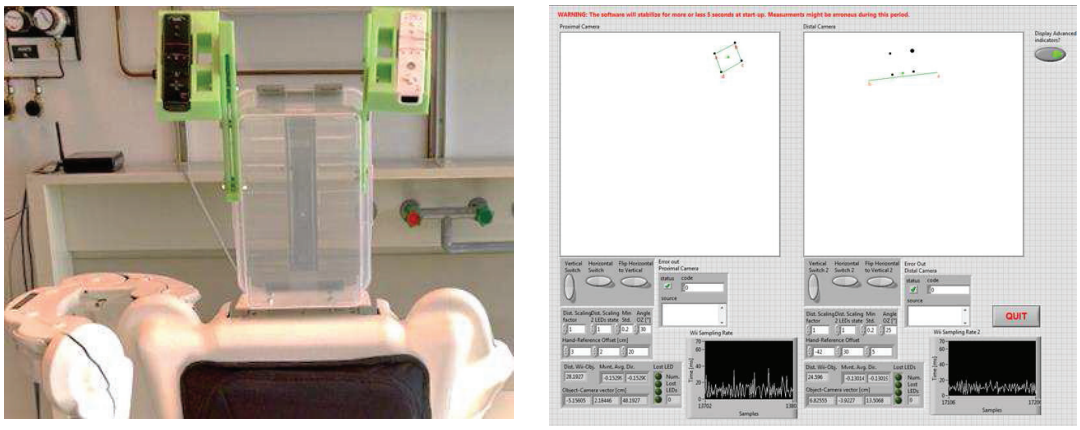


Figure 22: Head mounted IR detection system.

(Left: the head mounted system IR tracking system was implemented with two WiiMote (Nintendo) controllers. Right: Stereo glyph detection allowed to estimate the position and orientation in space of the object with a standard update rate lower than 30ms.)

In the preliminary experiments performed with the ALEX- HelpingHand system, the objects within 90 cm from the object head were correctly recognized with standard accuracy of 2 cm. When the freely movable glyph was repositioned by an operator, after a predefined timeout the system was able to assist the reaching by replacing the transparent control mode to a progressively assistive force field directed toward the object. The stimulation was then activated as needed in accordance to the stimulation pattern associated with the glyph. The lack of availability of the exoskeleton, and the unreliable stimulation apparatus did not allow to proceed with detailed testing.

2.4 TAM and SUS assessment

Short questionnaires based on the Technology Acceptance Model (TAM) [63] and on the SUS [64] were used for assessing the impact of the first generation Helping Hand on the clinical workflow, used for determining the aspects needing an improvement, and as a baseline for comparing new prototypes. The questionnaires were compiled after the completion of the clinical trial by the clinical engineer supervising MUNDUS trials. It was requested to provide feedback not on the MUNDUS system as a whole, but rather on the Helping Hand system alone, and to exclude from the overall judgement the evaluation of the exoskeleton and other non-core modules that could bias the overall result. The evaluation is thus focused on the wearable, on the real-time control system, on the control logic, on the interfaces and the usability of such subset.

Table 5: TAM Perceived Usefulness

Perceived Usefulness (Likert scale)	HH MUNDUS
Using the device improves performance in daily life activities	6
Using the device increases productivity in daily life activities	5
Using the device enhance effectiveness in daily life activities	5
I find the device to be useful in daily life activities	6
Normalized scores	**75%**

Table 6: TAM Perceived Ease of Use

Perceived Ease of Use (Likert scale) – setup phase	HH MUNDUS
The interaction with the device is clear and understandable	5
Interacting with the device does not require a lot of mental effort	4
the device is easy to use	5
It is easy to get the device to do what it's wanted it to do	4
Normalized scores	**58.3%**

Table 7: TAM Computer Self Efficacy

Computer Self-Efficacy (set of options) –setup phase	HH MUNDUS
I have control over using the device	6

I have the resources necessary to use the device	6
Given the resources, opportunities and knowledge it takes to use the device, it would be easy for me to use it	6
the device is not compatible with other systems I use	5
Normalized scores	**70.83%**

Table 8: TAM Computer Playfulness

Computer Playfulness (set of options) – setup phase	HH MUNDUS
how you would characterize yourself when you use the device?	
… spontaneous	
… creative	
… playful	X
… unoriginal	
Normalized scores	**33%**

Table 9: TAM Computer Anxiety

Computer anxiety (Likert scale)	HH EXO
Computers do not scare me at all	7
Working with a computer makes me nervous	1
Computers make me feel uncomfortable	1
Computers make me feel uneasy	1
Normalized scores	**100%**

Table 10 : TAM Perceived Enjoyment

Perceived enjoyment (Likert scale) – setup phase	HH MUNDUS
I find using the device to be enjoyable	4
The actual process of using the device is pleasant	5
I have fun using the device	4
Normalized scores	**55.56%**

Table 11: TAM Subjective Norm

Subjective norm (Likert scale)	HH MUNDUS
People who influence my behavior think that I should use the device	5
People who are important for me think that I should use the device	5
The senior management of the hospital has been helpful in the use of the device	6
In general the hospital has supported the use of the device	7
Normalized scores	**79.17%**

Table 12: TAM Voluntariness

Voluntariness (Likert scale)	HH MUNDUS
My use of the device is voluntary	1
My supervisor does not ask me to use the system	1
Although it might be helpful, using the device is certainly not compulsory	4
Normalized scores	**16.67%**

Table 13: TAM Image

Image (Likert scale)	HH MUNDUS
People in my organization who use the device have more prestige than those who do not	1
People in my organization who use the system have a high profile	1
Having the device is a status symbol in my organization	1

Normalized scores	**0%**

Table 14: TAM Job Relevance

Job Relevance (Likert scale)	HH MUNDUS
Usage of the device is important	5
Usage of the device is relevant	6
The use of the device is pertinent to various tasks	5
Normalized scores	**72.2%**

Table 15 : TAM Output Quality

Output Quality (Likert scale)	HH MUNDUS
The quality of the output I get from the device is high	5
I have no problems with the quality of the device output	2
I rate the results from the device to be excellent	3
Normalized scores	**38.8 %**

Table 16: TAM Results Demonstrability

Results demonstrability (Likert scale)	HH MUNDUS
I have no difficulties telling others about the results of using the device	7
I believe I could communicate to others the consequences of using the device	7
The results of using the device are apparent to me	7
I would have difficulties explaining why using the device may or may not be beneficial	1
Normalized scores	**100.00%**

Table 17: TAM Behavioral Intention

Behavioral Intention (Likert scale)	HH MUNDUS
Assuming I had access to the device, I intend to use it	NA
Given that I had access to the device, I predict that I would use it	NA
I plan to use the device in the next 6 months	NA
Normalized scores	

System Usability scale results

Table 18: SUS comparative analysis

System Usability Scale	HH MUNDUS
1. I think that I would like to use this system frequently.	4
2. I found the system unnecessarily complex.	2
3. I thought the system was easy to use.	3
4. I think that I would need the support of a technical person to be able to use this system.	3
5. I found the various functions in this system were well integrated.	4
6. I thought there was too much inconsistency in this system.	2
7. I would imagine that most people would learn to use this system very quickly.	3
8. I found the system very cumbersome to use.	2
9. I felt very confident using the system.	4
10. I needed to learn a lot of things before I could get going with this system.	2
Normalized scores	67.5

2.5 Discussion and Conclusions

We have developed a tool adaptable to different forearm sizes, both in length and circumference, and potentially applicable to clinical routines. The garment for NMES presented in this study embeds EAs and can exploit spatial and temporal stimulation patterns (i.e., a set of stimulation electrodes coupled with a set of stimulation intensities assigned to individual electrodes) for grasp restoration, supported by a real-time adaptable stimulator device. In contrast to current commercial and research NMES systems, our garment makes use of multiple sets of EAs that are shaped to conform to the hand and forearm. Hand intrinsic movements can be elicited by stimulating the thenar muscles, lumbricals and palmar interossei. Extrinsic muscles of the hand, when elicited by stimulation, allow flexion and extension of fingers, thumb adduction, wrist flexion/extension and ulnar/radial deviation. Because the garment is divided into six different matrices, each of them adaptable in size if needed, subsets of functionalities can be added simply by selecting a subset of matrices through the main PCB. Patients needing to train only thumb adduction and finger extension can benefit by using only the corresponding matrices LP and LD; patients requiring selective training or support for the intrinsic hand muscles can use the T and L matrices, and patients requiring support in more complex conditions can benefit from the full configuration.

HelpingHand could be used to restore grasping function in impaired subjects. The goal of our study was to develop a novel wearable NMES system with multiple arrays that could serve as a modular tool suitable for use as a platform for grasp rehabilitation, potentially improving the clinical applicability of NMES. The system targets both extrinsic and intrinsic hand grasp muscles, which is potentially very promising for improving its clinical efficacy and flexibility.

The validation experiments were designed to highlight the flexibility of our device, showing how different results can be achieved using different electrodes on each pad for each subject. To better characterize these differences, we used a camera-based system to obtain the most accurate kinematic measurements.

The embroidered EAs developed by Lawrence in collaboration with Bischoff Textile (St. Gallen, CH) featured active elements embedded in the fabric. Conductive yarn embroidery on fabric offers adaptable stretchability, but conductive yarns are prone to breaking under stress; multiple stitching is required to maintain conductivity at the cost of a larger and thicker footprint. Malesevic's thin array exhibited very good electrical properties, better electrical isolation, and higher routing density, but it was characterized as a general-purpose design. The HelpingHand garment represents an improvement beyond the two previous wearable NMES systems developed by [41] and by [31].

The controls allow effective kinematic-based hand pre-shaping and grasping with force feedback. The implementation here described of the HelpingHand system allows control of simple hand grasps by controlling, alone or combined, the activation of extrinsic and intrinsic hand muscles. The closed-loop experiments are presented here as a case study, but the glove can be easily replaced by sensorized objects or hand orthoses embedding sensors. Specifically, for individuals with contractures or spasticity, splints or hand orthoses can be used to constrain the hand in its intended use. Constraining implies that some rigidity in the device is necessary; thus, residual sensory feedback is reduced, as are available motions. The variability of splinting needs is mitigated clinically by the partial customizability of each commercially available device. Sensorized clasps can be adapted to operate with the chosen splint, or splints can be designed alongside the clasps, but the design requirements rely on the clinically chosen functional constraints and on an acceptable trade-off between reliable force detection, overall encumbrance, and acceptable sensory masking.

2.5.1 Limits of the current device

The first generation of HelpingHand tried to address the wearability issue using a "one size fits all" approach, and tried to use standardized electrode array positions by using a reference system derived from [65]. The central PCB was designed to align the four electrode arrays stimulating the extrinsic hand muscles. However, if not properly tightened to the subject or if subject to mechanical disturbances from the cables, it could cause a displacement between skin and underlying tissues. Additionally, the central PCB minimal width was limited by the connectors, chosen to match the ones on the stimulation apparatus, and the routing to the gated connectors for the flexible electrode arrays. Shear and torsional stress arising between the PCB connectors and the corresponding electrode arrays had a secondary effect, causing potential misalignments between the 200um pitch conductive lines or losing contact in case of extreme bending.

This generation of Helping Hand also had drawbacks solvable by redesign; for example, the PCB-arrays connector gates were designed for compactness, and a misalignment between connector and contact translated into poor contact conditions. This fault could appear when consistent shear stress was applied to the garment or when an impact occurred on the rigid PCB. The EAs exhibited good resistance to repetitive bending, but extreme curvature could cause permanent damage to the disposable EAs. This scenario occurred, for example, when extremely thin subjects donned the garment and the array was abruptly pulled and bent at 90°. From a usability perspective, gel patches are prone to quick deterioration because of donning/doffing stress and because of dehydration and need to be replaced, on average, after 10 hours of stimulation. Removing gel patches from the EA induced moderate mechanical stress on the EAs and thus progressively damaging the substrate during each removal operation. Depending on the operator the EAs substrate could sustain up to 30 gel changes.

Chapter 3 Hand Grasp Recovery with Integrated Cognition

Technologies that minimize the efforts to complete a task are quickly adopted by the targeted population. In rehabilitation different populations need to be targeted to achieve the best possible rehabilitative outcome. Tools hard to use for caregivers, or causing bad treatment acceptance, can lead to non-sufficient quantity of treatment, or therapy interruption. Thus, when designing rehabilitation tools, the tradeoff between effectiveness and usability is critical. Commercial rehabilitation devices are polarized towards usability, and widespread clinical easiness seems to be the priority. Patients' acceptance of tools and technologies is another limiting factor biasing the overall clinical choices. Device acceptance affects the spectrum of possible rehabilitation procedures, and different typology of patients may accept and benefit from different approaches or devices. Less practical elements also affect the patients' acceptance of a treatment because cognitive and perceptive impairments can emerge as a negative outcome from a neurological damage. Possible negative outcomes can translate in lack of body ownership, and lack of agency. Figure 23 shows an ICF model [9] expanded to include the aforementioned components. Among other factors, the changes in patients' perception of their own hemiplegic limb after stroke is one of the key factors that can be dynamically improved by a successful treatment. "Despite the lack of available scientific evidence for their efficacy, conventional therapies [based on physical and unstructured interaction between the patient and the therapist], continue to be implemented in the [neurorehabilitation] field" [66] and rather constitute the standard approach in the clinical practice.

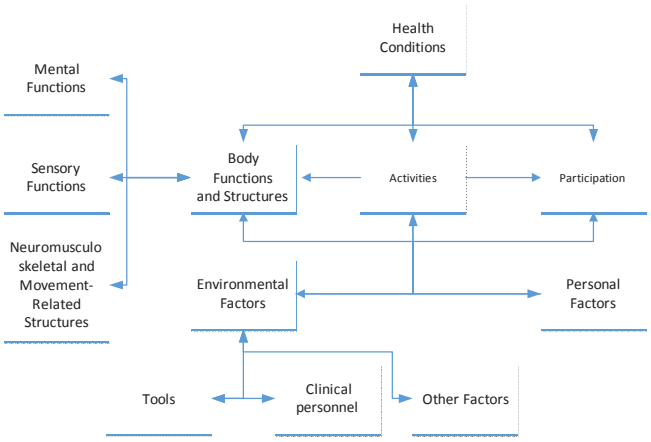


Figure 23: Interactions between the components of the ICF

We started a new project in which the HelpingHand system was aimed at the cognitive, motor and sensory recovery of the hand in subjects with hemiplegic impairments as a consequence of a stroke. The study was divided in three parts: 1) understanding if the post stroke rehabilitation could be improved with treatments combining an innovative robotic glove (GloReha, Idrogenet, Italy) and the novel Helping Hand system; 2) defining new protocols of sensory stimulation in healthy subjects to improve the perceptual body awareness; 3) and integrating the previous results in a new neuroprosthesis and to verify its efficacy on a new set of patients for integrated cognition (INCOGNITO).

Part 1 of the study is currently ongoing, with clinical testing ending on June 2017. The first part of this Chapter describes the technical development of the Helping Hand system, as an evolution of the original system described in Chapter 2. The discussion focuses on the technical requirements and the development strategy to increase the overall reliability, and to reduce the engineering

supervision needed to perform clinical treatments. The second part of this Chapter describes the preliminary results of the ongoing tests.

3.1 DESCRIPTION OF CONTEXT

The HelpingHand system, described in Chapter 2, provided insights of functionality but also proved the need to redesign the wearable electrodes, the main control logic, the stimulation apparatus, and the overall integration to provide a more reliable, intuitive, and clinically usable device. A first step in this direction was taken already during the preliminary integration of the ALEX exosketon, but, to allow easy transportability and efficient clinical usage, significant simplifications were needed. We also wanted to prepare the basis of a tool that could also be extended and used in accordance to the phases 2 and 3 of the project for motor and cognitive rehabilitation.

3.2 METHODS

3.2.1 Helping Hand for INCOGNITO : design criteria

The design of the new system started with the adoption of a non-commercial stimulation apparatus (INTFES v2, Tecnalia Serbia). The standard demultiplexer unit of the INTFES stimulation apparatus, usually supporting 16 or 24 active electrodes [59], [60], was modified by the manufacturer to support 60 active electrodes and 3 counter electrodes. The adoption of the new stimulation apparatus removed the constraint of a dedicated real-time pc, of a dedicated trolley to host the stimulation apparatus, and allowed to use lighter connecting cables between the demultiplexer unit and the electrode arrays.

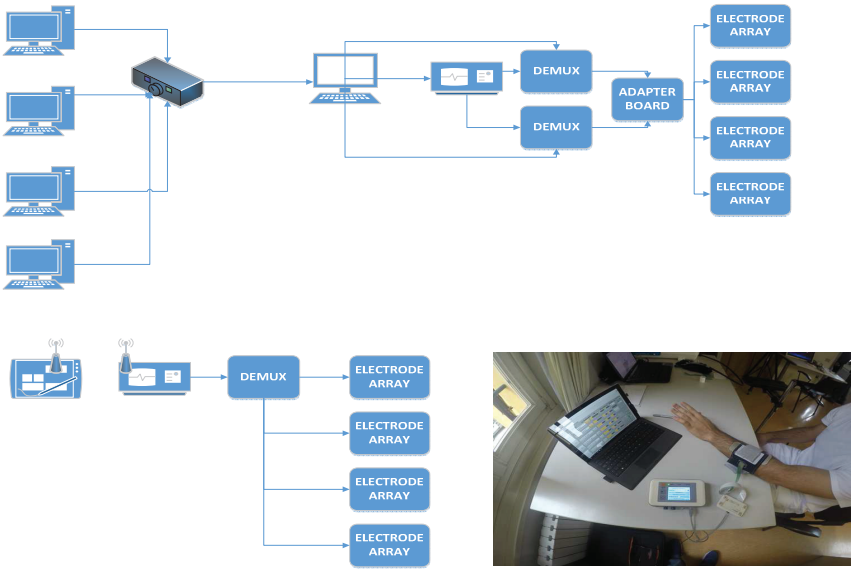


Figure 24: HelpingHand control architecture evolution

(Top: simplified architecture of the Helping Hand control system as described in Chapter 2; all the control devices are connected to the mains, communication between each pc is handled by a switch, the stimulation apparatus is controlled through three separate USB serial connections. Two demultiplexers are necessary to control the electrode arrays. Bottom: architecture of the updated HelpingHand system, and photo of a demo session with a minimal setup. The communication between a touch sensitive tablet and the stimulation apparatus is over Bluetooth. All the devices are battery powered, and allow improved mobility.)

The wearable was also redesigned to address the shortcomings of the previous prototype and to match the different capabilities of the new stimulator. Small and lightweight adapter boards were used to connect the new electrode arrays with FFC cables, long tails on the electrode arrays allowed to decouple the residual mechanical stress of the cables from the stimulation areas. The overall number of electrode arrays used for this prototypes was reduced to three specialized parts (Figure 25), designed in a symmetrical fashion to be usable both on left and on right limbs. The electrode array designed for the thenar eminence was redesigned for improved fractioning of the single active sites and for improved bending. The electrode array for the dorsal hand side was reduced in size, the number of active sites increased and their dimensions reduced for better selectivity. The gridded, electrode arrays were

redesigned to group the electrodes in rows of four elements, and thus to better conform to localized changes of skin curvature. The size of the active electrodes for extrinsic stimulation was reduced to 10 by 12 mm^2 to improve selectivity of stimulation on thinner subjects. Counter electrodes were integrated in the larger electrode array, and symmetrically positioned to allow multiple mounting.

Figure 25: Helping Hand INCOGNITO electrode arrays

(Left: the three electrode arrays used for the Helping Hand wearable. The long flexible tails aim at absorbing mechanical disturbances. Center: row-wise separation of the four by four electrode array. Right: counter electrodes are integrated in the larger electrode arrays.)

The mounting shown in Figure 26 and Figure 27 weights less than 30g on the hand, 200g on the forearm, and 300g on the arm. The weight distribution includes the fabric and the arm mounted demultiplexer. The stimulation apparatus, weighting less than 1kg, can be worn on the back of the user if mobility is needed or positioned on the workspace in proximity of the user.

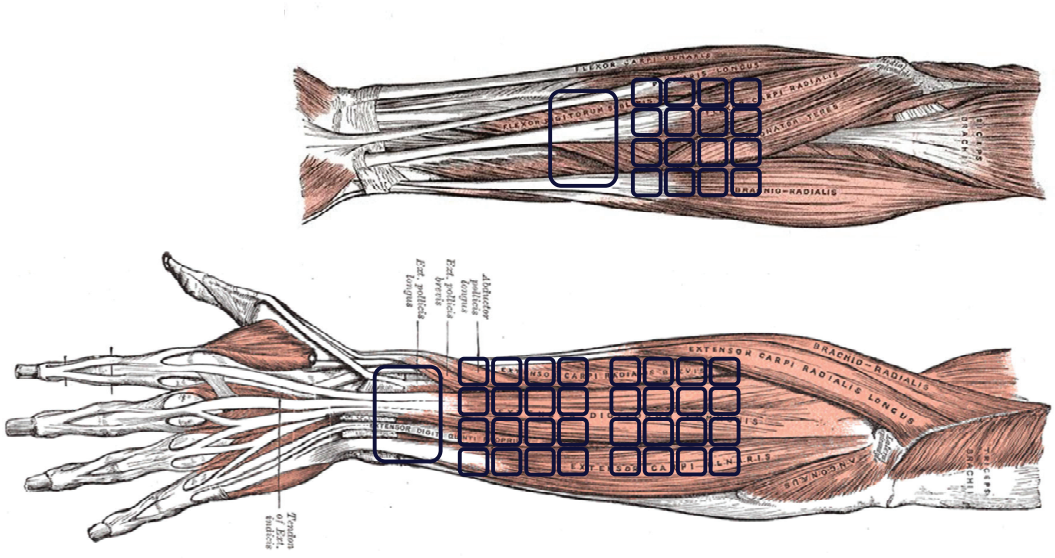


Figure 26: standard positioning of the squared electrode arrays.

(Sample positioning of the squared electrode arrays. Top: One electrode array is used to target the extrinsic flexors. Bottom: two electrode arrays are used for eliciting fingers extension and for the extension and abduction of the thumb.)

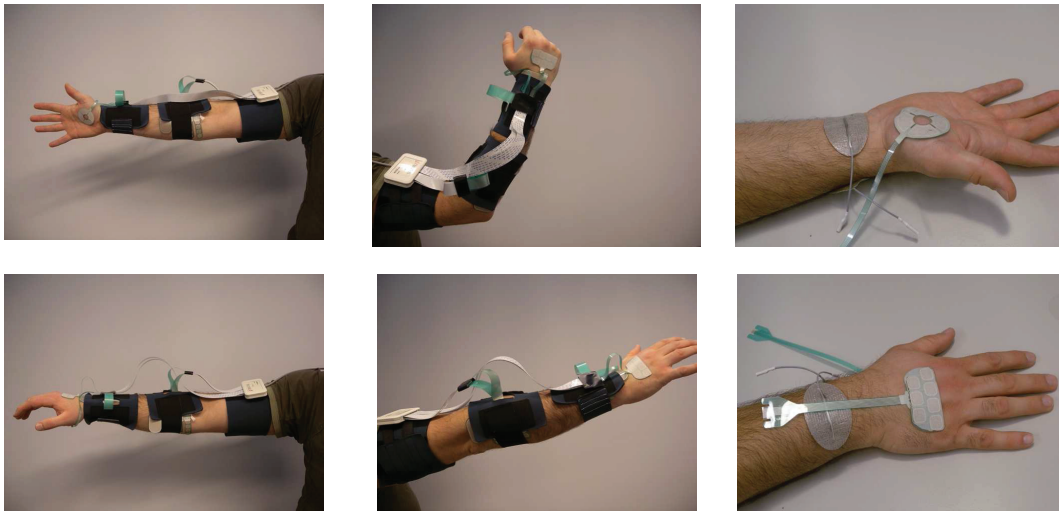


Figure 27: Wearability example for the Helping Hand INCOGNITO system

(Left and center: sample donning of the wearable system. The demux unit is hosted proximally to the elbow. Length-matched FFC cables flex to compensate to the usual arm-elbow-wrist motion. Right: sample positioning of the electrode arrays for stimulation of the thenar muscles and of the lumbrical muscles.)

3.2.2 Graphical Interface and Usability

Although smart calibration algorithms can look for an "optimal" stimulation pattern to elicit a desired motor outcome, it does not incorporate the clinical skillset of the practitioner, nor is able to include the unmeasured cues a clinician could otherwise interpret.

Practitioners used to standard electrode technology are keen to adopt a trial and error approach, by empirically repositioning the electrodes on the skin for each change in the desired configuration. Each operation of electrode removal and reapplication on the skin damages the thin gel layer in contact with the skin, affecting the quality of tack between skin and electrode and potentially modifying the surface current distribution. Another practical adaptation done by practitioners is to modify the shape and size of the electrodes by trimming large electrodes into smaller ones; this second practical adaptation is due to the fact that small electrodes target superficial excitable tissue, whereas large electrodes target superficial and deeper layers of excitable tissue [51], [67].

We designed a graphical user interface (GUI) that mimics the aforementioned clinical practice, and targets the issues described above, while preserving the clinician ability to explore the space of parameters in an implicit way. The GUI, hosted on a 12" windows tablet (Surface 3), is a touch compliant program designed in LabVIEW 2013 (National Instruments), used to guide the practitioner through the main operations expected in a treatment (Figure 30).

Likewise physical electrodes can be repositioned on the skin, virtual electrodes (VEs) can be shifted across the electrode array, and custom stimulation combinations can be tested online. When a VE is enabled, the active sites in the proximity of the virtual electrode centroid are allowed to conduct electrical pulses. We used the Minkowski distance as a criterion to determine the size of the VE and its shape in an implicit way for the clinician. The Minkowski distance between the VE centroid $X = (x_1, x_2)$ and the centroid of the k[th] active site $Y_k = (y_{k,1}, y_{k,2}) \in \Re$ is $d(k,p) = \sqrt[p]{\sum_{i=1}^{2} |x_i - y_{k,i}|^p}$. The order p of the Minkowski distance defines the shape of a VE, whereas the threshold $t \in \Re^+$ defines the size of the activation area. To determine which sets of parameters were more meaningful and intuitive for the expected operators, we provided an alpha version of the GUI to clinical practitioners used to FES for informal testing. We preset three parameters options, able to generate the patterns shown in Figure 28, and randomly associated each parameter set to one of the VEs of the GUI. The practitioners, naïve to the different patterning strategies and to the randomization order, were asked to try and elicit in separate sessions a thumb abduction, a fingers extension, a stereotyped power grasp, a wrist flexion and a wrist extension. The practitioners were also asked to choose which stimulation was perceived as most comfortable and able to elicit the desired outcome.

Figure 28 reports a few examples of VE composition rules. The VEs generated on the left panel (p=1 and t=0.8) appeared easier to use with the four by four electrode arrays, more selective, and easier to combine to obtain synergistic activations of hand extrinsic muscles.

The GUI represents each EA as a grid on which Virtual Electrodes (VEs) can be moved. A VE defines the location of stimulation, shape, and intensity of stimulation. On each stimulation map up to three VEs can be enabled and independently combined.

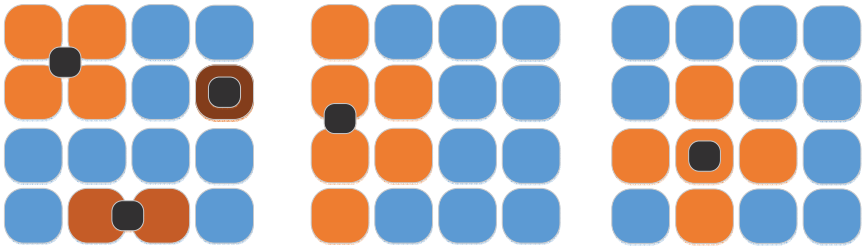


Figure 28: Virtual Electrode parametric shaping for position and depth encoding

(Left: squared/rectangular virtual electrodes generated with t=0.8 and p=1. Center: rounded virtual electrode generated with t=1.5 and p=2. Right: cross-shaped virtual electrode generated with t=1.5 and p=1/2. Naïve healthy subjects tested the different composition rules while trying to self-calibrate the stimulation maps.)

The GUI was designed to ease the calibration process and, rather than forcing a predefined state flow of operations, implemented the conversation diagram shown in Figure 29. This approach was tested to simplify the interactivity, aiming for an intuitive interaction between the operator, the patient and the device itself. The GUI was also designed to be directly usable by the patient for a man-in-the-loop calibration.

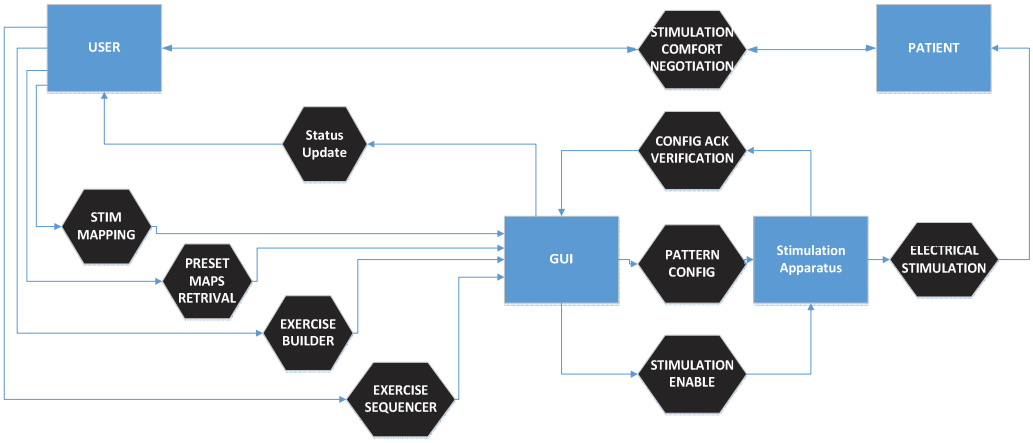


Figure 29: INCOGNITO Conversation Diagram

(The conversation diagram describes the lightly structured flow of operation. The Bluetooth serial protocol allows transmitting and verifying new configurations at update rates not faster than 1 Hz. Any user interaction from the GUI side interrupts stimulation, deploys the updated configuration, and enables it in case of configuration match.)

Figure 30: INCOGNITO GUI

(Top Left: a walkthrough guides the operator in establishing wireless connectivity, and in verifying the physical connectivity. Top Right: user profiles and associated custom stimulation maps can be set through the touch interface. Each stimulation map includes virtual electrodes that define location and intensity of stimulation. Bottom Left: An exercise builder allows defining custom treatments as a sequence of preset maps. Bottom right: device in operative conditions.)

3.2.3 Design of the Study

The Italian Ministry of Health and the local ethical committee for the hospitals of Como-Lecco and Sondrio provided the approval for the clinical studies and its preparatory activities. To evaluate the most appropriate integrated cognitive, sensory and motor rehabilitation of hand functions, in the first phase were compared the outcomes of four predefined treatments. Dose matched trials were used to compare treatments based on 1) conventional physiotherapy, 2) mechanical hand stimulation with a robotic glove (GloReha, Idrogenet), 3) neuromuscular hand stimulation with Helping Hand, and 4) the use of both the GloReha and of HelpingHand. The treatment lasted 9 weeks with 3 treatments of one hour per week. As the full Helping Hand system allows for training multiple grasp modalities, by targeting intrinsic and extrinsic hand muscles and by allowing to sequence motor primitives, the variety of different treatments would allow to target the patients with personalized treatments, and thus rendering the first trial results hard to compare. Consequently, for the first part of the project, clinicians decided to restrict the training to the extrinsic extensors as means to facilitate hand opening and preshaping, with expected improvements on functional tasks not requiring to improve the grasp force, but rather to enable pre-existing grasp capabilities by allowing controlled fingers extension and wrist stabilization. With the chosen setup, typical stimulation tasks could include: index and thumb extension, fingers 1-4 extension with balanced wrist extension, fingers 1-2 extension with radial deviation, fingers 3-4 extension with ulnar deviation. The task sequence choice was performed on a patient specific base, aimed at countering the dominant motor recruitment deficits. As a consequence, stimulation maps could selectively target one or more of the above desired effects, and be arbitrarily sequenced.

Patients' inclusion criteria were: chronic (after 6 months) stroke patients, hemiplegic left or right unilateral lesion, impairment at hand and/or arm, absence of concomitant neurologic or psychiatric pathologies, Mini-Mental State Examination score above 20, limited spasticity (MAS<3), and responsiveness to electrical stimulation. The sixty participants of the initial patient pool were assigned evenly among the four possible treatments, with twelve patients per group assigned randomly and three based on the motor impairment at inclusion. Clinical evaluation of the patient conditions was done as reported in Table 19.

Table 19: tests administered during the INCOGNITO therapy

Outcome	Assessment	Note	Pre Week 0 T0	Inter Week 4 T1	Post Week 9 T2	Follow-up Week 13 T3
Cognitive Evaluation	Mini-Mental State Examination (MMSE)	MMSE > 20 as inclusion criteria	✔			

Effectiveness	Modified Ashworth Scale (MAS)	Anterior, Medial and Posterior Deltoid, Elbow, Wrist and Fingers flex/extensor muscles. Ashworth. MAS < 3 as inclusion criteria	✔	✔	✔	✔
Effectiveness	Medical Research Council (MRC)	Anterior, Medial and Posterior Deltoid , Elbow, Wrist and Fingers flex/extensor muscles	✔	✔	✔	✔
Effectiveness	Motricity index	Collin and Wade [68]	✔	✔	✔	✔
Effectiveness	Motor Activity Log (MAL)	Lang et al. (2008)[69]	✔		✔	✔
Effectiveness	Action Research Arm Test (ARAT)	Yozbatiran N et al. (2008) [70]	✔		✔	✔
Effectiveness	Box & Blocks Test (BB)	Mathiowetz et al. [71]	✔		✔	✔

3.3 RESULTS

The first aims of these tests is to evaluate Helping Hand in terms of technological usability and reliability in an unsupervised clinical context. The second aim is to evaluate its effectiveness in delivering therapeutic effects to the patients and in the ability to provide long-lasting effects that provide motor skills transferrable to activities of daily living. The study is also structured to compare the results with the conventional physiotherapic treatment, with a robotic treatment that targets a different rehabilitation modality, and to evaluate if the combination of two enriched treatments can provide a positive interaction able to promote better recovery.

3.3.1 Technological Assessment

The HH prototype was deployed the clinic for unsupervised use. A two hours training was given to the operators involved in the trials. No major failure or malfunction of the device has been reported during the trials, and loss of communication appeared sporadically in low battery conditions. During the trials, with the exception of the first week of clinical use, no remote assistance was needed and the system reliability operated in conditions of daily use.

The first generation of clinical users was able to successfully train a second generation of clinical users and of patients. The patients were also able to adapt as needed the stimulation intensity and location of stimulation during the trials.

3.3.2 Clinical results

The Integrated Cognition tests (phase 1) completion is expected in June 2017. Summary results from the dataset, limited at the moment of writing to 13 patients treated with the conventional therapy (Conv) and 5 treated with the HH system, are shown below. The description of each patient progression during the treatment is summarized in Appendix B. The low number of patients does not allow having high statistical significance, and stratification of the results in accordance to the specific pathologic features further reduces the numbers and widens the prediction error.

Since the patients involved in the trials have different residual skills and different capabilities at inclusion, all the measures were unbiased with respect to the initial conditions and normalized according to the residual potential improvement. The generic feature F of the group G recorded at time T_k would be normalized to:

$$\bar{F}_{G,T_k} = \frac{F_{G,T_k} - F_{G,T_0}}{\max F - F_{G,T_0}}$$

The spectrum of measures taken on the patient aims at providing a comprehensive clinical perspective of the evolution of the patient's skill throughout the treatment, and to measure how much treatment is retained in the follow-up phase. Statistical significance of a feature measured within the same group at different times was tested with Wilcoxon signed rank test. Comparisons between groups were performed with the Wilcoxon rank sum test. The spectrum of measures, in association with the whole aim of the integrated cognition concept, focuses on the separate assessment of the performances of the shoulder, elbow, wrist and fingers, on the ability to voluntarily recruit the involved districts in a-specific way, in broad and finer movements, and in the self-reported perception and use of the limb in everyday life.

In this set of tests, HH was clinically used on the hand extrinsic extensors, whereas the conventional treatment focused on the arm and hand as a whole. As a consequence, improvements from the Helping Hand are expected to be related to the tasks requiring hand preshaping for successful execution. It is important to highlight, among others, some practical factors, that can affect the overall validity of the results we will later show. The limited numerosity of the sample size for each group does not allow to stratify the results. There is no possibility to verify placebo-nocebo effects, patients within the conventional group are provided with the standard treatment dose and with the supplemental treatment; patients within the HH group are provided with the standard treatment dose and the supplemental HH treatment; there is no sham treatment as all the clinical workforce is aimed at providing treatments expected to be effective for the patients. Effects appearing in the treatment of HH may be exogenous to the HH treatment, or appearing as an interaction with the standard physiotherapic treatment.

Motricity Index

Pinch: HH correlates with a conditional impact on the pinch capabilities; the median increase of performance of 36.36% is stable throughout the treatment and retained during the follow up (p= 0.125). HH performs better than Conventional at T1 (p=0.0107), at T2 (p=0.0441), and at T3 (p=0.0259).

Elbow Flexion: HH does not impact on the elbow flexion capabilities; the positive result at T3 is not robust, and expected to be caused by exogenous factors. Weak evidence of the Conventional group to perform better than HH at T2 (p=0.23) and at T3 (p=0.0924). The median performance gain is null for both groups. The mean gain for the conventional group is 19.89% at T2, and 15.99% at T3.

Abduction: 20.8% median increment for the HH group during the hospitalization, but not retained during the follow-up. No increment in the Conventional group. Evidence suggest HH to perform better than conventional at T1 (p=0.0123), at T2 (p=0.0714) and at T3 (p=0.1776).

Total: The conventional treatment group shows a median increment of 3.2% at follow up (p=0.027), no median change during treatment. The HH group shows a median improvement of 28.95% during hospitalization (p=0.063), which increases to 34.78% at follow up (p=0.031). HH seems to perform better than conventional at T1 (p=0.0221), T2 (p=0.0856), T3 (p=0.0107). Median improvements are 28.95% (T1), 28.95% (T2), and 34.78% (T3).

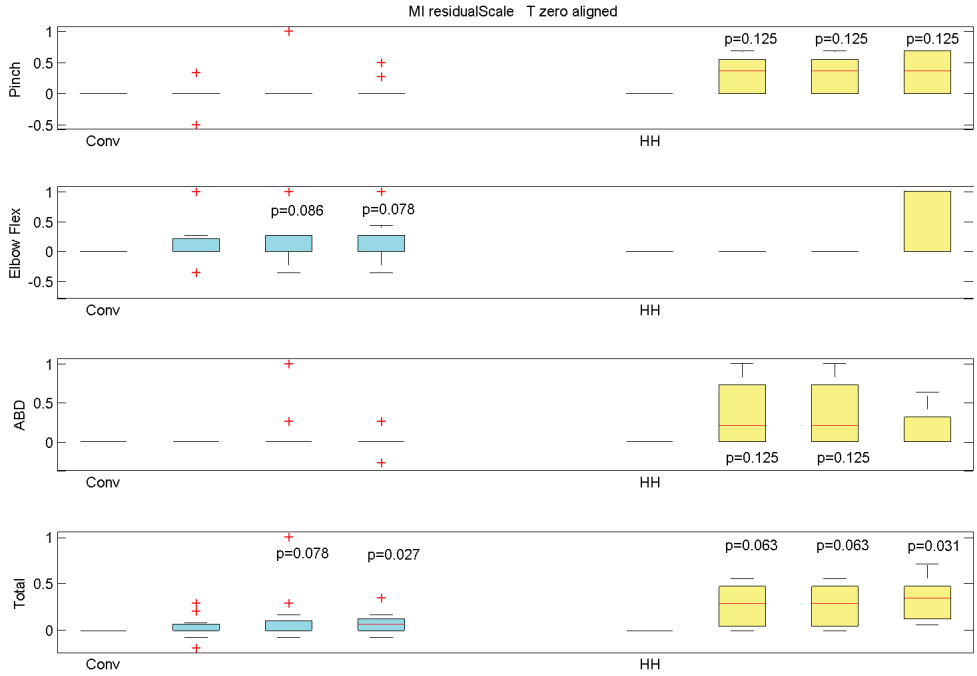


Figure 31: HH INCOGNITO Motricity Index results

(From top to bottom: pinch recruitment capability, elbow flexion against gravity, shoulder abduction, and total score. Measures are taken at inclusion, half of therapy, end of therapy, and at follow up. Conventional therapy progression results on the left, Helping Hand therapy progression results on the right.)

Action Research Arm Test

Conventional therapy provides significant but limited in impact (median null, mean performance gain < 2%) on GrossMT and on Total. HH provides improvement rate on pinch (median 6.82% at T2 and 4.55% at T3) and on the total score (median 44% at T2 and 33% at T3).

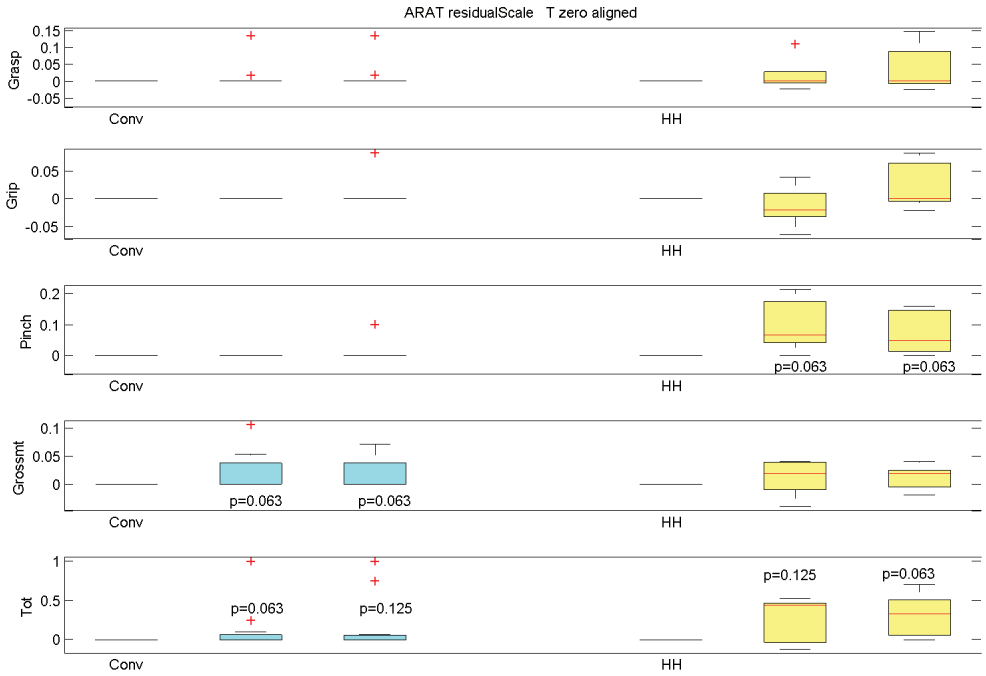


Figure 32: HH INCOGNITO Action Research Arm Test results

(From top to bottom: grasp capability, grip capability, pinch capability, broad arm movement capability, and total score. Measures are taken at inclusion, end of therapy, and at follow up. Conventional therapy progression results on the left, Helping Hand therapy progression results on the right.)

Medical Research Council - Upper Limb Assessment

For HH mixed results appear in the MRC scores in the shoulder and elbow area, with no significant result appearing to have impact during treatment. The HH treatment seems to affect the Wrist Flexors score with median improvement of 50% at T2 and T3. No impacting result is visible from the data on Fingers Flexors. Finger extensors, actually targeted in the HH treatment, show a median improvement of 25% at T2 and T3. No robust improvement can be deduced from the Conventional treatment group.

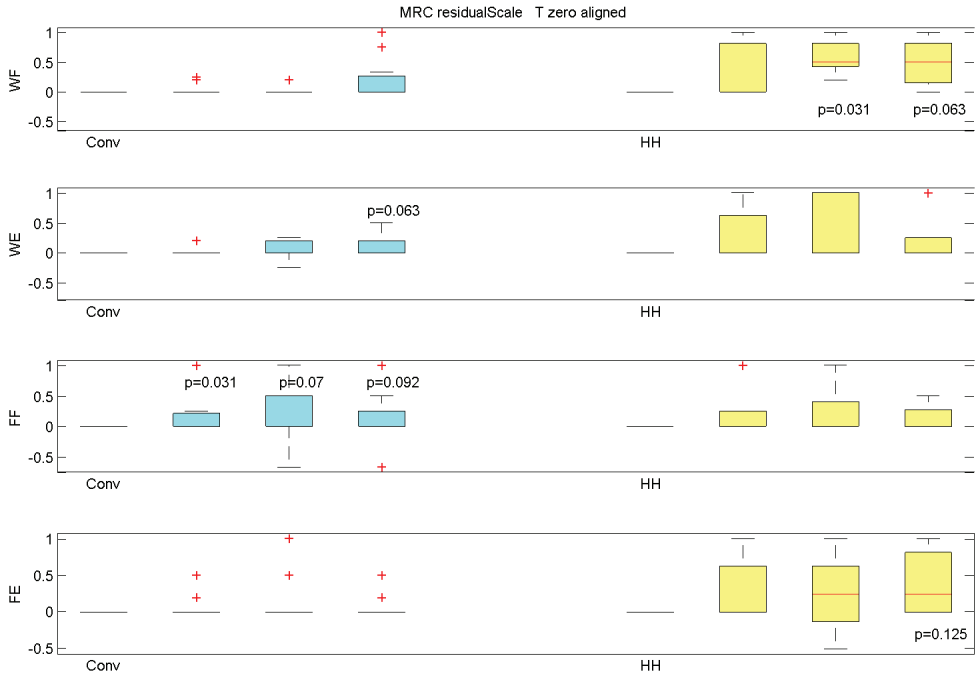


Figure 33: HH INCOGNITO MRC Upper Limb results

(From top to bottom: volitional recruitment of wrist flexion, wrist extension, fingers flexion, fingers extension. Measures are taken at inclusion, half of therapy, end of therapy, and at follow up. Conventional therapy progression results on the left, Helping Hand therapy progression results on the right.)

Box & Block

B&B was performed on the ipsilateral and on the contralateral arm. No statistically significant improvement is detectable within each of the two groups. The next panel shows an estimation of the performances as the ratio between contralateral and ipsilateral outcome. Robust improvements emerge in the comparison of HH versus the Conventional treatment with a median improvement of 6% at T2 (p=0.145), and 1.3% and at T3 (p=0.091).

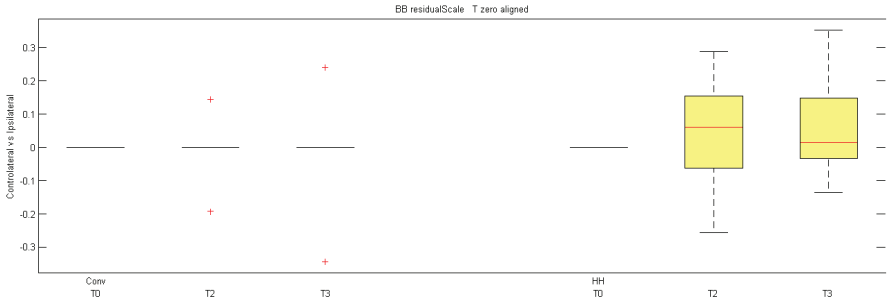


Figure 34: HH INCOGNITO Box & Block results

(Box & Block normalized score. Measures are taken at inclusion, end of therapy, and at follow up. Conventional therapy progression results on the left, Helping Hand therapy progression results on the right.)

Motor Activity Log

The MAL measures the self-reported perception and use of the impaired limb. For the conventional treatment there is no robust change in 'how' the limb is perceived, nor in 'how much' is the limb used in everyday life. For the HH group, the reported perception of the limb has a median increase of 8.6% at T2, and 12.4% at T3; additionally the frequency of use has a median increase of 6.2% and 14%.

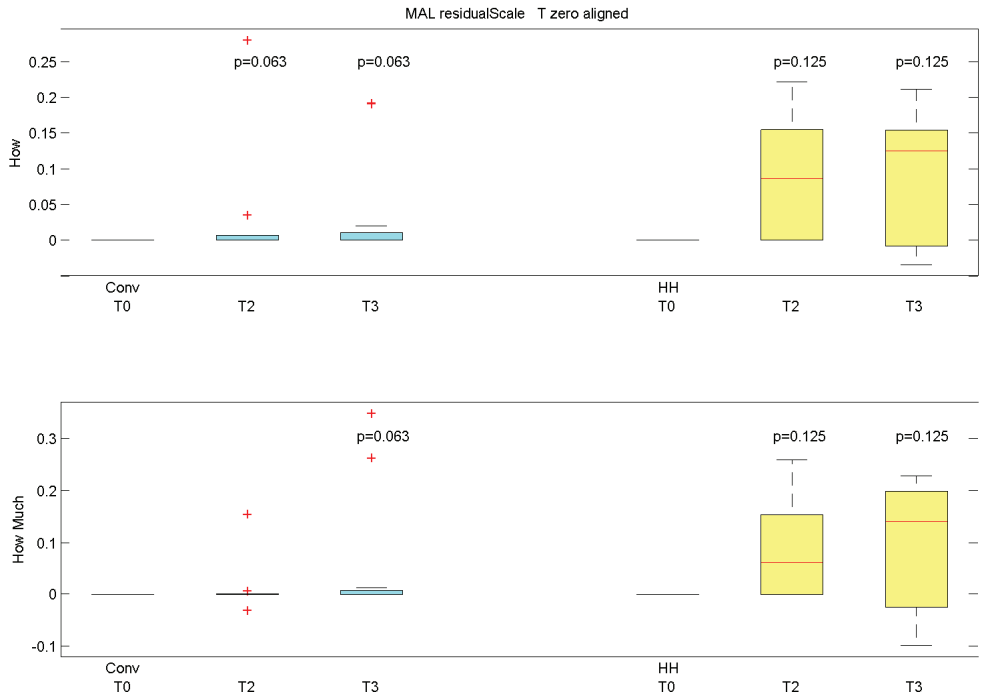


Figure 35: HH INCOGNITO Motor Activity log

(Top: how well the patient use the treated limb in ADL. Bottom: patients' report about the quantity of use of the treated limb. Measures are taken at inclusion, end of therapy, and at follow up. Conventional therapy progression results on the left, Helping Hand therapy progression results on the right.)

3.4 DISCUSSIONS AND CONCLUSIONS

The Helping Hand system, described in this chapter, was adopted into the clinical tests without major drawbacks, device failures, or inability for clinicians to use or to transfer the usage knowledge to a different operator. The availability of one device, whose usage rate is currently proximal to the saturation, is a factor limiting the number of testable clinical questions. However, the almost saturation of use of the device is a method of stress testing the clinical device that provides insights not only on the usability of the device, but also on its robustness, and on the willingness of operators and patients to use the device.

For the above reasons, only a limited number of features were used at this stage of testing, thus focalizing the clinical validation only on the activities mostly affected by a sufficient hand preshaping. In this perspective the hypothesis that the use of HH would improve the performances where finer manipulation is necessary is confirmed. HH showed improved skills in pinch grasping (Motricity Index, and ARAT) and retained the improved skill during follow up. Better fingers extension was achieved (MRC-FE) and retained at T3, as well as the improved control of the wrist flexion (MRC-WF). The improved ability to pinch, and to have control in finer movements seems to find confirmation in the B&B test. The ability to transfer in real life the improved motor skills seems to find confirmation in an improved perception of the upper limb (MAL-How), and in its frequency of use (Mal-How Much). Grasp force was not trained, and no improvement was visible in power grasp and in grip tasks. Better arm abduction capabilities

emerged, but were not retained during the follow up. The HH treatment does not target directly the shoulder and the elbow districts, so the minor improvements that seem to emerge during the hospitalization are less likely to be a consequence of HH.

3.4.1 TAM and SUS assessment

Short questionnaires based on the Technology Acceptance Model (TAM) [63] and on the SUS [64] were used for assessing the impact of the second generation Helping Hand on the clinical workflow, used for determining the aspects needing an improvement, and as a comparison term previous and new prototypes. The questionnaires were compiled after the completion of the clinical trial by the clinical engineer supervising INCOGNITO trials. It was requested to provide feedback on the system as a whole. The evaluation is thus focused on the wearable, on the real-time control system, on the control logic, on the interfaces and the global system usability.

Table 20: INCOGNITO TAM Perceived Usefulness

Perceived Usefulness (Likert scale)	HH INCOGNITO
Using the device improves performance in daily life activities	7
Using the device increases productivity in daily life activities	7
Using the device enhance effectiveness in daily life activities	7
I find the device to be useful in daily life activities	7
Normalized scores	**100%**

Table 21: INCOGNITO TAM Perceived Ease of Use

Perceived Ease of Use (Likert scale) – setup phase	HH INCOGNITO
The interaction with the device is clear and understandable	7
Interacting with the device does not require a lot of mental effort	5
the device is easy to use	7
It is easy to get the device to do what it's wanted it to do	7
Normalized scores	**91.67%**

Table 22: INCOGNITO TAM Computer Self Efficacy

Computer Self-Efficacy (set of options) –setup phase	HH INCOGNITO
I have control over using the device	7
I have the resources necessary to use the device	7
Given the resources, opportunities and knowledge it takes to use the device, it would be easy for me to use it	7
the device is not compatible with other systems I use	1
Normalized scores	**100.00%**

Table 23: INCOGNITO TAM Computer Playfulness

Computer Playfulness (set of options) – setup phase	HH INCOGNITO
how you would characterize yourself when you use the device?	
… spontaneous	
… creative	
… playful	X
… unoriginal	
Normalized scores	**33%**

Table 24: INCOGNITO TAM Computer Anxiety

Computer anxiety (Likert scale)	HH INCOGNITO
Computers do not scare me at all	7
Working with a computer makes me nervous	1
Computers make me feel uncomfortable	1

Computers make me feel uneasy	1
Normalized scores	**100%**

Table 25 : INCOGNITO TAM Perceived Enjoyment

Perceived enjoyment (Likert scale) – setup phase	HH INCOGNITO
I find using the device to be enjoyable	4
The actual process of using the device is pleasant	4
I have fun using the device	4
Normalized scores	**50%**

Table 26: INCOGNITO TAM Subjective Norm

Subjective norm (Likert scale)	HH INCOGNITO
People who influence my behavior think that I should use the device	7
People who are important for me think that I should use the device	6
The senior management of the hospital has been helpful in the use of the device	7
In general the hospital has supported the use of the device	7
Normalized scores	**95.83%**

Table 27: INCOGNITO TAM Voluntariness

Voluntariness (Likert scale)	HH INCOGNITO
My use of the device is voluntary	7
My supervisor does not ask me to use the system	1
Although it might be helpful, using the device is certainly not compulsory	7
Normalized scores	**66.67%**

Table 28: INCOGNITO TAM Image

Image (Likert scale)	HH INCOGNITO
People in my organization who use the device have more prestige than those who do not	4
People in my organization who use the system have a high profile	4
Having the device is a status symbol in my organization	4
Normalized scores	**50%**

Table 29: INCOGNITO TAM Job Relevance

Job Relevance (Likert scale)	HH INCOGNITO
Usage of the device is important	7
Usage of the device is relevant	6
The use of the device is pertinent to various tasks	7
Normalized scores	**94.4%**

Table 30 : INCOGNITO TAM Output Quality

Output Quality (Likert scale)	HH INCOGNITO
The quality of the output I get from the device is high	6
I have no problems with the quality of the device output	7
I rate the results from the device to be excellent	7
Normalized scores	**94.4%**

Table 31: INCOGNITO TAM Results Demonstrability

Results demonstrability (Likert scale)	HH INCOGNITO
I have no difficulties telling others about the results of using the device	7
I believe I could communicate to others the consequences of using the device	7
The results of using the device are apparent to me	7
I would have difficulties explaining why using the device may or may not be beneficial	1
Normalized scores	100.00%

Table 32: INCOGNITO TAM Behavioral Intention

Behavioral Intention (Likert scale)	HH INCOGNITO
Assuming I had access to the device, I intend to use it	7
Given that I had access to the device, I predict that I would use it	7
I plan to use the device in the next 6 months	7
Normalized scores	100.00%

System Usability scale results

Table 33: INCOGNITO SUS analysis

System Usability Scale	HH INCOGNITO
1. I think that I would like to use this system frequently.	5
2. I found the system unnecessarily complex.	1
3. I thought the system was easy to use.	5
4. I think that I would need the support of a technical person to be able to use this system.	2
5. I found the various functions in this system were well integrated.	5
6. I thought there was too much inconsistency in this system.	1
7. I would imagine that most people would learn to use this system very quickly.	4
8. I found the system very cumbersome to use.	2
9. I felt very confident using the system.	4
10. I needed to learn a lot of things before I could get going with this system.	1
Normalized scores	90

Chapter 4 Task driven grasp RETRAINER

Starting from the exo-compatible prototype, HelpingHand was further redesigned with the aim to tune and validate advanced, robot-based technologies to facilitate recovery of arm and hand function in stroke survivors and to verify extensively the use of the system by end-users. We improved the Technological Readiness Level of the platform to allow multicentric trials, with expert and naïve clinics involved in the testing. The targeted patients' groups has been updated to acute stroke patients, with the aim to provide in the short term a clinical solution, and in the long term a low-cost solution deployable for home use. Within the redefined environmental scenario, and because of the shift from an assistive perspective to a restorative perspective, several components required adaptations and extensive improvements.

4.1 DESCRIPTION OF CONTEXT

The adaptation of the HelpingHand to a potential home use took place in the RETRAINER project [72] with acronym S2. The S2 subsystem provides grasp rehabilitation with an assist-as-needed NMES-induced contraction of the extrinsic hand muscles. Providing rehabilitation to end-users with grasp deficiencies was targeted with a twofold approach. First, an RFID system contextually NMES-assisted hand opening and objects grasping. These combined features allow designing rehabilitation exercises of different complexity, and adaptable to the patient capabilities. Second, patients with different residual wrist control have different supporting orthoses designed to constrain and monitor motion as functionally needed.

The Italian Ministry of Health, the German Ministry of Health, and the local ethical committee for the hospitals of Como-Lecco and Sondrio, and the ethical committees of Villa Beretta - Presidio di Riabilitazione dell'Ospedale Valduce and of Neurologische Klinik Falkenstein approved the clinical studies and its preparatory testing activities.

4.2 METHODS

4.2.1 Hardware architecture

The architecture of S1 and S2 shares the same stimulation apparatus, a redesigned version of the MUNDUS stimulator, an Embedded Control System (ECS) hosted on a pocket-size computer (Beagle Bone Black, Beagleboard.org Foundation) able to provides real-time control of the connected modules, a touch-tablet (Surface Pro 3, Microsoft Corp.) used to host a graphical user interface (GUI), and the RFID antenna system. The GUI communicates with the ECS, manages state-machine for the control of the exercises, tasks, patients' data, and data tracking in general. The GUI is also connected to an RFID module providing contextual information about the proximity to reference points in space and tagged objects.

S2 includes two sensorized hand-orthoses, used to provide different constraining characteristics in different scenarios, the multiplexer module for the redesigned stimulator, and custom made electrode arrays. The ECS provides real-time control of the stimulation apparatus, and synchronized acquisition of the hand kinematics and grasp forces. In this design of the HH system, technical changes of the stimulation apparatus from the RehaStim Delta (Chapter 2) to the RehaMove Pro, reduced the overall number of channels available for the electrode arrays. Clinical partners consequently decided to prioritize stimulation of extrinsic flexors and extensors, and to exclude more advanced grasp types obtainable with intrinsic hand muscles.

Figure 36 shows the UML component diagram of the RETRAINER hand system. The overall control system of S2, visible in Figure 37, decouples the operations between high level motor primitives, which are handled by the GUI in relation to the necessary training of the patient, and the low level control, handled by the ECS.

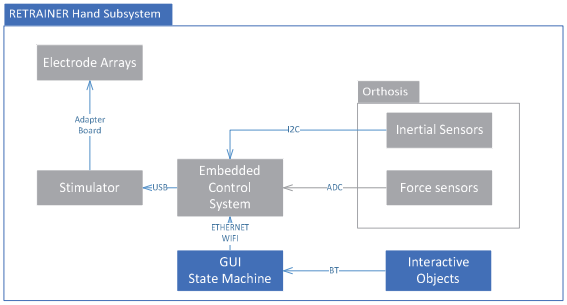


Figure 36: UML component diagram of the RETRAINER hand system architecture.

(Real-time components are shown in grey, non real-time components are shown in blue).

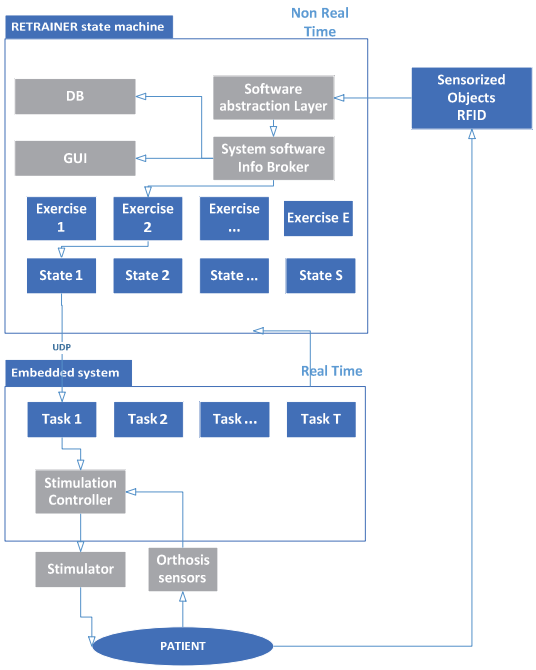


Figure 37: Overall structure of the RETRAINER S2 system

(Top area: the patient operates in a workspace in which objects and target areas are coded with RFID labels. A touch-based GUI stores clinically relevant exercises. Sequence of states characterize the exercises. Bottom area: a real-time task is associated to each state, task completion is triggered by environmental interactions or timeout.)

4.2.2 Orthoses and sensors

One important factor in rehabilitating functional grasp is the ability to adapt to individual needs. Constrain Induced Movement Therapy is one affordable way to exploit the residual functionalities of a subject and to retrain functional movements. In general, wearable NMES systems are not combined with grasp assistive orthoses. Standard splints and orthoses for stroke subjects provide palmar support, thus preventing real objects interaction. Under the clinical request to preserve as much as possible the residual tactile feedback, and to provide personal orthoses adaptable to the user needs, we iteratively produced the orthoses shown in Figure 38.

The new wearables included a new kind of orthosis for grasp assistance (Type-A, Figure 38), and a simple orthosis for wrist exercises (Type-B, Figure 39). The low cost of production of the electrode arrays and of the orthosis allows providing personalized and affordable wearables. To promote hand grasp and maintain the residual hand tactile sensibility, palmar support is minimized and wrist/hand locking is obtained through hand volar supports. The support structures, produced in PLA, are thermally shapeable to

adapt to non-standard hand compensation schemes. Each rigid part of the Type-A wearable orthosis is available in five sizes, to match the inevitable anthropometric variability, and to best fit with the clinical need.

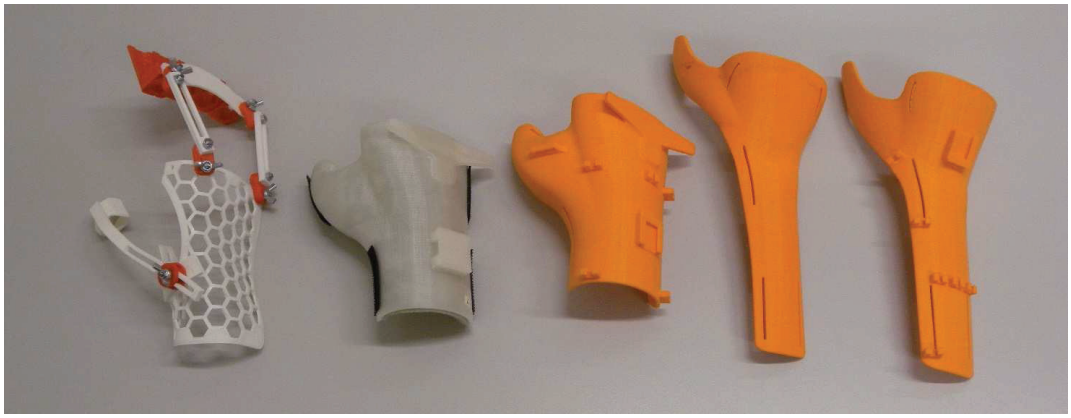


Figure 38: Evolution of the Type-A Hand Orthosis

(From Left to Right: evolution of the hand orthosis for constraining hand and wrist motion. The orthoses can be softened when heated above 70°C, and further shaped to adapt the wrist angle and the thumb opposition to specific needs. The thumb, if needed, is held in place by a soft rubber-like ring that hosts force sensors.)

Two hand orthoses are designed to reflect the needs of the various exercises. A set of exercises requires a controlled hand opening, with the wrist motility under the control of the patient, or for exercising wrist mobility also with NMES. The other set of exercises requires the forearm to stay in neutral positions and to assist grasp of cylindrical objects of diameters ranging from 30 mm to 70mm. The first orthosis holds two inertial sensors (InvenSense, MPU9250, San Jose, California), used to monitor the motion of the hand with respect to the wrist. The second orthosis prevents the hand-wrist movements and holds the thumb in opposition. A gummy ring is used to easily fix the thumb on its support, and to host a force sensor (Tekscan Inc., Flexiforce A201, A401) used to detect object grasp. Flexible clasps, also containing force sensors, are placed on medium and ring finger constrain the movements of the first and second phalanges. Rigid orthoses are available in five sizes for left and right side. Adaptation of the orthoses to the individual needs can be performed by heating the part and selectively bending upon need. Flexible clasps and rings are available in eleven sizes. The orthoses are shown in Figure 39.

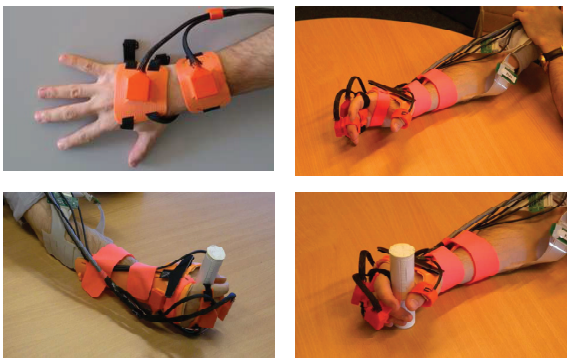


Figure 39: Orthoses, design and wearability.

(Top left quadrant: wrist motion control orthosis. Remaining quadrants: wrist locking orthosis. The RFID antenna is directionally mounted on the type-A orthosis.)

4.2.3 Electrode arrays and stimulating apparatus

The original HelpingHand prototype suffered multiple problems, as described in Chapter 2. Unreliability of stimulation could be caused by undesired responses of the stimulator, bad skin contact or cabling issues. A new stimulation apparatus (RehaMove Pro, Hasomed, Germany) solved the usability and reliability issues that affected the previous prototype. The original EAs design suffered of mechanical stress issues, suboptimal conformability to body parts dynamically changing shape as a result of electrical stimula-

tion, need of a supporting exoskeleton, and suboptimal connectivity. The updated EAs design relies on the concept presented in Chapter 3. EPFL-TNE/LPM designed and manufactured the new prototypes of electrode arrays; conductive silver tracks were screen printed on a PET substrate, and selectively isolated with a custom dielectric formulation. Each electrode arrays (EAs) contains 16 independent active pads arranged in four rows and columns. Two ground electrodes are symmetrically positioned on the sides. Active sites measure 10x12mm^2, whereas grounds measure 20x40 mm^2. The EAs can be then cut to improve the local bendability for skin fitting. The interface between electrode arrays and skin is commercial hydrogel (AG735, Axelgaard Inc.), which guarantees proper electrical impedance, mechanical adherence to the skin and provides stability of the contact. The third generation of EAs, based on a polymeric thick film ink (Electrodag™ 725A, Acherson Henkel), a high temperature stabilized PET substrate, and a custom formulated dielectric, provided the desired electrical reliability, abrasion resistance, and shelf life. Resilient cabling was obtained with thickness-matched non-ZIF connectors, and cables were length matched for the desired motion.

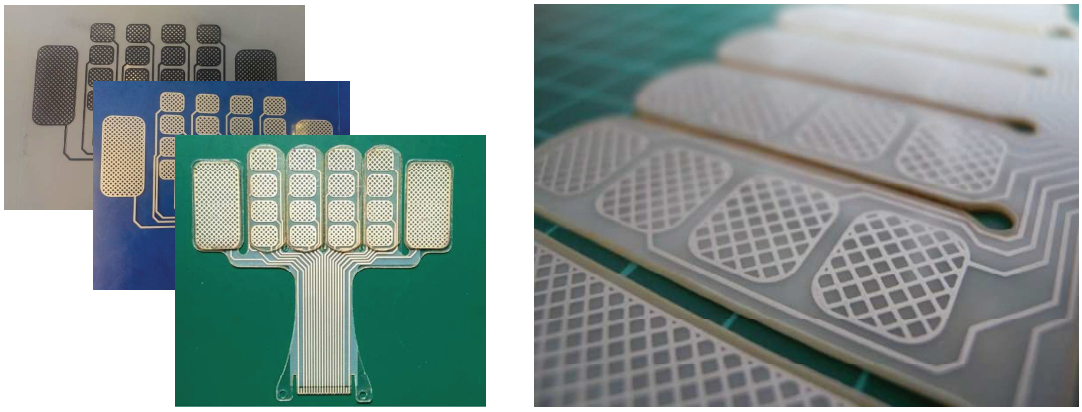


Figure 40: Custom electrode arrays.

(Left: layout and substrate adaptation through three generations of EAs. Right: details of the screen printing finishing. The electrodes can be trimmed in accordance to the desired use and mounting)

The mounting of the electrode arrays reflects the same concept in Figure 26, and the stimulation apparatus is designed to support two independent counter electrodes and 48 active sites. Two EAs are positioned on the forearm on the extrinsic extensors, and one on proximal extrinsic flexors, thus the most superficial hand extrinsic muscles that can be transdermally elicited can also be selectively targeted. S2 deals with the calibration of the stimulation maps and of the sensorized orthosis with interaction modalities mimicking the approach described the previous Chapter. The same 12” windows-tablet with touch capabilities is used; the GUI, here implemented by Ottobock, allows to guide the operator through different phase, such as sensors calibration, orthosis donning, NMES parameters setting and exercises execution stimulation. Figure 41 shows the newly designed interface for stimulation mapping. A more comprehensive exemplification of the S2 GUI is shown in Appendix A.

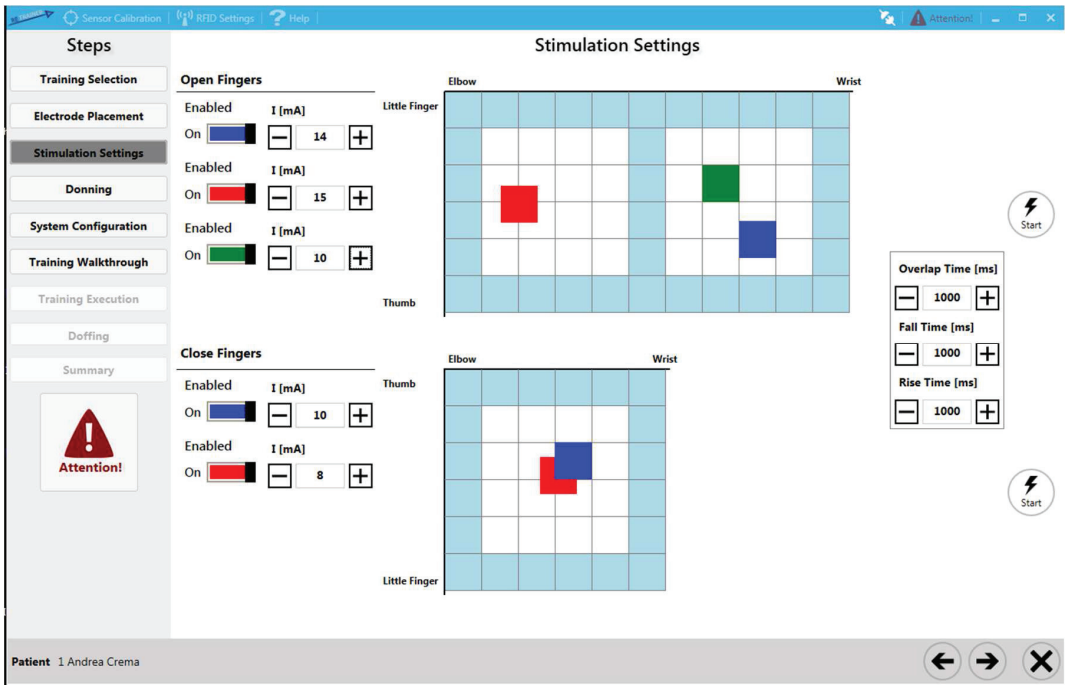


Figure 41: HH S2 touch interface for stimulation maps calibration.

(The stimulation settings of RETRAINER are derived from the ones of HH incognito (Chapter 3). The S2 system as a whole offers a higher responsiveness, and triggers the stimulation apparatus at higher frequency, and allows faster trial&error calibration. Differently from HH incognito that allows multiple stimulation maps storage, this interface saves for each patient only two stimulation maps, used for one stereotyped opening pattern, and one stereotyped closing pattern.)

4.2.4 Controller design

The controller used in RETRAINER is a reimplementation of the controller shown in Chapter 2. The controller (Figure 42) uses a standard PI architecture to modulate the stimulation pulsewidth, whereas the predefined stimulation maps are used to provide the spatial patterning associated with the desired action. Different sets of tuning parameters are implemented to control the different subtasks (kinematic driven fingers extension and flexion, kinematic driven wrist extension and flexion, and force-feedback grasp assistance) required by the exercises. Spatial and temporal features of the stimulation are handled by the stimulation planner, which patterns over a receding horizon a variant of the Minkowski VEs described in Chapter 3.

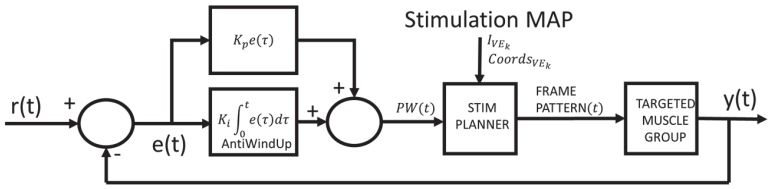


Figure 42: S2 control scheme

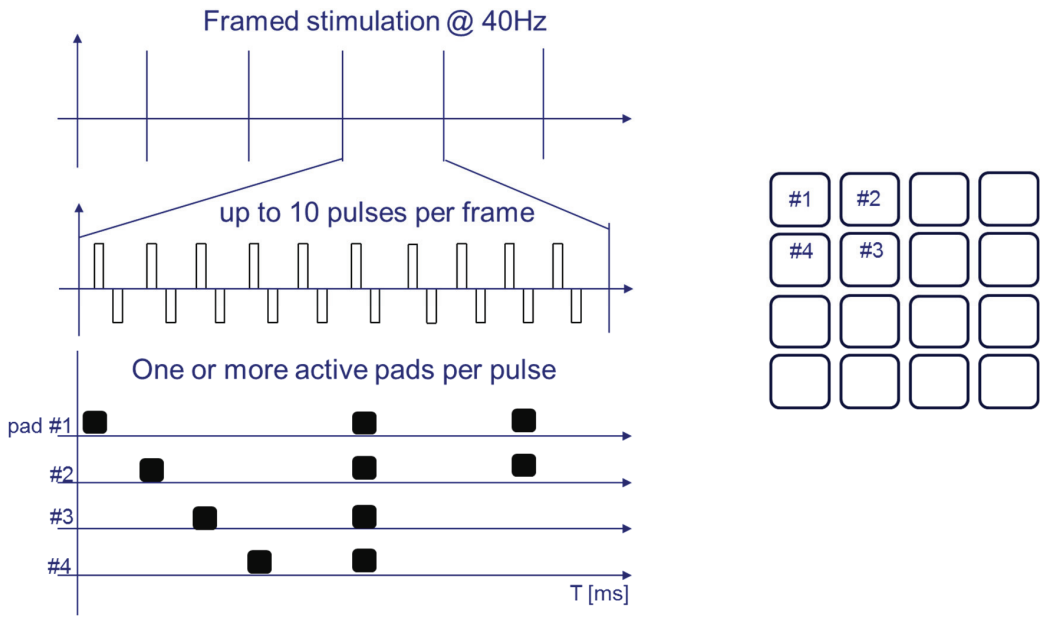


Figure 43: sample patterning obtainable with S2

(The stimulation configuration is updated to the RehaMove Pro stimulator in a framed fashion, with up to 10 pulses per frame. The frame update rate is up to 40 Hz, thus allowing responsive adaptation to real-time control needs. In this exemplification, only one frame of stimulation is shown. Pulses one to four are sequentially activated on pads one to four on "one by one" size virtual electrodes. Pulse six is applied on pads one to four on a "two by two" virtual electrode. Pulse nine is applied on a "one by two" virtual electrode.)

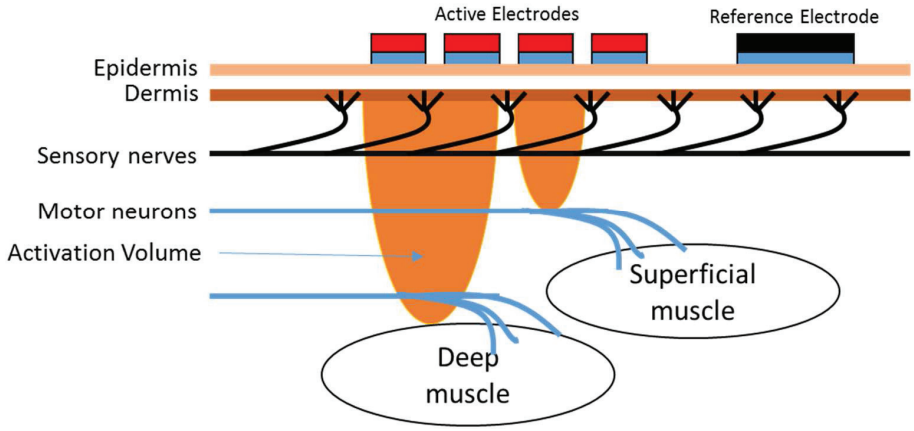


Figure 44: sample effects of the multiresolution stimulation patterning

(The first two electrode pads from the left, synchronously active to generate a larger electrode, have a wide and deeper activation field able to target superficial and deeper muscles. Position of the active electrodes and arrangement of the underlying tissues determine which muscles can be recruited. The third electrode pad from the left is active alone, thus generating a smaller activation volume able to target selectively only the superficial layers of excitable tissues.)

4.3 RESULTS

Stimulation comfort and overall tolerance to electrical stimulation is a topic hard to objectively quantify. Comfort is influenced, among the controllable parameters, by the current density, electrode sizes and stimulation parameters. Perceptive sensory masking, as well as the properties of the skin-electrode interface and the composition of the underlying tissues, are often out of the

control of the clinical experimenter. Every healthy subject involved in the testing of the final prototype was able to define personalized stimulation map, acceptable from a perceptual viewpoint, and able to elicit the movements necessary for the desired tasks.

The controller has been tested on six healthy subjects with different levels of muscle fatigue. If the identification phase of the motor points is correct, with right location and intensity of stimulation, the stimulation modulation can track the desired setpoint. The controller has also been tested during the pilot phase on

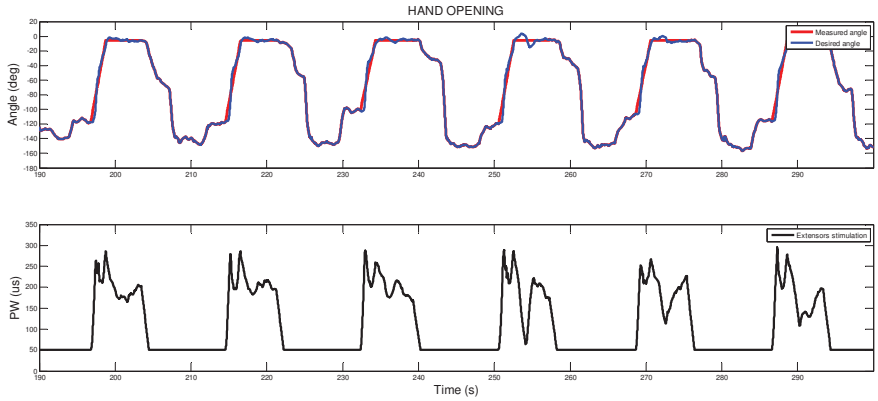


Figure 45: position based opening control

Figure 45 shows the results of the test during which only the extrinsic extensors were stimulated. The top panel depicts the desired and the actual angle trajectory. When the opening controller is not enabled, the target angle is set to match with the actual angle; when the controller is enabled, the target angle trajectory reaches the desired angle threshold with a ramp. The bottom panel shows the pulsewidth modulation used to induce the desired motion. The blue stripes show five activation sequences of the controller. At the end of each sequence, the pulsewidth decreases linearly according with the GUI selectable FallFactor. When the pulsewidth reaches a value of 50us, the stimulation current is set to zero.

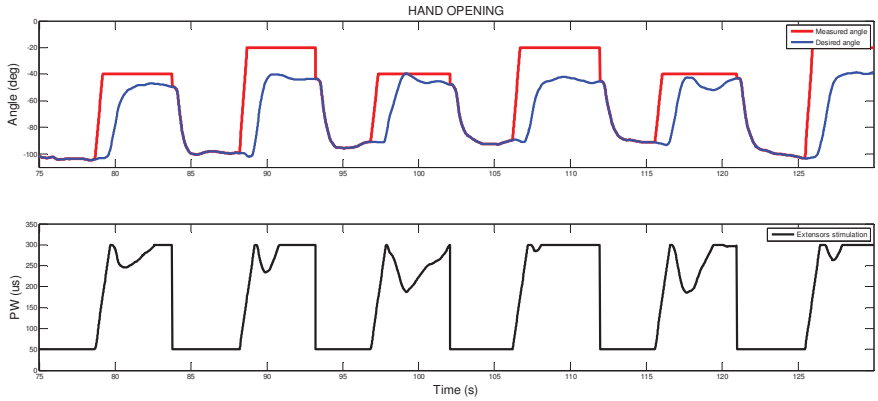


Figure 46: Position based opening control, test with multiple setpoints.

(The muscle is fatigued, and the pulsewidth saturates before the desired outcome is reached. A timeout prevents excessively prolonged stimulation in case one task cannot be successfully completed.)

Figure 46 shows the results of the test during which only the extrinsic extensors were stimulated. Differently from Figure 45, now the muscle is fatigued and the angle threshold is repeatedly changed above and at the liminal contraction capability. The topmost panel depicts the desired and the actual angle trajectory. The second panel shows the modulated pulsewidth necessary to sustain the desired motion. Saturation at 300 us occurs in both cases, but with different duration.

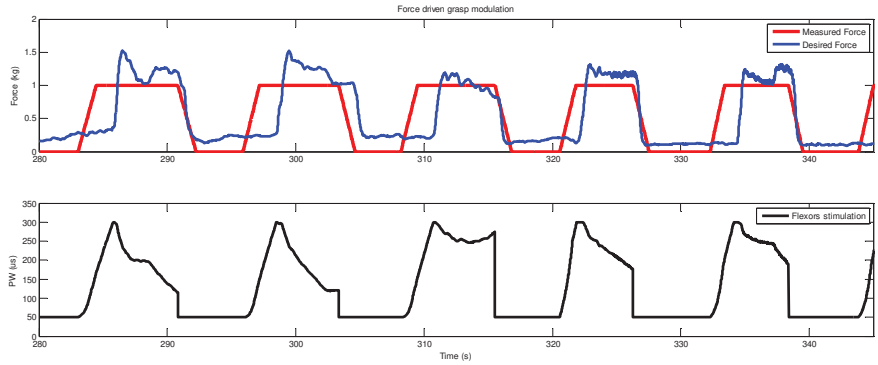


Figure 47: force based grasping control

Figure 47 shows the results of the test during which only the extrinsic flexors were stimulated. Top panel: shows the desired grasp force, as imposed from the GUI, and the exerted force. To prevent object slippage, a safety margin of 200g of equivalent grasp force is added to the desired force. The bottom panel shows the modulated pulsewidth as applied to the extrinsic flexors.

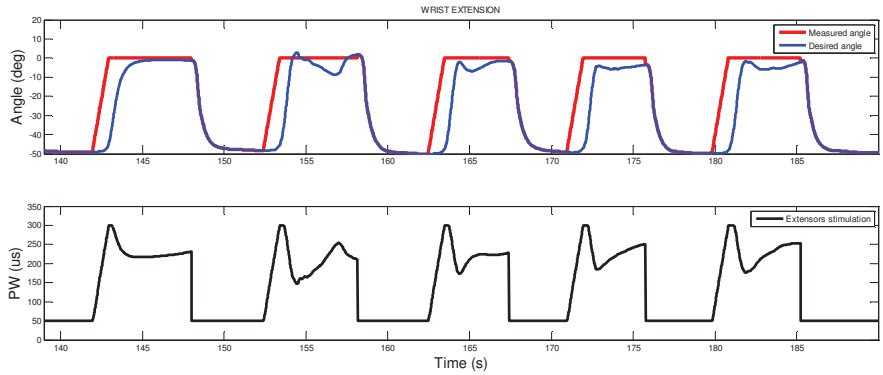


Figure 48: Position based wrist extension control

Figure 48 shows the results of the test during which only the extrinsic flexors were stimulated. The top panel depicts the desired and the actual angle trajectory. When the controller is not enabled, the target angle is set to match with the actual angle; when the controller is enabled, the target angle trajectory reaches the desired angle threshold with a ramp. The bottom panel shows the pulsewidth modulation used to induce the desired motion. The blue stripes show five activation sequences of the controller. At the end of each sequence, the pulsewidth decreases linearly according with the GUI selectable Fall Factor. When the pulsewidth reaches a value of 50us, the stimulation current is set to zero.

S2 was deployed in the involved clinical centers. One of the clinic involved in the associated multicentric trial, and already exposed to a preliminary technology (Chapter 2), successfully completed the pilot tests and started the clinical trials in December 2016. Preliminary examples of the event driven grasp assistance on patients are shown in Figure 49.

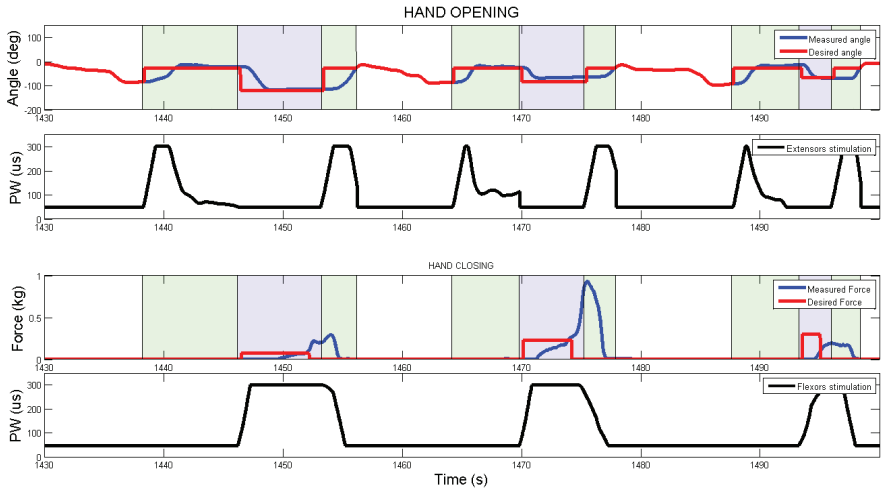


Figure 49: Grasp sequence with S2, Patient Zero

(Sequence of grasp and release tasks performed on the S2 patient Zero. The light green background is associated to fingers extension tasks. The teal background is associated to grasping tasks. The patient is able to grasp, but moderately impaired in hand preshaping. Top two panels: stimulation is used to open the hand; the controller removes the stimulation when the patient is able to voluntarily exceed the desired opening threshold. Bottom panels: low levels of electrical stimulation, unable to induce grasp, are provided to the patient as a perceptive cue associated to the desired action.)

4.4 DISCUSSIONS AND CONCLUSIONS

We designed a further evolution of the HelpingHand system. The Technological Readiness Level of the device changed from "technology validated in lab - in relevant environment" (TRL 4-5) to "system prototype demonstration in operational environment" (TRL 7) [73], [74] . Independent experts reviewed the clinically deployed system and stated the design, integration and finally the manufacturing and assembly of the provided HelpingHand S2 systems "was usercentred, with good understanding and implementation of user-related issues, like usability, safety, easiness of use". The prototypes, demonstrated with real end-users, were rated as clearly robust. Furthermore attention was given to the needs and demands of the professionals (therapists, medical personnel), and the project started preparation steps towards the qualification process for a medical device and CE marking. The clinical testing will be extensive with around 68 stroke patients involved in a 15-month clinical study - multicentric randomized control study. The clinical trials will provide evidence to confirm or deny a TRL 8, by exposing the validated efficacy of the system, and by providing insights on the residual engineering and manufacturing risk. Clinical validation will be the major driver toward further improvement and for the potential commercialization.

4.4.1 TAM and SUS assessment

Short questionnaires based on the Technology Acceptance Model (TAM) [63] and on the SUS [64] were used for assessing the impact of the third generation Helping Hand on the clinical workflow, used for determining the aspects needing an improvement, and as a comparison term for previous and future prototypes. The questionnaires were compiled by the clinical engineer supervising RETRAINER trials after the completion of the pilot trial in the "expert" clinic. This assessment focuses on the S2 prototype as a whole.

Acceptance and usability will be throughly assessed in the expert and in the naïve clinic through a standardized tool, incorporated in the RETRAINER GUI, thus allowing a more automatized data acquisition and providing feedback not only from the clinical engineers, but extended to clinicians and patients using the system.

Table 34: RETRAINER TAM Perceived Usefulness

Perceived Usefulness (Likert scale)	HH S2
Using the device improves performance in daily life activities	6
Using the device increases productivity in daily life activities	6
Using the device enhance effectiveness in daily life activities	6
I find the device to be useful in daily life activities	7

Normalized scores	**87.5%**

Table 35: RETRAINER TAM Perceived Ease of Use

Perceived Ease of Use (Likert scale) – setup phase	HH S2
The interaction with the device is clear and understandable	6
Interacting with the device does not require a lot of mental effort	6
the device is easy to use	6
It is easy to get the device to do what it's wanted it to do	6
Normalized scores	**83.33%**

Table 36: RETRAINER TAM Computer Self Efficacy

Computer Self-Efficacy (set of options) –setup phase	HH S2
I have control over using the device	6
I have the resources necessary to use the device	7
Given the resources, opportunities and knowledge it takes to use the device, it would be easy for me to use it	7
the device is not compatible with other systems I use	1
Normalized scores	**95.83%**

Table 37: RETRAINER TAM Computer Playfulness

Computer Playfulness (set of options) – setup phase	HH S2
how you would characterize yourself when you use the device?	
… spontaneous	
… creative	
… playful	X
… unoriginal	
Normalized scores	**33%**

Table 38: RETRAINER TAM Computer Anxiety

Computer anxiety (Likert scale)	HH S2
Computers do not scare me at all	7
Working with a computer makes me nervous	1
Computers make me feel uncomfortable	1
Computers make me feel uneasy	1
Normalized scores	**100%**

Table 39 : RETRAINER TAM Perceived Enjoyment

Perceived enjoyment (Likert scale) – setup phase	HH S2
I find using the device to be enjoyable	7
The actual process of using the device is pleasant	7
I have fun using the device	7
Normalized scores	**100%**

Table 40: RETRAINER TAM Subjective Norm

Subjective norm (Likert scale)	HH S2
People who influence my behavior think that I should use the device	6
People who are important for me think that I should use the device	6
The senior management of the hospital has been helpful in the use of the device	7
In general the hospital has supported the use of the device	7
Normalized scores	**91.67%**

Table 41: RETRAINER TAM Voluntariness

Voluntariness (Likert scale)	HH S2
My use of the device is voluntary	1
My supervisor does not ask me to use the system	1
Although it might be helpful, using the device is certainly not compulsory	7
Normalized scores	33.33%

Table 42: RETRAINER TAM Image

Image (Likert scale)	HH S2
People in my organization who use the device have more prestige than those who do not	1
People in my organization who use the system have a high profile	1
Having the device is a status symbol in my organization	1
Normalized scores	0%

Table 43: RETRAINER TAM Job Relevance

Job Relevance (Likert scale)	HH S2
Usage of the device is important	7
Usage of the device is relevant	6
The use of the device is pertinent to various tasks	7
Normalized scores	94.4%

Table 44 : RETRAINER TAM Output Quality

Output Quality (Likert scale)	HH S2
The quality of the output I get from the device is high	6
I have no problems with the quality of the device output	7
I rate the results from the device to be excellent	6
Normalized scores	88.8%

Table 45: RETRAINER TAM Results Demonstrability

Results demonstrability (Likert scale)	HH S2
I have no difficulties telling others about the results of using the device	7
I believe I could communicate to others the consequences of using the device	7
The results of using the device are apparent to me	7
I would have difficulties explaining why using the device may or may not be beneficial	1
Normalized scores	100.00%

Table 46: RETRAINER TAM Behavioral Intention

Behavioral Intention (Likert scale)	HH S2
Assuming I had access to the device, I intend to use it	7
Given that I had access to the device, I predict that I would use it	7
I plan to use the device in the next 6 months	7
Normalized scores	100.00%

System Usability scale results

Table 47: RETRAINER SUS comparative analysis

System Usability Scale	HH S2
1. I think that I would like to use this system frequently.	5
2. I found the system unnecessarily complex.	1
3. I thought the system was easy to use.	5
4. I think that I would need the support of a technical person to be able to use this system.	2
5. I found the various functions in this system were well integrated.	5
6. I thought there was too much inconsistency in this system.	1
7. I would imagine that most people would learn to use this system very quickly.	4
8. I found the system very cumbersome to use.	2
9. I felt very confident using the system.	4
10. I needed to learn a lot of things before I could get going with this system.	1
Normalized scores	90

Chapter 5 Technology Acceptance and Systems Usability

Technology Acceptance Model (TAM) builds the prediction of individual adoption and use of technology on two main beliefs that affect the behavioral intention of the individual; they are *perceived usefulness* defined as "the extent to which a person believes that using technology will enhance his or her job performance" and *perceived ease of use* defined as "the degree to which a person believes that using technology will be free of effort". System Usability (SUS), as developed by [64], is a ten-item attitude Likert scale giving a global view of subjective assessments of usability. TAM and SUS questionnaires are not objective measures for comparing different robotic or hybrid tools for rehabilitation. However globally accepted comparison tools do not exist [76], and the used questionnaires still retain local validity for assessing evolutions of the same device within the same set of evaluators.

A short questionnaire based on TAM and on SUS was used for assessing the impact of the HelpingHand MUNDUS, HelpingHand INCOGNITO, HelpingHand RETRAINER, as described in Chapters 2, 3 and 4. Assessment was performed by the clinical engineering experts directly involved in the tests on patients. Surveys were administered at different timelines of the various projects. Rating for HH MUNDUS was provided at the end of testing (~ 200 hours of use), for HH INCOGNITO rating took place mid-way through the testing(~500 hours of use), and HH RETRAINER was evaluated at the completion of the pilot tests(~30 hours). The practitioner that evaluated the HH MUNDUS system, also evaluated the HH RETRAINER system. The practitioner that evaluated the HH INCOGNITO system was also involved in the testing of HH MUNDUS, but did not provide an evaluation of the system. This reduced evaluation was aimed at obtaining the guidelines necessary to improve the technological readiness level (TRL) [63], [73], [74] of the prototypes, reduce the necessary supervision, and improve the reliability with the aim of simplifying the tests in multiple clinical centers with different levels of experience, and different operative background. As a consequence, any possible analysis has to take into account possible discrepancies of judgement between the practitioners, and consider the results as opinions of expert users that may not reflect the experience of more naïve clinical units. A section of the HH RETRAINER GUI [75] aims at filling this gap, and allows collecting in a standardized way such information, potentially providing a much higher amount of information from different types of users.

Summary results of the three HelpingHand generations are detailed in the paragraphs below.

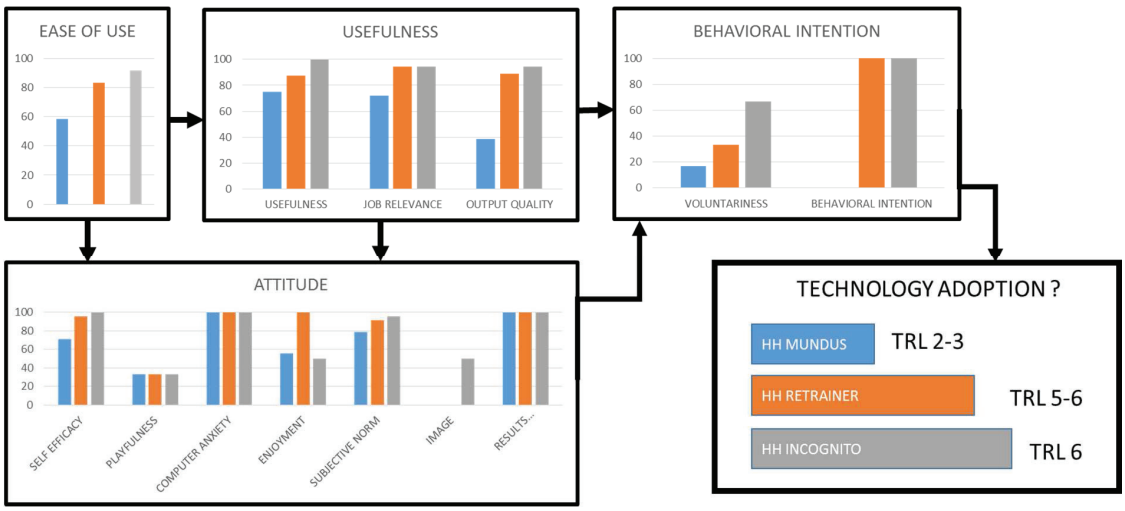


Figure 50: Technology Acceptance Model for the three generations of Helping Hand.

The HH INCOGNITO and HH RETRAINER systems are globally perceived mode useful, easy to use, and likely to be used than the original HH MUNDUS prototype. In all the conditions the practitioners evaluated themselves as highly skilled with technological gadgets, confident in the use of computers, and freely able to express their opinions. They rated themselves as self-efficient with the new devices. The HH RETRAINER system appeared more enjoyable to use than the HH INCOGNITO. From a subjective norm, all the devices were perceived as useful, but improvements in usefulness, job relevance and output quality emerged clearly with the new versions. From an attitudinal viewpoint the biggest improvement derived from providing improved GUIs and removing the need to use the command line as a way to interact with the system, which improved the self-efficacy. From the behavioral intention perspective, the INCOGNITO systems appeared easier to use and more usable on a voluntary basis. The most recent prototypes seemed to offer improved job relevance for the practitioners, and are expected to provide a significantly higher output quality in the treatment of upper limb deficiencies.

The SUS scale, as evaluated by different personnel of the same 'expert' clinic found the INCOGNITO (90%) and the RETRAINER (90%) systems more usable than the original MUNDUS (67%) system. Global improvements were seen throughout all the items, but the largest usability improvement was on the overall ease of use. The redesign aimed at minimizing weights and volumes had no apparent impact in the perceived usability.

Table 48: SUS comparative analysis

System Usability Scale	HH EXO	HH C	HH S2
1. I think that I would like to use this system frequently.	4	5	5
2. I found the system unnecessarily complex.	2	1	1
3. I thought the system was easy to use.	3	5	5
4. I think that I would need the support of a technical person to be able to use this system.	3	2	2
5. I found the various functions in this system were well integrated.	4	5	5
6. I thought there was too much inconsistency in this system.	2	1	1
7. I would imagine that most people would learn to use this system very quickly.	3	4	4
8. I found the system very cumbersome to use.	2	2	2
9. I felt very confident using the system.	4	4	4
10. I needed to learn a lot of things before I could get going with this system.	2	1	1
Normalized scores	67.5	90	90

Chapter 6 Discussions

The goal of this Thesis is to provide the technical and scientific rationale, and clinical evidence supporting translational neurorehabilitation in the treatment of upper limb grasp rehabilitation by means of NMES.

The developed tools and the studies presented in previous Chapters capitalize on state-of-the-art NMES techniques (Chapter 2 "Design of a Wearable Platform for GRASP assistance", Chapter 3 "Integrated Cognition for re-covery of hand grasp functions", Chapter4 "Task-driven grasp rehabilitation"), and extend their translational applicability by deploying prototypes in the clinical environment. Throughout the Chapters it's presented the evolution of Helping Hand, a wearable for grasp rehabilitation and its specialization to specific contexts and uses.

In Chapter 1 it was discussed how the standard single electrode technologies were a limiting factor in preparing clinically usable grasp rehabilitation for non-trivial tasks. It was also compared how the switch from standard 'carbonized rubber'-'metallic mesh'-gel electrodes to embroidered/textile electrode proved useful only on applications requiring large electrodes.

In Chapter 2, the discussion focused on the technological switch to screen printed electrode arrays with electrode density compatible with the needs of NMES mediated grasping assistance. We designed the first generation of the HelpingHand system, validated the electrode size requirements necessary for selective and comfortable stimulation, and the technical limitations of screen printed circuits interfacing. We also performed preliminary environment-driven tests by combining a hybrid control with the first version of the Helping Hand with a powered exoskeleton (HH EXO).

In Chapter 3 we capitalized on the technical and usability limitations encountered in Chapter 2, and designed the second generation of the HelpingHand aimed a modular use, improved fitting, with improved reliability. We designed and validated a simple configuration method for creating task-specific stimulation maps, and the GUI interactivity for clinical easy adoption. Helping Hand Clinical (HH C) is currently tested in a trial aimed at evaluating on 60 chronic stroke patients the impact of different technologies in the motor and cognitive rehabilitation of grasp. Preliminary evidence, limited to 5 subjects that completed the trial with Helping Hand, suggests that HelpingHand Clinical improves the perception of the affected limb, improves the hand preshaping for grasp tasks, and that the associated hand motor skills obtained during the clinical rehabilitation, are also better retained in the follow up phase.

In Chapter 4, a different embodiment of the Helping Hand system was designed, and integrated with a new kind of sensorized hand orthosis for grasp assistance in contextual exercises. The low cost of production of the electrode arrays and of the orthosis allows providing personalized and affordable wearables. To promote hand grasp and maintain the residual hand tactile sensibility, palmar support is minimized and wrist/hand locking is obtained through hand volar supports. The thermally shapeable orthosis adapts to non-standard hand compensation schemes. Real-time control of hand preshaping and grasping allows providing assistance as needed in environmental interaction tasks. Causal assistance in task-driven exercises is a key feature for treating acute and subacute stroke patient. By targeting the patients when the cortical reorganization with faster changes, this device has the possibility to promote faster recovery. A 15-month clinical study - multicentric randomized control study, with 68 stroke patients is about to start to validate the usability of the platform in expert and naïve clinics.

The Helping Hand, started as a wearable optional module for an exoskeleton based training, has evolved in a standalone platform that can be adapted for different uses. The progressive increment of the overall technology readiness level allowed starting two independent clinical trials. For HH C, the reliability of the device is proven, and clinical results are encouraging. For HH S2, clinical trials have just started, and are aimed at providing clinical and technological validation of this prototype. It is worth to notice that the reasonable costs of the device would allow to further extend, when clinically validated, to home use for extensive rehabilitation.

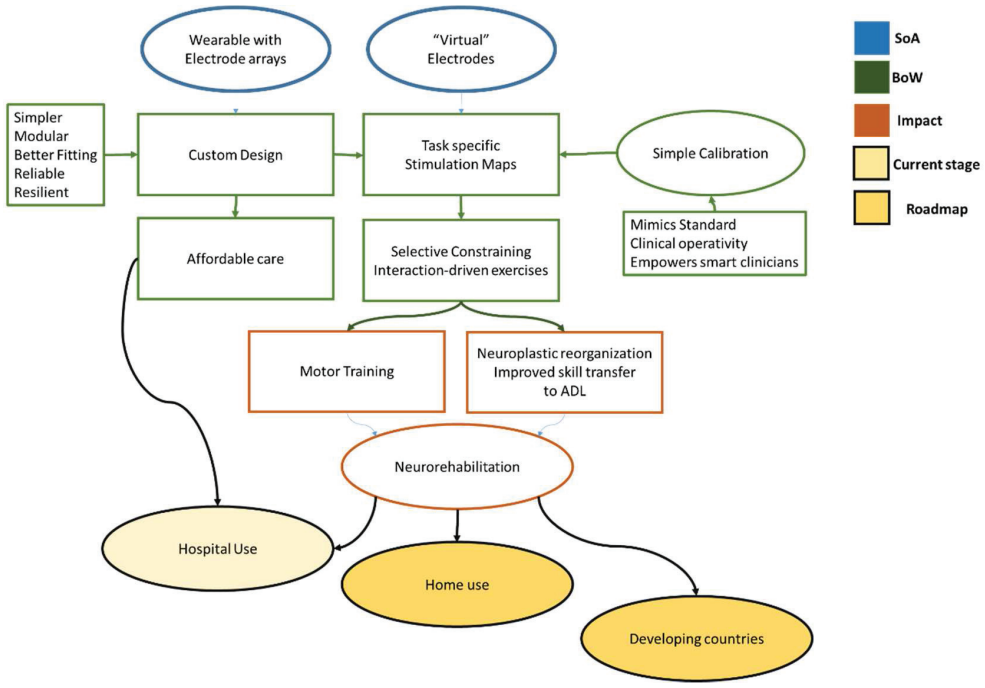


Figure 51: Wearable systems for Grasp rehabilitation after stroke.

The roadmap for the prosecution of the investigations of Helping Hand for Hospital use and Home Use is already defined, and functional to the necessity of creating platforms for grasp rehabilitation of different complexity, with multimodal devices usable in specialized manner in clinical context, and simpler tools for task-specific home treatments.

Appendix A HelpingHand Walkthrough

This appendix contains screenshots of the GUI developed by Ottobock Health Products within the activities of the RETRAINER project described in Chapter 4. The walkthrough presented in the following pages guides the operator through the donning of the wearable, the selection of the necessary components, calibration of the stimulation patterns, definition of the desired grasp forces and hand kinematics, and the execution of the exercises.

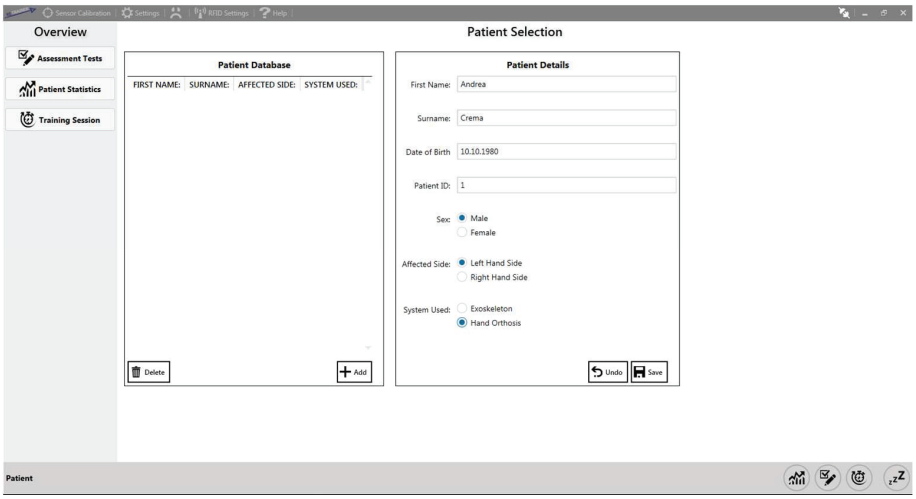


Figure 52: RETRAINER GUI - Database

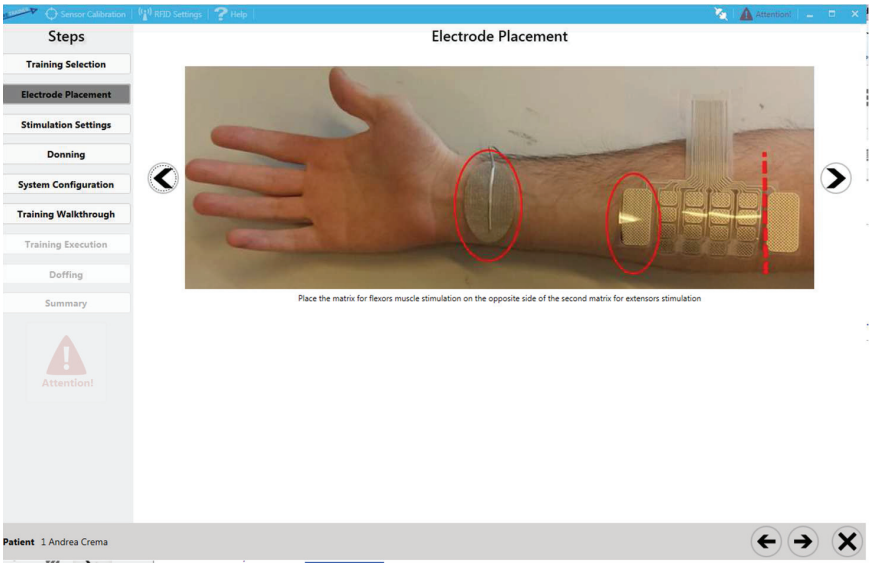


Figure 53: RETRAINER GUI Assisted electrode positioning

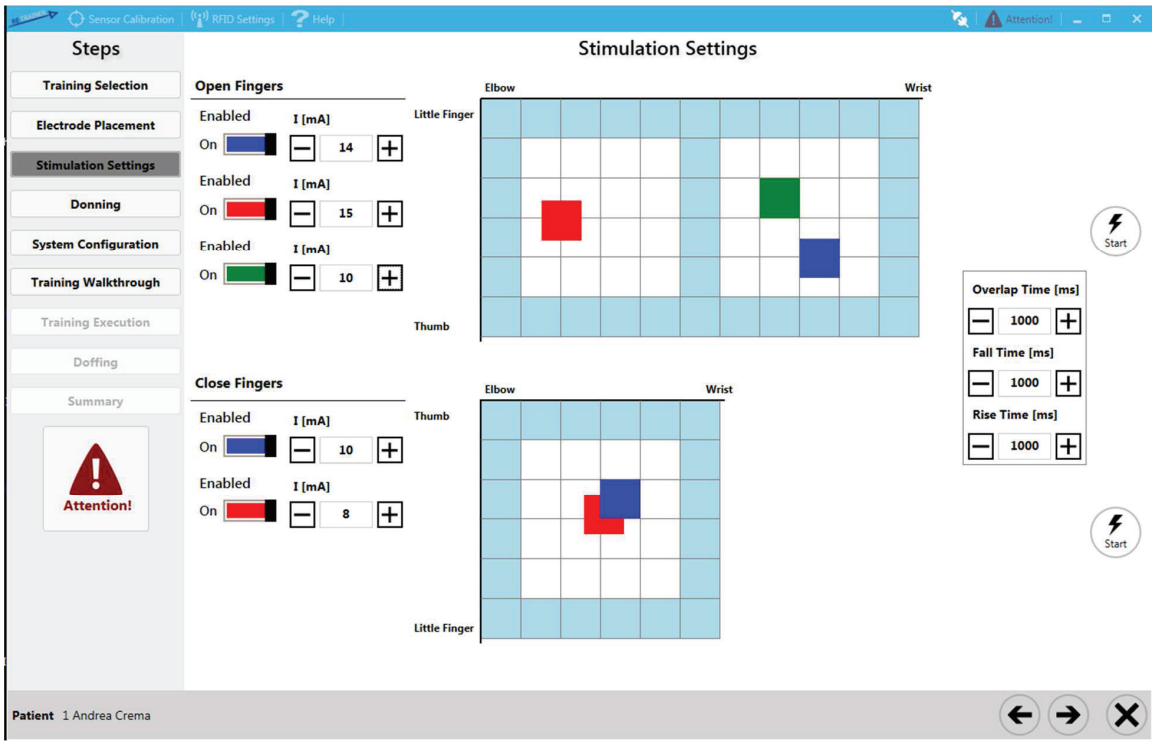


Figure 54: RETRAINER GUI Stimulation Maps

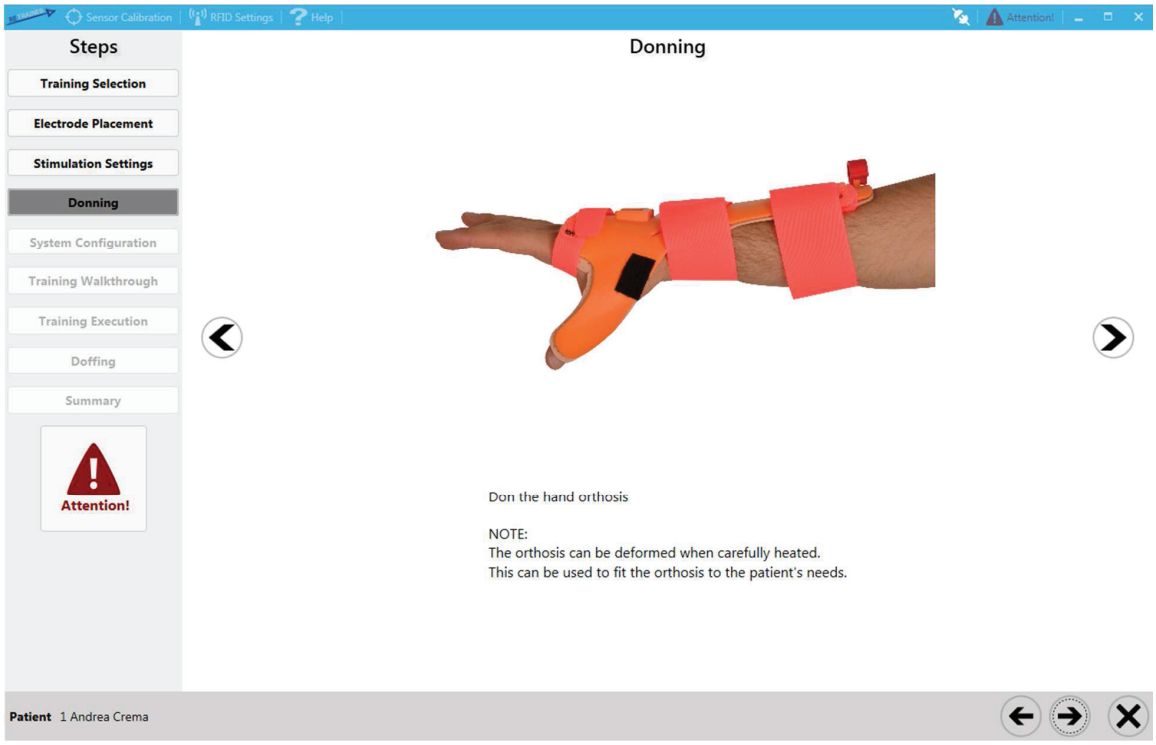


Figure 55: RETRAINER GUI Orthosis donning

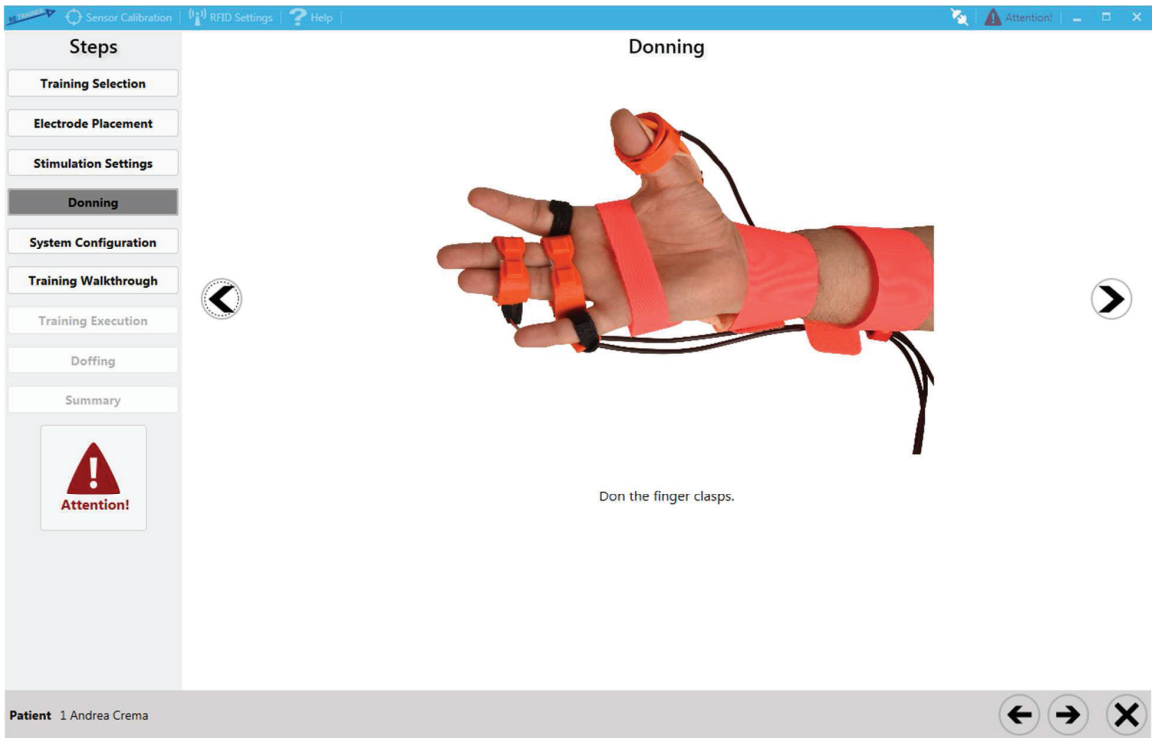


Figure 56: RETRAINER GUI Clasp Donning

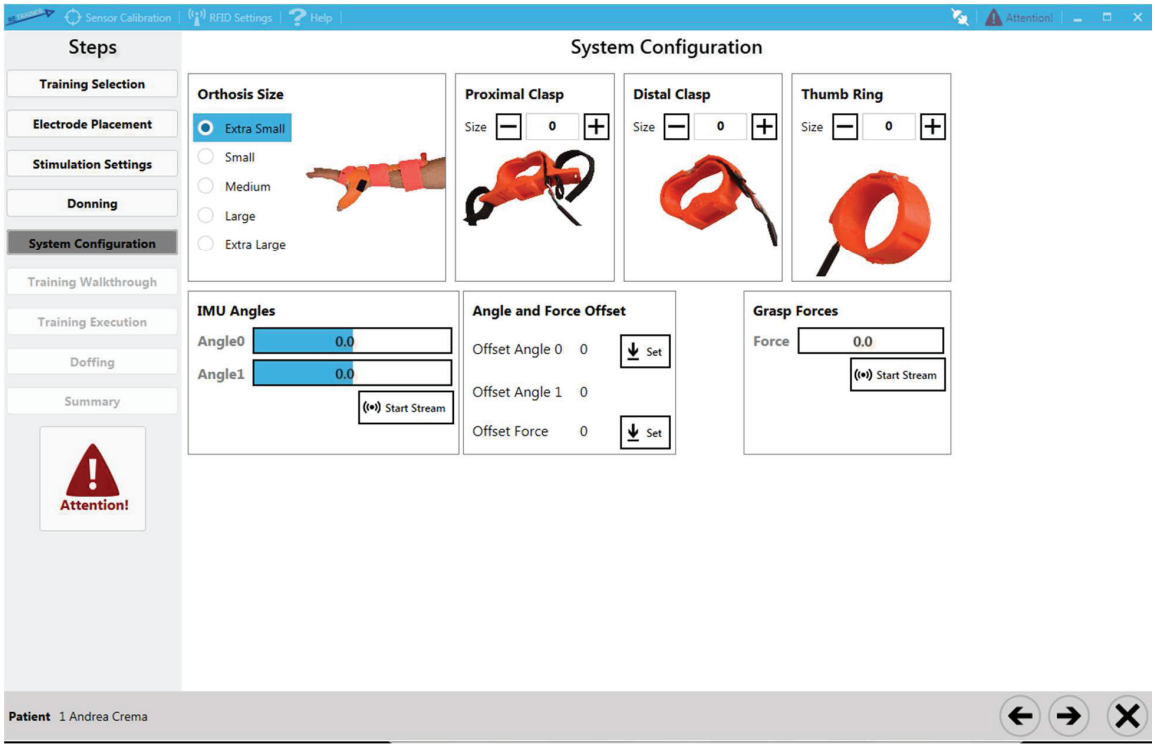


Figure 57: RETRAINER GUI Orthosis configuration

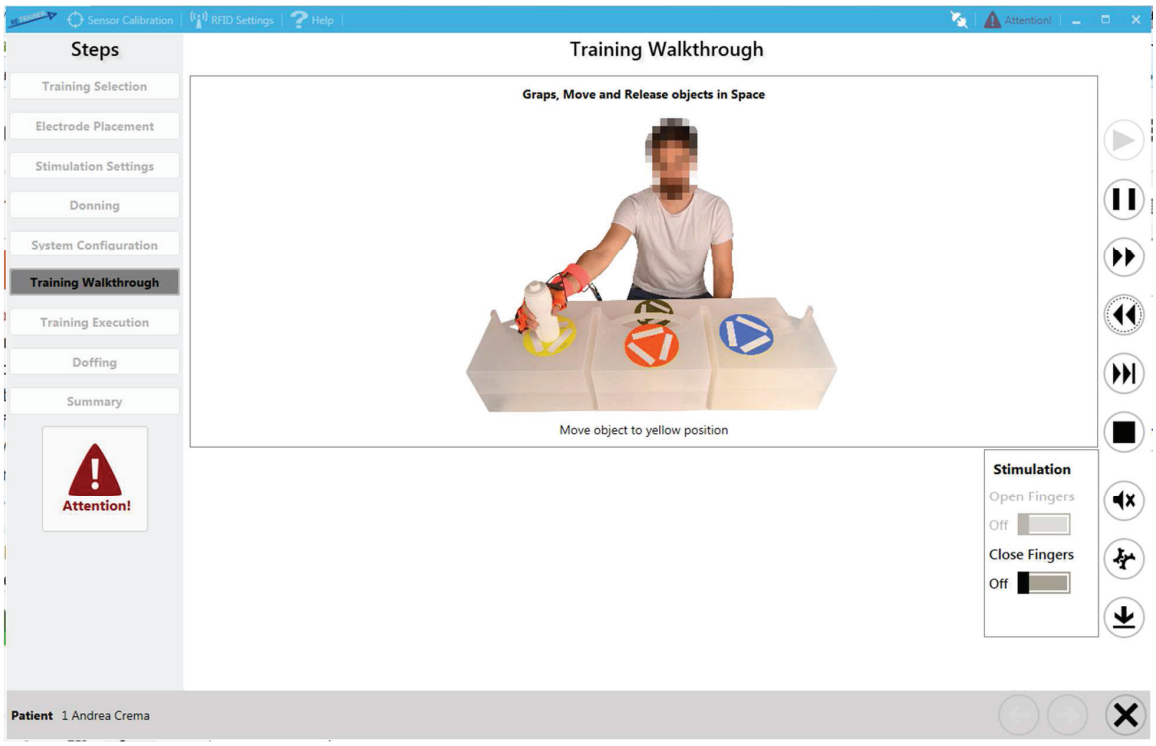


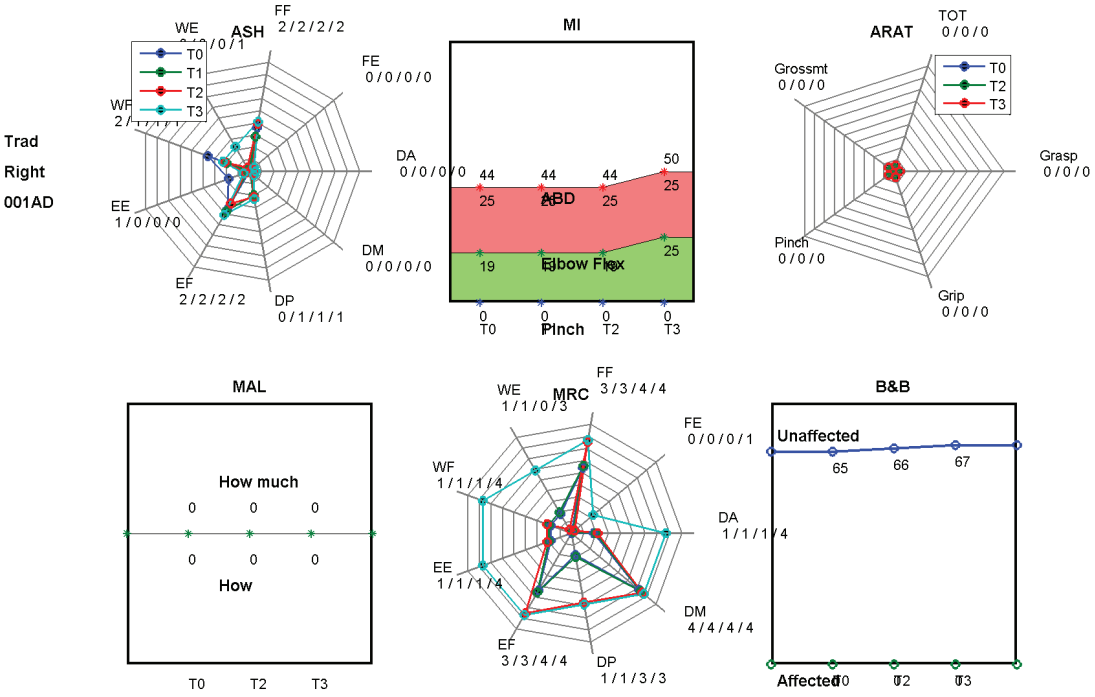
Figure 58: RETRAINER GUI Exercise walkthrough

Appendix B Detailed Clinical results for Incognito

This section aims at providing a snapshot of the global effect of the therapy in selected patients by offering positive and negative examples for the conventional therapy and the helping hand group. Each test is represented in a multidimensional graph aimed at providing a quick dynamic overview of the patient progression. Ashworth and MRC-UL show through a radar plot the outcomes for the shoulder (Deltoid Anterior, Deltoid Medialis, and Deltoid Posterior), elbow (Elbow Extensors, Elbow Flexors), wrist (Wrist Extensors, Wrist Flexors) and fingers (Fingers Flexors, Fingers Extensors). Similarly the ARAT is shown as a radar for Grasp, Grip, Pinch, GrossMT, and total score. The Motricity Index (Pinch, Elbow Flex, arm ABDuction) and the Motor Activity Log are represented through stacked graphs to show the dynamic adaptation to the treatment. The Box&Block test shows the results of the test on the ipsilateral limb (presumed to be Unaffected by the stroke) and on the contralateral limb (Affected) subject to treatment.

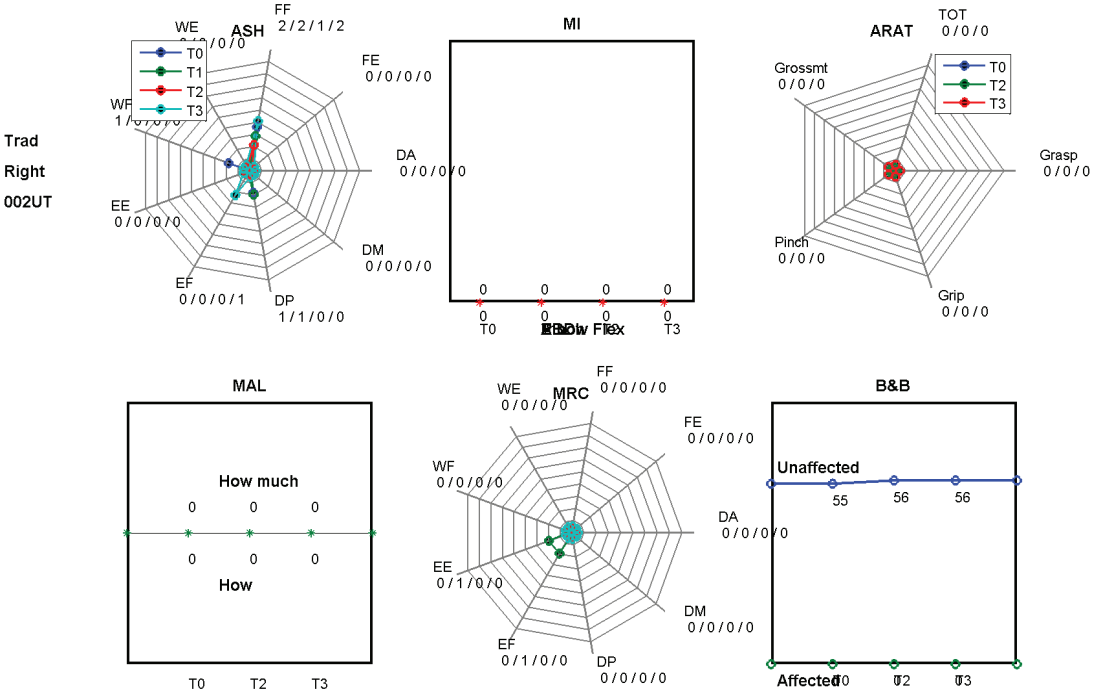
Patient 001AD, Conventional treatment

The affected limb was, prior to injury, dominant. The spasticity of the fingers flexors prevents the ability to recruit fingers extensors. Moderate ability to recruit finger flexors, but unable to overcome external resistance. No functional grasp is visible, due to the inability to preshape the hand in a functional way.



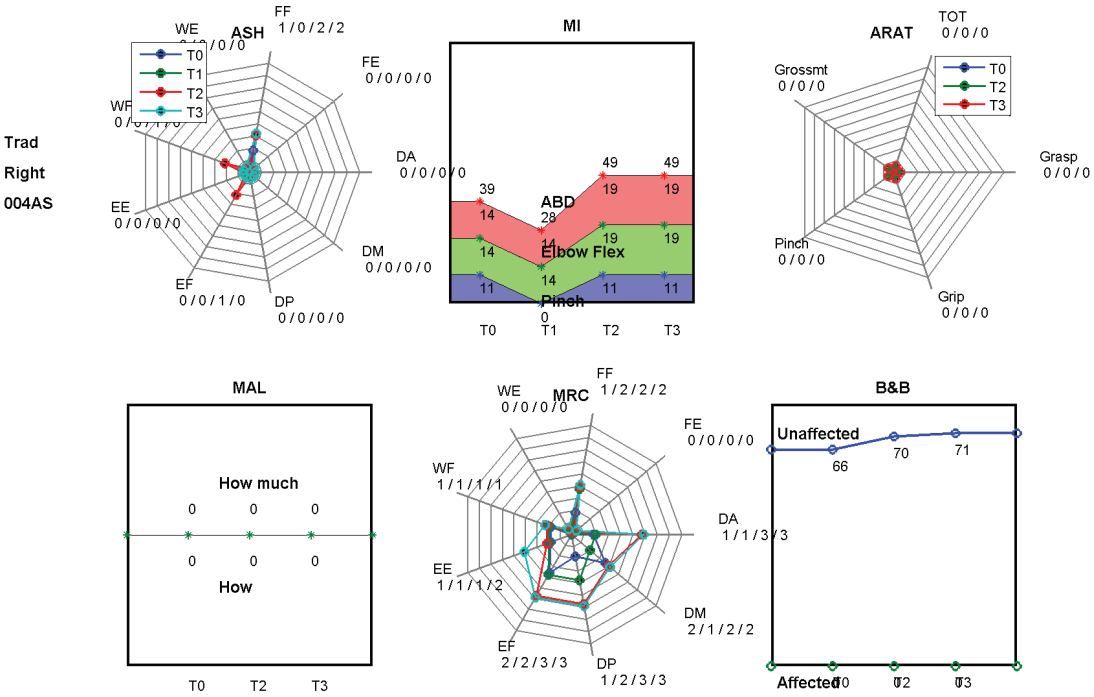
Patient 002UT, Conventional treatment

The affected limb is not dominant. Moderate spasticity of the fingers flexors. No significant functional improvement.



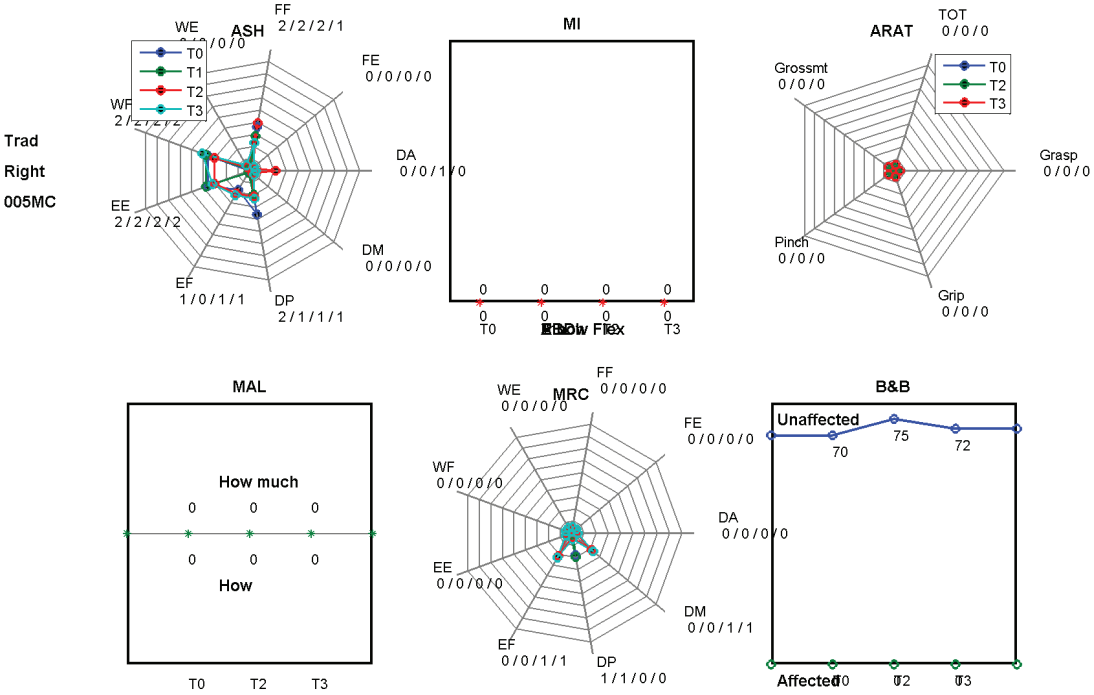
Patient 004AS, Conventional treatment

The affected limb is not dominant. Marked muscle tone on fingers flexors and moderate recruitment ability. Flaccidity of fingers extensors. Improvements associated only to the reaching capabilities.



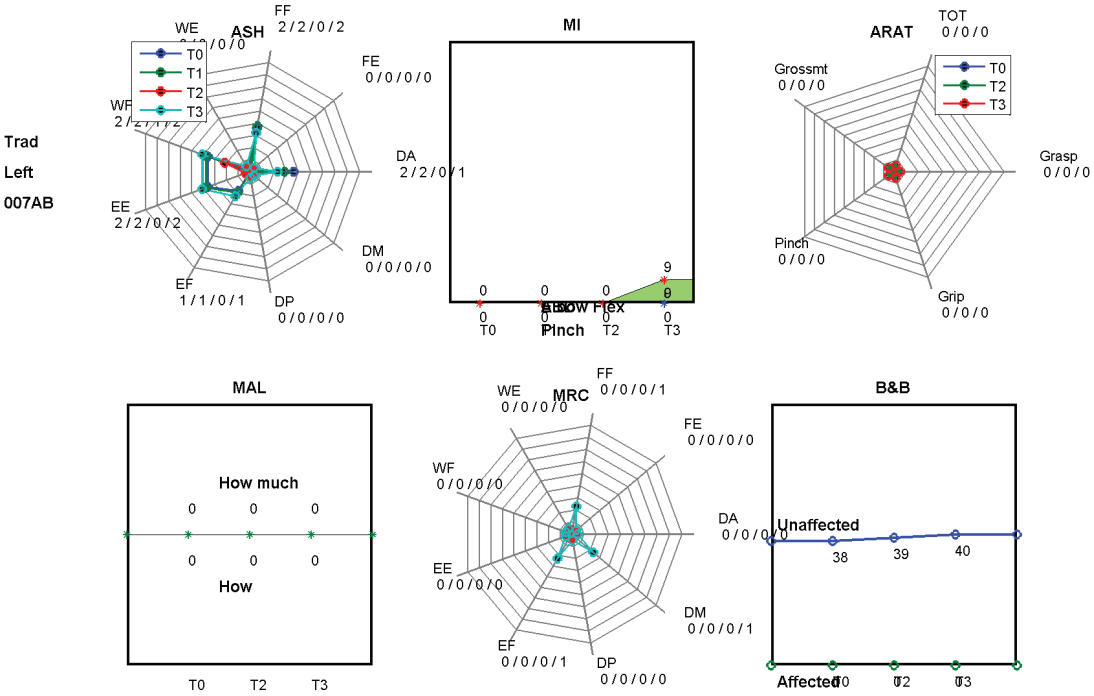
Patient 004AS, Conventional treatment

The affected limb is dominant. Inability to recruit the UL muscles. No functional improvement.



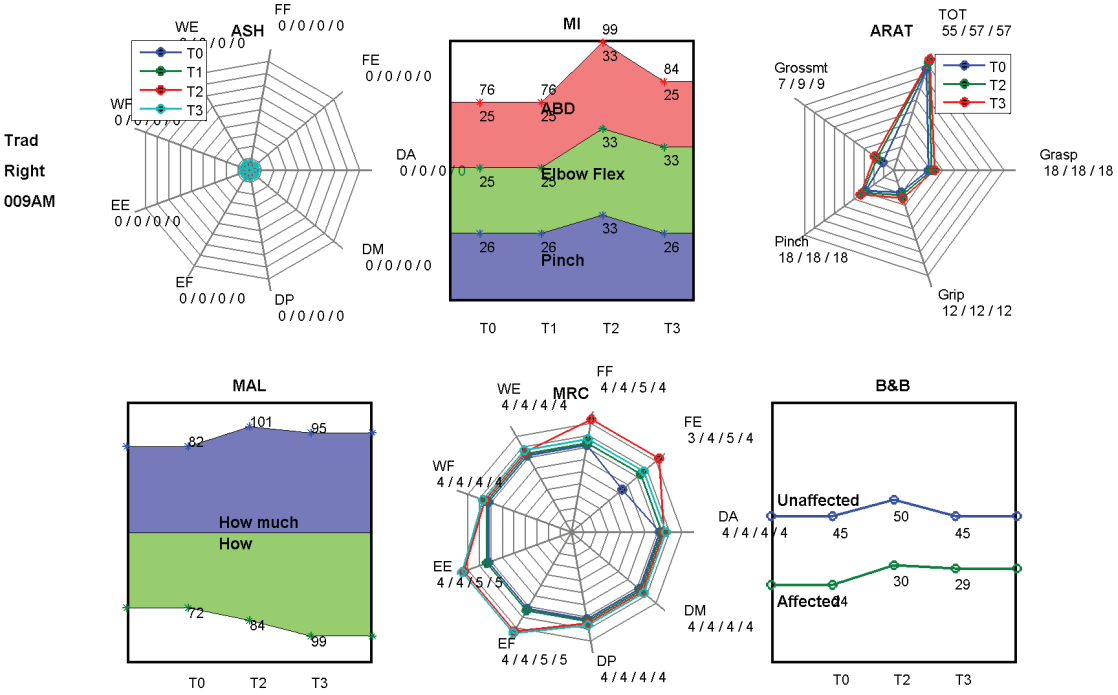
Patient 007AB, Conventional treatment

The affected limb is not dominant. Inability to recruit the UL muscles. No functional improvement.



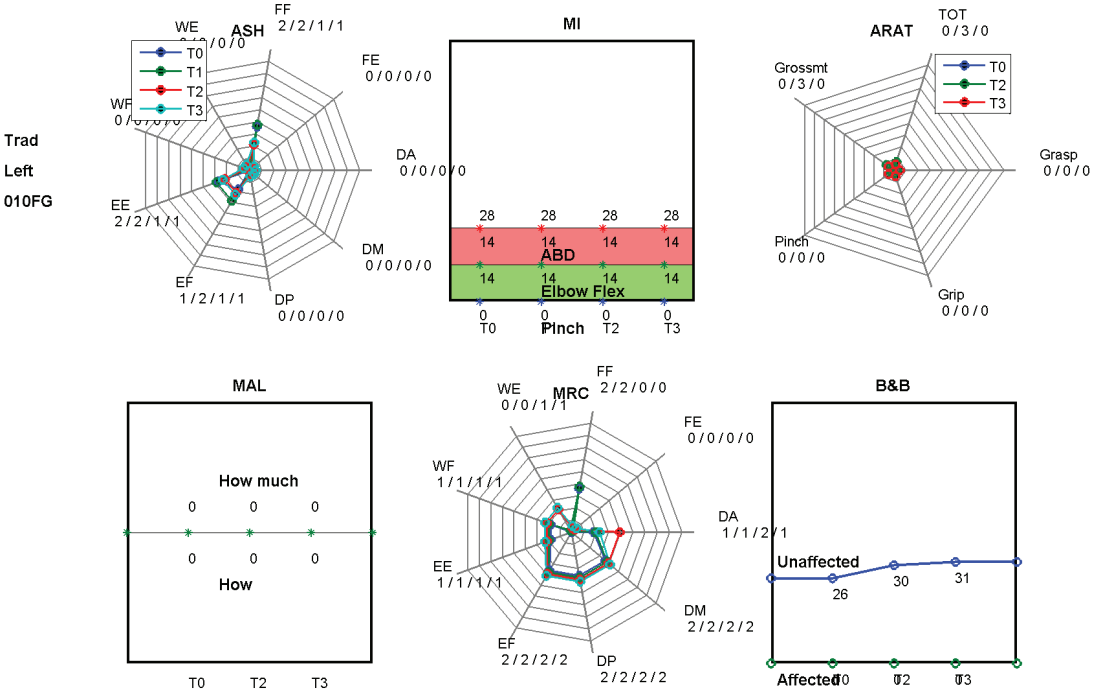
Patient 009AM, Conventional treatment

The affected limb is dominant. Absent spasticity. Functional grasp and spatial exploration at inclusion. MRC, MI and ARAT show improvement during therapy, partially retained at follow up. Improved perception and use of the limb over time.



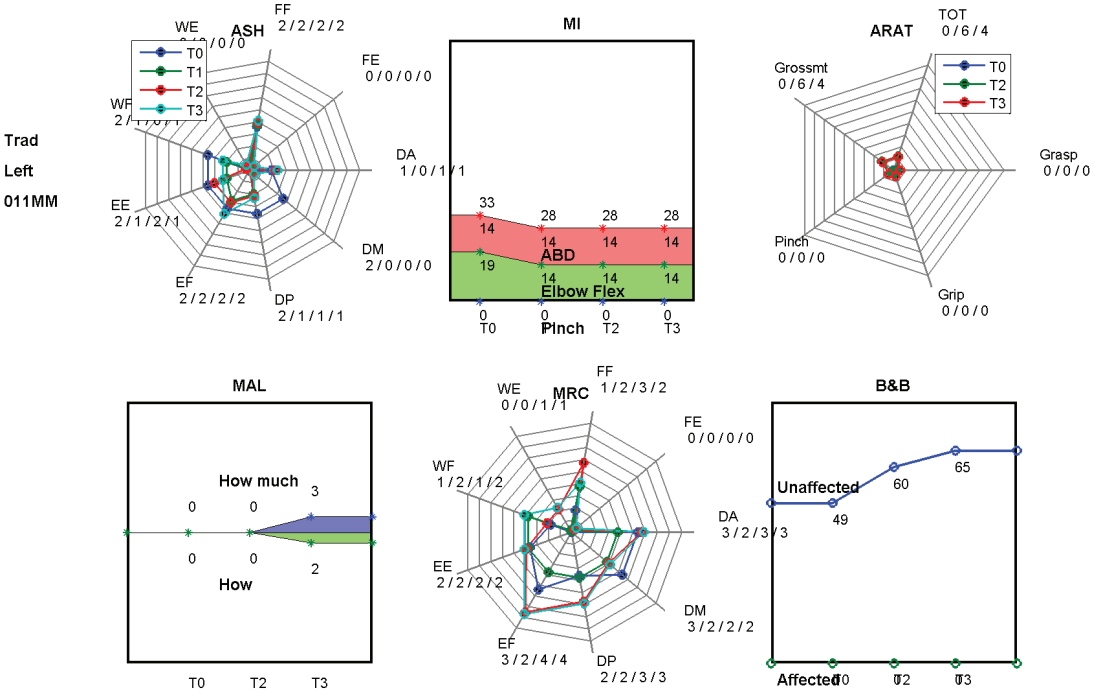
Patient 010FG, Conventional treatment

The affected limb is not dominant. Moderate spasticity on fingers flexors and on the elbow district . Flaccid fingers extensors, not recruitable on a volitional basis, translate into the inability to preshape and grasp.



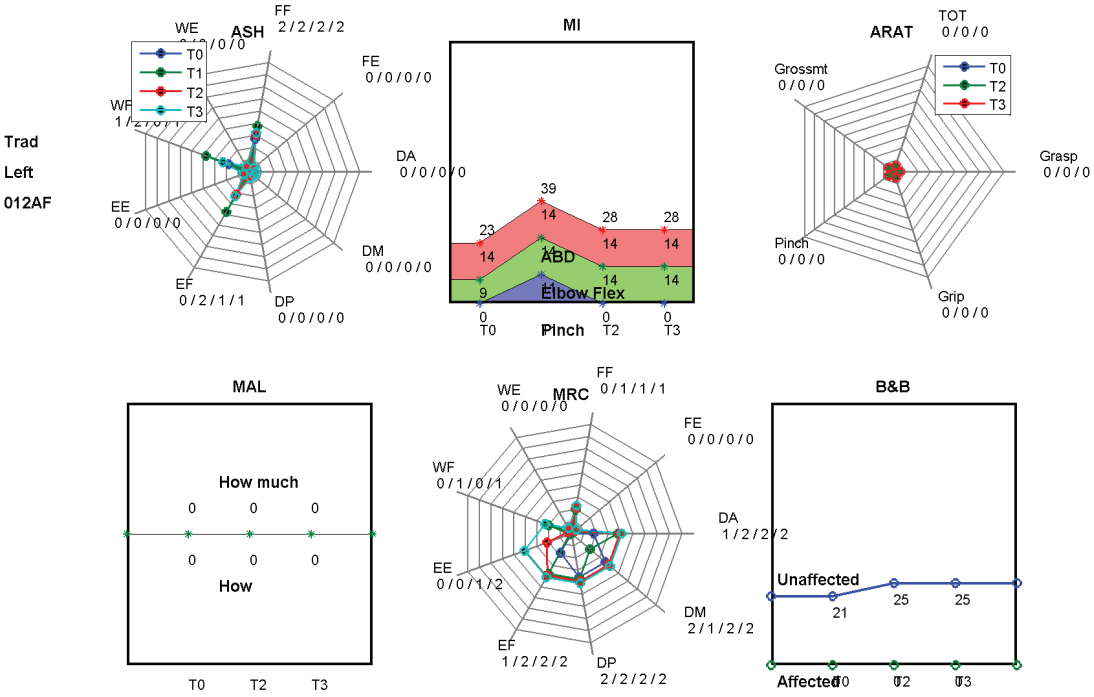
Patient 011MM, Conventional treatment

The affected limb is not dominant. Moderate spasticity on fingers flexors and on the proximal districts . Flaccid fingers extensors, not recruitable on a volitional basis, translate into the inability to preshape and grasp. No functional improvement visible.



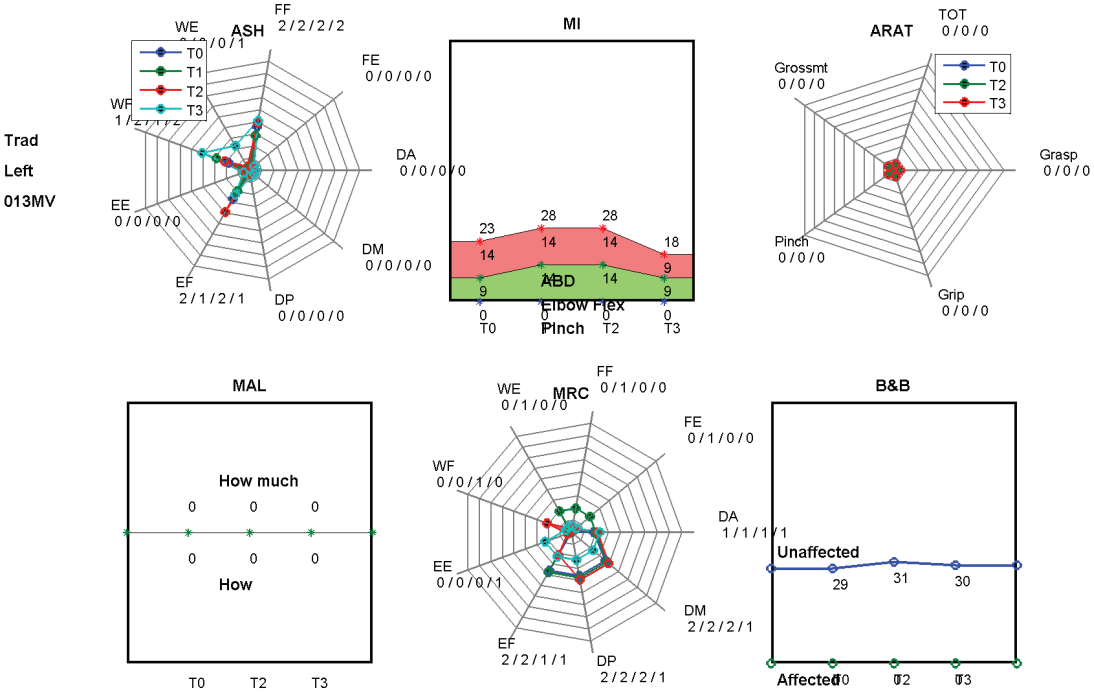
Patient 012AF, Conventional treatment

The affected limb is not dominant. Moderate spasticity on fingers flexors, wrist extensors, and elbow flexors reduced during treatment. The inability to recruit the fingers extensors and the limited grasp force do not provide functional grasp.



Patient 013MV, Conventional treatment

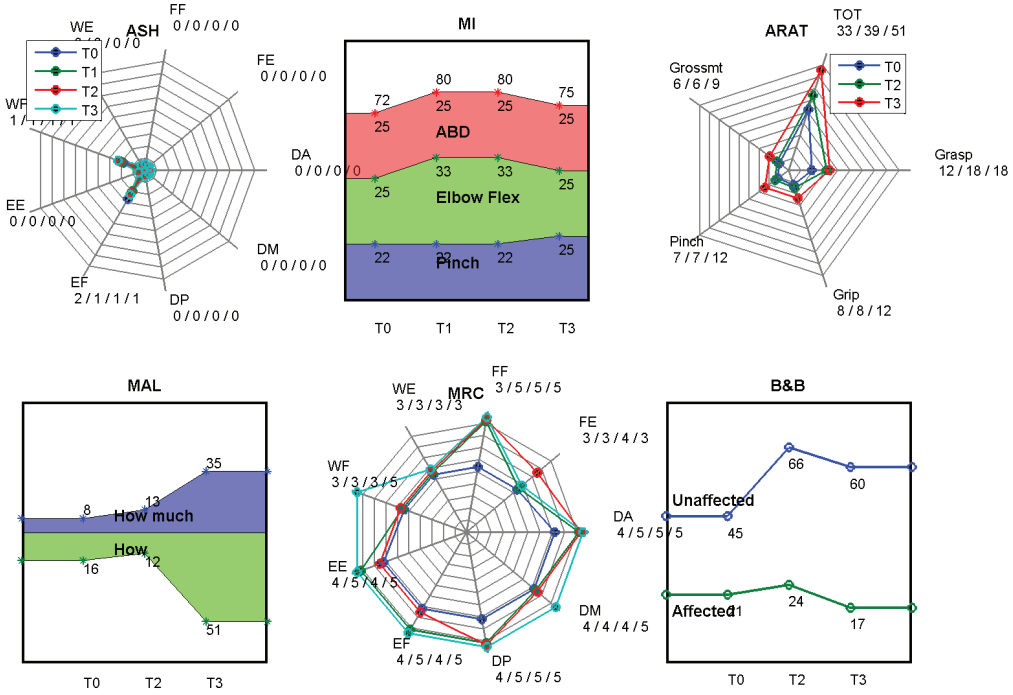
The affected limb is not dominant. Moderate spasticity on fingers flexors, wrist, and elbow flexors. Upper limb muscles globally recruitable but unable to efficiently overcome resistance or gravity. No retainable functional improvement.



Patient 014EA, Conventional treatment

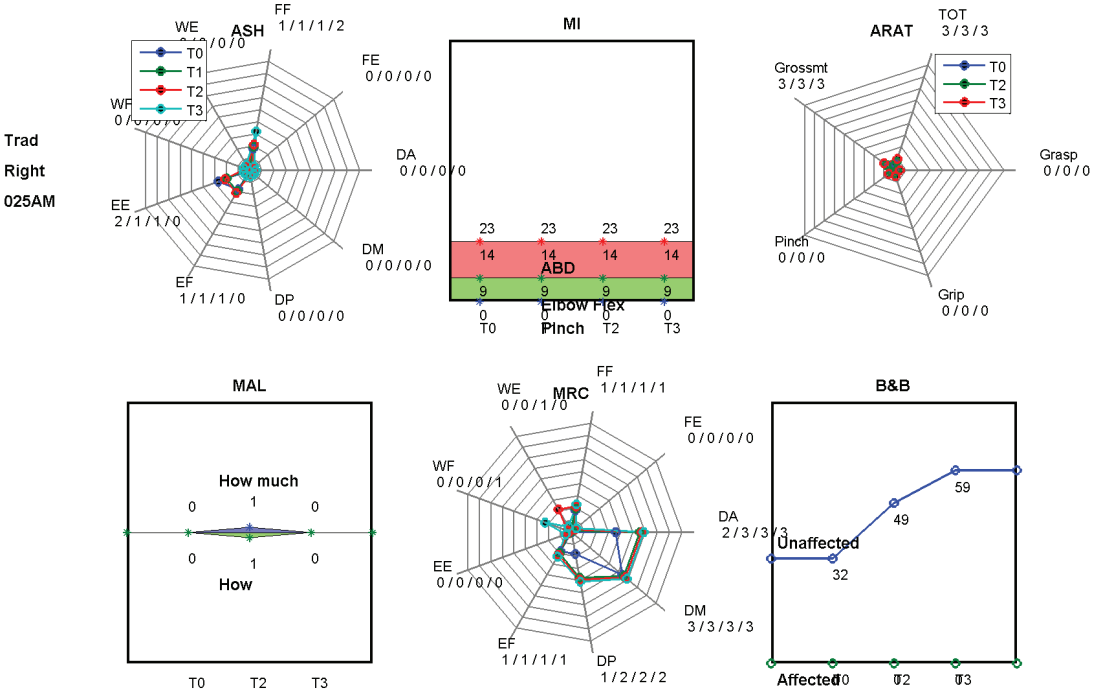
The affected limb is not dominant. No meaningful spasticity. Moderate force at inclusion, globally improved during treatment. Progressive improvement of reaching and grasp, with consistent motor and perceptive improvement at T3.

Trad
Left
014EA



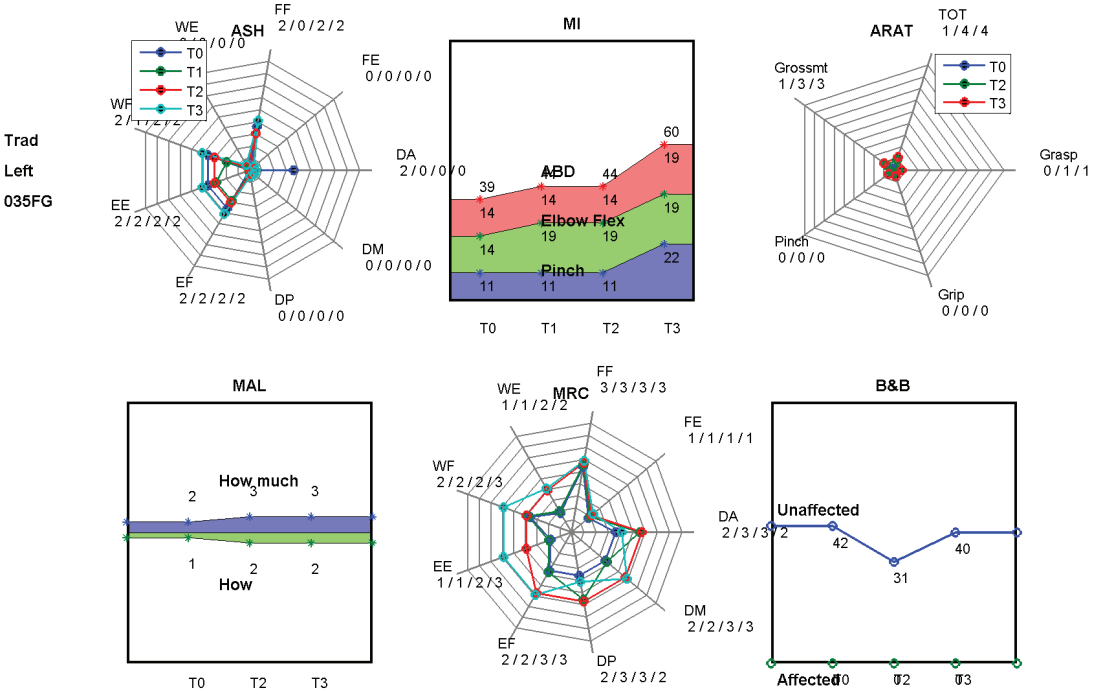
Patient 025AM, Conventional treatment

The affected limb is dominant. Limited spasticity on fingers flexors and at the elbow. Flaccid limb, with residual ability to recruit deltoids. No functional improvement.



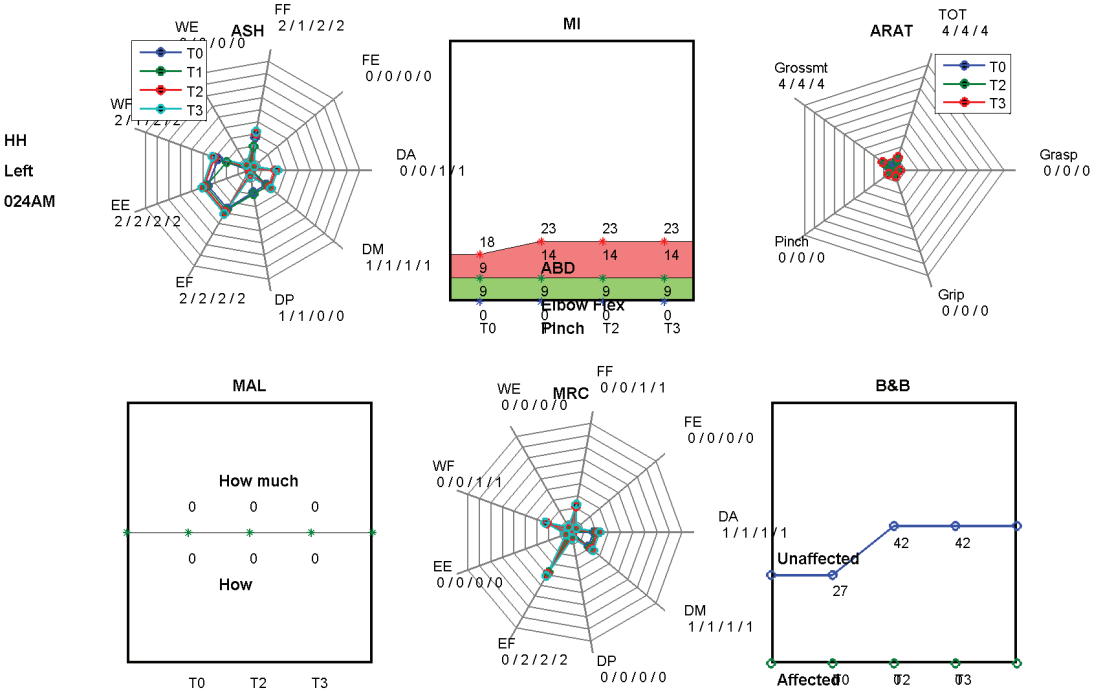
Patient 035FG, Conventional treatment

The affected limb is not dominant. Limited spasticity on elbow, wrist and fingers flexors. Flaccid limb, with residual ability to recruit deltoids. MI-Pinch apparently incoherent with ARAT, MRC, and B&B.



Patient 024AM, Helping Hand

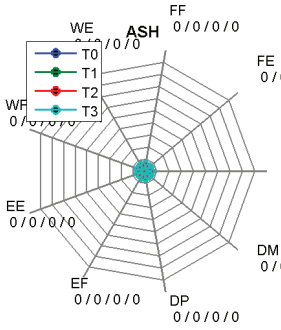
The affected limb is not dominant. Limited spasticity on elbow, wrist flexors and fingers flexors. No response of fingers extensors to the treatment. Limited abduction improvement during the hospitalization.

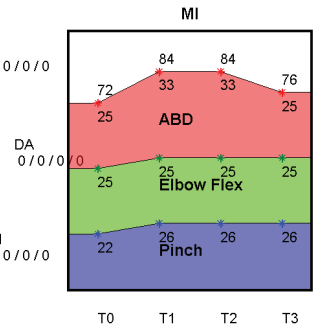


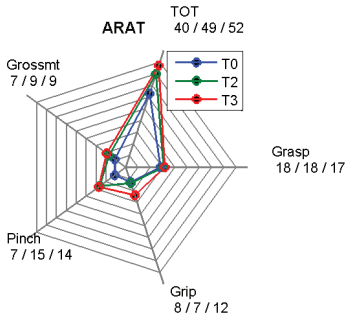
Patient 027OG, Helping Hand

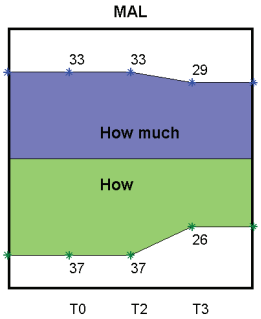
The affected limb is not dominant. Absence of spasticity. No response of fingers extensors to the treatment. Limited abduction improvement during the hospitalization. Good pinch and grip improvements during treatment, confirmed by a global improvement of muscles recruitment. Self-reported use and perception of limb stable during the treatment, but decreasing at follow up.

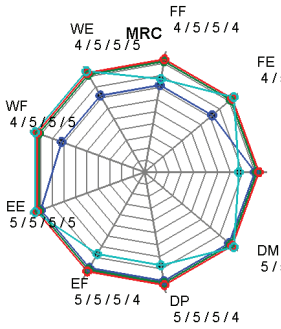
HH
Left
027OG

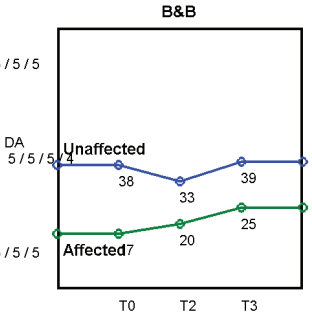






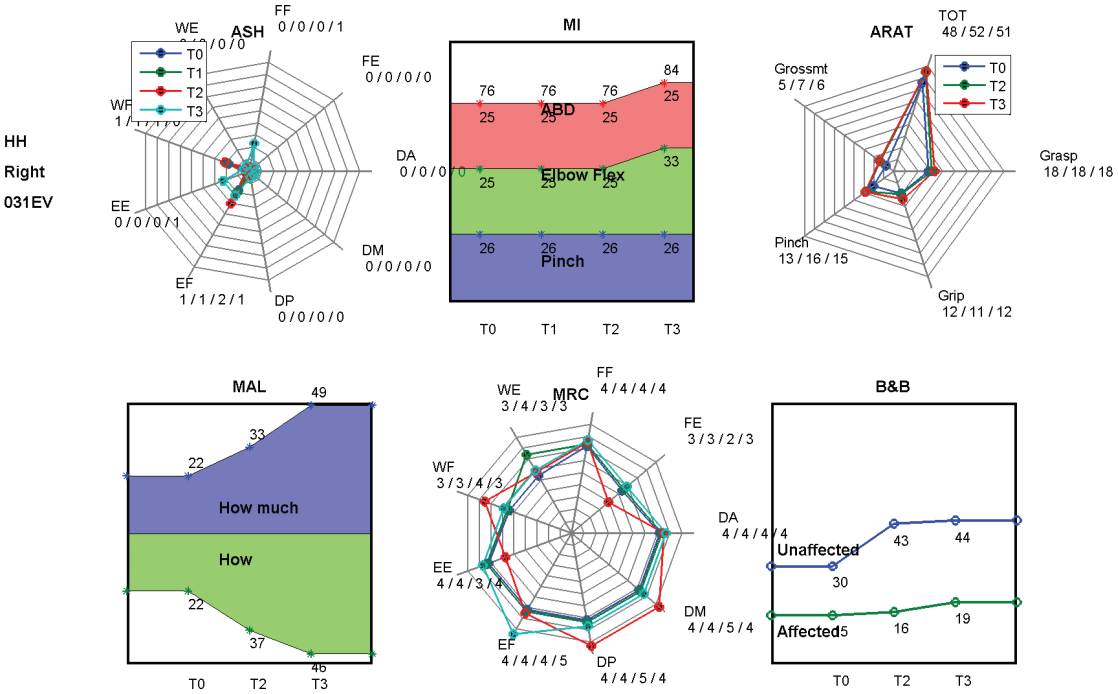






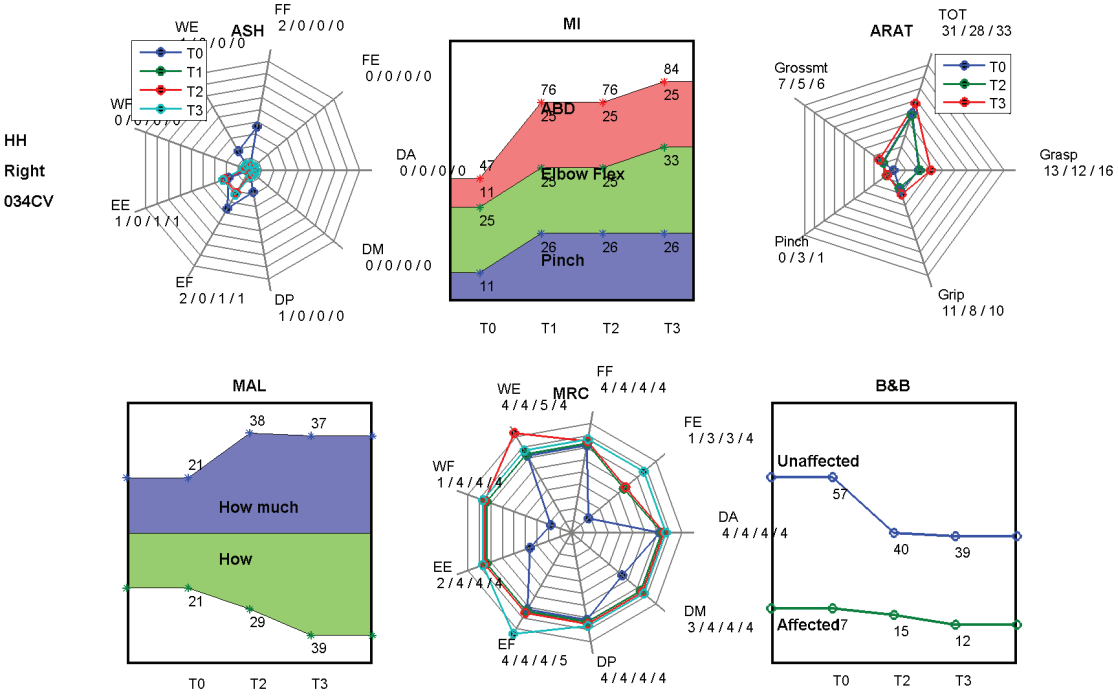
Patient 031EV, Helping Hand

The affected limb is dominant. Limited effects of distal spasticity. Moderate improvement in pinch, elbow flexion and in broad arm movements. Moderate recruitment of fingers extensors, stable during treatment. Progressive increase of self-reported perception of the limb and of the frequency of use.



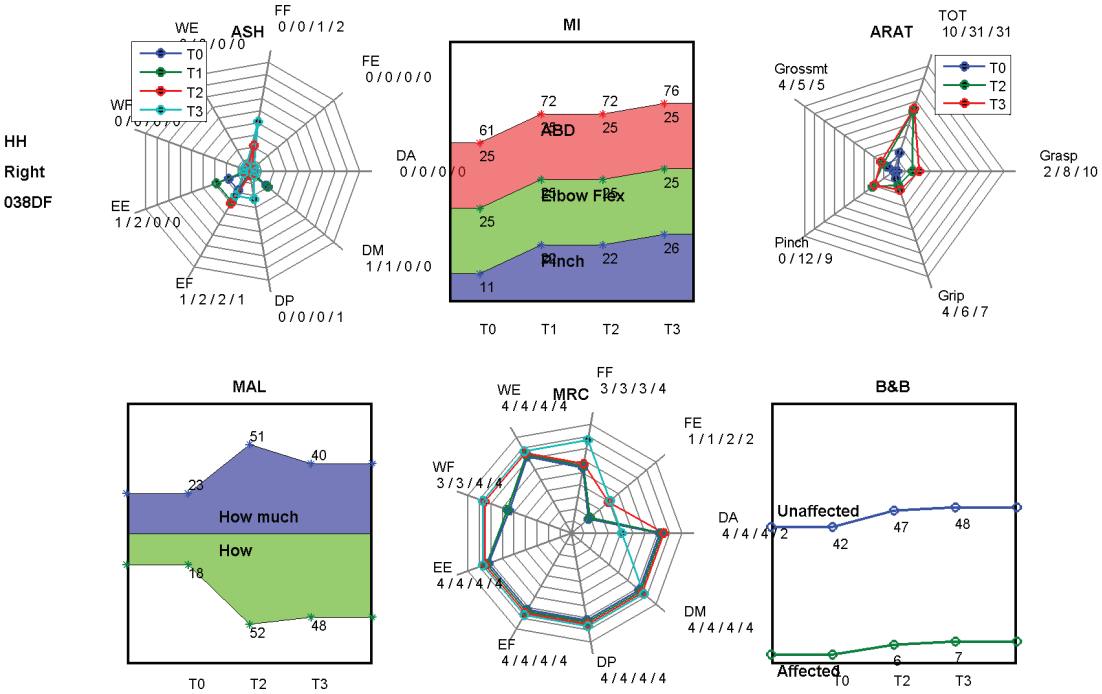
Patient 034CV, Helping Hand

The affected limb is dominant. Limited effects of distal spasticity, reduced during treatment. Consistent improvement in pinch, elbow flexion and in broad arm movements at T1; further improvement of elbow control at T3. ARAT and B&B pinch results apparently incoherent with MRC and MI fingers results. Progressive increase of self-reported perception of the limb and of the frequency of use.



Patient 038CV, Helping Hand

The affected limb is dominant. Limited effects of distal spasticity, reduced during treatment, but increasing at followup on fingers flexors. Consistent improvement in pinch at T1 and T2, and of grip and grasp during the whole treatment. Progressive increase of self-reported perception of the limb and of the frequency of use.



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J. Zajc, C. Wiesene, **A. Crema**, S. Ferrante, C. Bonizzi, T. Schauer, M. Russold. "Unified Control Interface for multiple Devices used for Upper Limb Rehabilitation after Stroke". IFESS Workshop 2016, Vienna

ANDREA CREMA

Chemin du Stand 19E, 1024 Ecublens – Switzerland

http://people.epfl.ch/andrea.crema

<andrea.crema@gmail.com>

Mobile: 00 41 76 7764612

EDUCATION

Ecole Polytechnique Fédérale de Lausanne, Switzerland
[Ph.D. in Electrical Engineering] **2017**
Dissertation: "Wearable System for Grasp Rehabilitation after stroke"

Politecnico di Milano, Italy
[M.Sc. in Biomedical Engineering] **2007**
Thesis: "A device for muscular fatigue assessment through volitional and NMES-induced EMG detection"

OTHER EDUCATION

Eidgenössische Technische Hochschule Zürich, Switzerland

- Model Predictive Control, Automatic Control Laboratory
- Statistical Learning Theory, Institute for Machine Learning
- Human Motion Analysis, Institute for Machine Learning

Imperial College London

- Training in Computational Methods for Neurorehabilitation, Winter School

Swiss Center for Technological Innovation (CTI) Training Program

- Venture Challenge

TEACHING EXPERIENCE

Ecole Polytechnique Fédérale de Lausanne, Switzerland
[Teaching Assistant] **2012-2014**
Fundamentals of Neuroengineering

WORKING EXPERIENCE

Eidgenössische Technische Hochschule Zürich, Switzerland
Scientific Assistant **2009-2011**
Automatic Control Laboratory, Neuroprosthetics Control Group

Istituto Auxologico Italiano, Milano, Italy
Clinical Researcher **2008**
Neurorehabilitation Clinical Unit

S.E.M. – Celestica Inc., Vimercate
Technical Developer **2007**
Test Fixture unit

PROJECTS

MUNDUS: "Multimodal Neuroprosthesis for Daily Upper Limb Support", FP7 ICT-4-7.2 - Accessible and Assistive ICT.

INCOGNITO: "Integrated cognitive, sensory, and motor rehabilitation of hand functions".

RETRAINER: "REaching and grasping Training based on Robotic hybrid AssIstance for Neurological patients: End users Real life evaluation", H2020 G.A. 644721

LINARM++: "Affordable and Advanced Linear Device for ARM rehabilitation"

NCCR ROBOTICS REHAND, NCCR NEUROPLASTICITY, CTI

LANGUAGES

[Italian – native language]
[English – C1]