Compensating Hand Function in Chronic Stroke Patients Through the Robotic Sixth Finger

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***Abstract*—A novel solution to compensate hand grasping abilities is proposed for chronic stroke patients. The goal is to provide the patients with a wearable robotic extra-finger that can be worn on the paretic forearm by means of an elastic band. The proposed prototype, the Robotic Sixth Finger, is a modular articulated device that can adapt its structure to the grasped object shape. The extra-finger and the paretic hand act like the two parts of a gripper cooperatively holding an object. We evaluated the feasibility of the approach with four chronic stroke patients performing a qualitative test, the Frenchay Arm Test. In this proof of concept study, the use of the Robotic Sixth Finger has increased the total score of the patients of 2 points in a 5 points scale. The subjects were able to perform the two grasping tasks included in the test that were not possible without the robotic extra-finger. Adding a robotic opposing finger is a very promising approach that can significantly improve the functional compensation of the chronic stroke patient during everyday life activities.**

***Index Terms*—Assistive devices, wearable robotics, hand grasping, chronic stroke patients.**

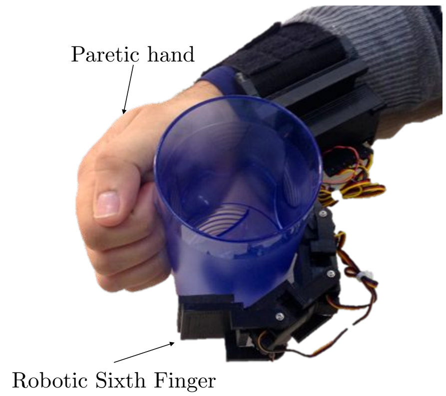

Fig. 1. The Robotic Sixth Finger concept. An additional robotic finger is worn by the patient on the forearm and is used in grasping tasks.

I. Introduction

STROKE is a leading cause of long-term disabilities, which are often associated with persistent impairment of an upper limb [?]. Findings of available prospective cohort studies indicate that only 5% to 20% of stroke patients with a paretic upper limb manage to fully recover six months after the stroke [?]. However, 33% to 66% show no recovery of upper limb functions after the same period [?], [?]. A key role in functional recovery of stroke patients with a paretic upper limb seems to be played by the improvements of the paretic hand [?], [?]. The recovery of hand functionality also contributes to a better independence in the Activity of Daily Living (ADL). In this respect, the rehabilitation projects, by which the rehabilitation team customized to the patient typologies and intensity of interventions, have been recently integrated with robotic-aided therapies. Such treatments represent a novel and promising approach in rehabilitation of the post-stroke paretic upper limb. Several robotic devices have been developed to provide safe and intensive rehabilitation to patients with mild to severe motor impairments after neurologic injury [?], [?]. The use of robotic devices in rehabilitation can provide high-intensity, repetitive, task-specific and interactive treatment of the impaired upper limb and can serve as an objective and reliable means of monitoring patient progress [?], [?], [?]. Focusing on the hand therapy, Lum et al. reviewed in [?] several works on robot-assisted approaches to motor neurorehabilitation highlighting the prototypes used in clinical tests. In [?], the authors presented a comprehensive review of hand exoskeleton technologies for rehabilitation and assistive engineering, from basic hand biomechanics to actuator technologies. However, the majority of these devices are poorly wearable, and designed to increase the functional recovery in the first months after stroke, when, in some cases, biological restoring and plastic reorganization of the central nervous system take place. To the best of our knowledge, few devices have been designed to actively compensate hand grasping function when patients are in a chronic state. In fact, when in the paretic upper limb the motor deficit is stabilized, the rehabilitation consists mainly in ergotherapy, which aims primarily in teaching compensatory strategies by using the non-paretic upper limb and by using commercial special aids [?]. This potentially increases the functional disparity between the impaired and the unaffected upper limb [?], [?].

This work focuses on the compensation of hand function in chronic stroke patients. Our idea is to augment the functional abilities of the patient with an additional robotic finger prosthe-

This work has received funding from the EU FP7/2007-2013 project No 601165 WEARHAP and EU Horizon 2020/2015, project No 688857 SOFTPRO.

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sis, the Robotic Sixth Finger, that is worn on the wrist/forearm of the patient, as in Fig. 1. Such robotic finger is used together with the paretic hand/arm to constrain the motion of the object to be grasped. The system acts like a two-finger gripper, where one finger is represented by the Robotic Sixth Finger while the other by the patient paretic limb. The Robotic Sixth Finger is designed to increase upper limb functionality and subsequent independence in ADL when no more functional motor improvements seem to be achievable by stroke patients. The area of impact may be identified by the "International Classification of Functioning, Disability and Health (ICF)" [?], domain "fine hand use (d 440)", "performance" in "Activity and Participation" component.

The design of the proposed assistive tool has been driven by robotic and rehabilitation teams, starting from patients requirements in improving upper limb functionality, when the motor deficit is unchangeable. This need is particularly felt by young and social-active patients, for achieving better independence, and for continuing rehabilitation in a compensatory perspective. A preliminary version of the device together with preliminary usability tests with healthy subjects have been presented in [?]. In [?], we have introduced an object-based mapping algorithm to control the motion of the Robotic Sixth Finger. The main feature of the mapping was to create a synergy between the human hand posture and the robotic extra-limb configuration. Such approach required to track the human hand motion to generate suitable trajectories for the device. Thus, it could not be exploited in post-stroke patients due to the very limited residual mobility of the hand. One of the challenging questions for the Robotic Sixth Finger as tool for stroke patients is how to control its motion.

In this work, we propose a novel approach for the user interface which is explicitly designed for post-stroke patients. The user can control the finger flexion/extension through an electromyographic (EMG) signal captured by surface electrodes placed on the user's frontalis muscle. We have also redesigned the device to be used with this controller. With respect to the device presented in [?], the Robotic Sixth Finger presented in this paper can autonomously adapt its configuration to the shape of the grasped object. This is possible using an admittance control at the joint's level that will be presented in Section II.

To test the usability of the proposed prosthesis for grasp compensation, we set up a pilot experiment involving four subjects in a chronic state. The subjects worn the Robotic Sixth Finger and were asked to perform the tasks comprised in the Frenchay Arm Test [?]. This test included different manipulation tasks that patients were not able to perform, but were successfully accomplished with the aid of the robotic extra-finger.

The rest of the paper is organized as follows. In Section II the Robotic Sixth Finger prototype together with the adopted control strategies are described in details. Section III presents the qualitative test performed and the achieved results. Finally, Section IV reports a discussion on the usability and limitation of the proposed device, while in Section V conclusion and future work are outlined.

TABLE I
THE ROBOTIC SIXTH FINGER TECHNICAL DETAILS

Module dimension	$42 \times 33 \times 20$ mm
EMG board dimension	$67 \times 55 \times 31$ mm
Support base dimension	$78 \times 24 \times 5$ mm
Module weight	8 g
EMG board weight	98 g
Support base weight	18 g
Max torque per motor	0.15 Nm
Stall current	440 mA
Velocity of one module	0.2 rad/s
EMG Board power supplies	5 V, 3.3 V
Device external batteries	7.5 V, 2.2 Ah
Continuous operating time	3.5 h (@stall torque)
Max device payload	610 g

II. THE ROBOTIC SIXTH FINGER

A. Device structure and low-level control

The Robotic Sixth Finger is composed by four one-DoF modules. Each module consists of a servomotor (HS-53 Microservo, HiTech, Republic of Korea), a 3D printed plastic part (acrylonitrile butadiene styrene, ABSPlus, Stratasys, USA) and a soft rubber part used to increase the friction at the contact area. Modules are equipped with a Force Sensing Resistor (FSR) (408, Interlink Electronics Inc., USA) placed under the rubber part and able to measure the normal component of the force applied on the module surface. The modules are connected so that one extremity of each module is rigidly coupled with the shaft of the motor through screws, while the other has a pin joint acting as revolute joint. The CAD exploded view of the modular finger and the real prototype are shown in Fig. 2. Technical details of the device are reported in Table I.

The module connection results in a pitch-pitch configuration, which replicates the flexion/extension motion of the human finger. In [?] also abduction/adduction motion was obtained by means of a dedicated module placed on the finger base. In this work this possibility will not be considered. The modular part of the finger is connected to a support base which contains also the electronic housing. An elastic band allows to easily wear the device on the forearm. An external battery is used to provide power to all the circuits. All the electronics is enclosed in a 3D printed box attached to the support base to preserve the extra-finger wearability. The module actuators are PWM controlled servomotors. The PWM signals are generated by an Arduino Nano board [?].

The motion of the Robotic Sixth Finger is controlled by the user through the EMG interface, as it will be described in Section II-B. Two possible flexion trajectories can be selected in order to grasp objects with different sizes and shapes. The two possible arising grasps have been defined as precision and power grasps, see Fig 3. In precision grasps, the target is

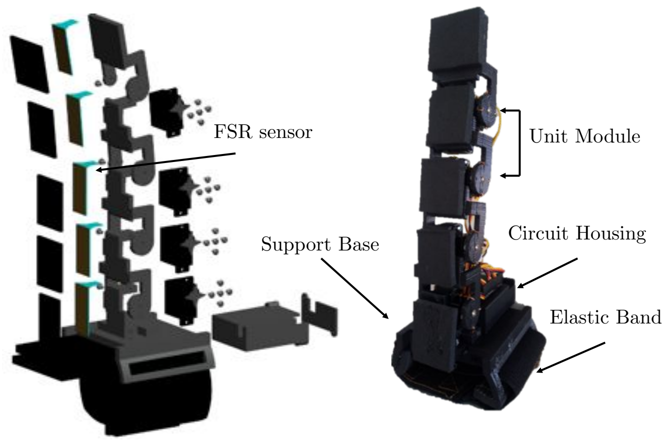

Fig. 2. The Robotic Sixth Finger. On the left the CAD exploded view, while on the right the prototype used in the experiments.

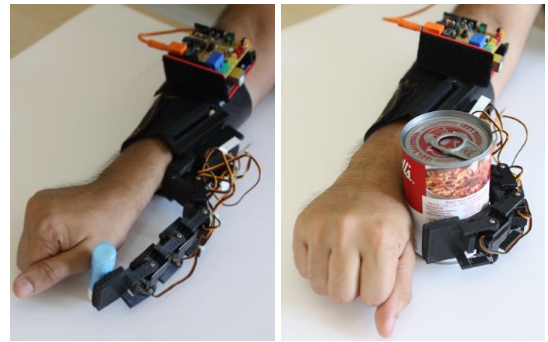

Fig. 3. The two grasp modalities of the robotic extra-finger. On the left, a precision grasp is obtained between the fingertip of the device and the radial aspect of the thenar eminence. On the right, a power grasp is obtained between the whole device and the user wrist.

to hold the object between the paretic limb and the device fingertip pad. To this aim, the fingertip is kept parallel to the paretic limb during flexion motion. In power grasps, each module flexes with a fixed step size in order to wrap the finger around the object. The patient selects with the EMG interface the type of grasp according to the object size or the task to be executed. When the grasping phase is started, the extra-finger flexes according to the type of grasp selected. We consider the completely extended finger as the starting position to enlarge the set of possible graspable objects. The finger closing velocity is a priori set by using Arduino servo library. We set the velocity to 0.2 rad/s to let the patient reorient the device during flexion, if needed. The force sensors on the modules are used to detect contacts with the grasped object. We simplify the non-linear relation between the voltage variation on the sensors and the equivalent applied force considering a piecewise-linear function. Vernier dynamometer (Vernier, USA) was used to calibrate and verify the output of the sensors. A module is in contact with the object when the force measured with the FSR reaches a predefined threshold.

In precision grasps, the contact is expected to occur between the object and the fingertip module. In power grasps, in order to obtain suitable contact points, we set different closing priorities according to the position of the module in the finger. If the fingertip module comes in contact first, the remaining modules stop. If another module comes in contact first, modules below to it stop, while the module above keeps moving.

Once the grasping phase is completed, it is necessary to control the force exerted by the device on the object to guarantee the stability of the grasp. The forces contributing to the grasp stability are the result of the action of the paretic limb together with the action of the Robotic Sixth Finger. We designed a controller that is able to autonomously regulate the force exerted by the extra-finger according to that required by the user. When the patient wishes to tight the grasp, he or she pushes the object toward the device with his or her hand/wrist. This action results in a force variation measured by the FSR placed in each module and in a displacement of the servomotors from the position reached at the end of the grasping phase. We introduce a parameter k_d to regulate the position error of the servomotor proportional to force observed by the FSR. We set a linear relation between the force variation measured by the FSR placed in each module and the value of k_d. In particular, the range of forces read by the force sensors (0 N - 6 N) was linearly mapped in the range $0.3 - 3$ of parameter k_d. Then, the possible angle displacement Δq is computed as

$$\Delta q = k_d(q_{des} - q_m),$$

where q_m is the actual position of the servomotor while q_{des} is its desired position. We modified the servomotor in order to measure its actual position by accessing the internal encoder measurements. The only servomotor parameter that can be set is its desired position q_{des}. At time instant t the desired position for the $i-$th servomotor is computed as

$$q_{des,i}(t) = q_{m,i}(t-1) + \Delta q_i(t-1).$$

In presence of a rigid grasped object, the measured positions of the extra-finger joints do not change due to the object constraints. So that, changing the desired position of the servomotors we can control the force exerted by the device onto the object.

The resulting behavior is similar to an admittance control of the motor. Generally, in admittance control framework, the compliant (or stiff) behavior of the joints is achieved by virtue of the control, differently from what happen in mechanical systems with a prevalent dynamics of elastic type [**?**]. Varying the parameter k_d the module appear to be more or less stiff with respect to an external applied force.

We set priorities between modules for the simulated compliance variation, similarly to what we did for the grasping procedure. So that, if, for instance, only the fingertip module is in contact with the object, all the other modules accordingly change their stiffness. This solution allows to control the stiffness of modules that are not in contact with the object. When the patient wishes to release the grasped object, he or she needs to lower the force exerted by his or her hand/wrist on the object so to decrease the value of k_d. Eventually, using the EMG interface, the robotic finger can be placed back to its home position by following a predefined trajectory.

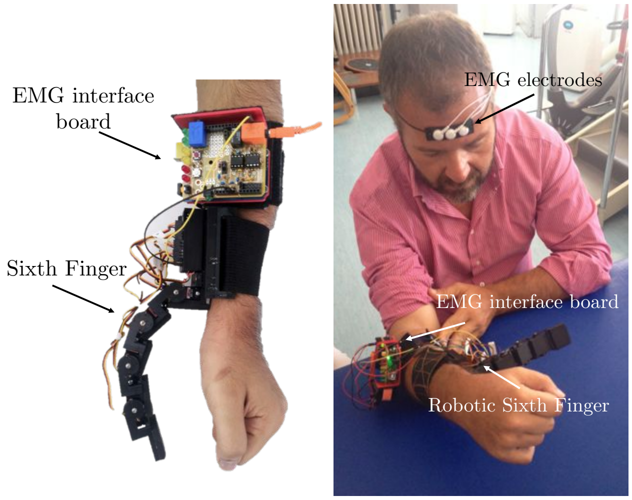

Fig. 4. On the left, the EMG board used. On the right the EMG electrodes placed on the patient head.

Note that if the patient is not able to exert force on the object, due to his or her motor deficit or to the position of the Robotic Sixth Finger on the forearm, the grasp tightness can be controlled through the EMG interface. The patient can activate the finger flexion, wait for finger shaping and then activate again the flexion to tight the grasp. This solution requires a higher cognitive effort from the patient that has to estimate which is the sufficient grasp force necessary to hold the object. When possible, admittance control is preferable also in order to optimize battery consumption.

B. EMG user interface

The interface with the user must be designed so to appear intuitive and simple. As a preliminary solution, the patient could activate the robotic extra-finger flexion/extension through a push button embedded on a ring worn on the healthy hand [**?**], [**?**]. Although this solution dramatically simplified the interaction with the device, wearing a ring on the contralateral hand and operating the switch could prevent the healthy hand from doing other tasks. For example, when performing bimanual tasks or when grasping an object, the subject had to be careful not to activate the switch unintentionally. For this reason, we have developed an EMG interface which maintains the principle of simplicity of the switch, but that leaves the patient free to use his or her healthy hand.

Thanks to the proposed EMG interface, patients can consciously control the Robotic Sixth Finger by contracting the frontalis muscle on their forehead. Bipolar EMG electrodes are positioned on the frontalis muscle, since its functionality, due to a bilateral cortical representation, is always spared in case of a hemispherical stroke. Activation of the muscle is achieved by moving the eyebrows upward. Functionality of muscles of the paretic limb is usually sub-optimal, hence scarcely reliable for EMG control. Moreover, using the paretic limb for a dual task (i.e., EMG control and grasping) can be too demanding for most of the patients. In the proposed system, patients worn a headband where surface electrodes are placed, see the right side of Fig. 4. The electrical activity measured by the electrodes (one ground and two recording electrodes for true differential recordings) is acquired through an embedded system (Muscle SpikerShield, Backyard Brains, Ann Arbor, MI - USA) that can be worn on the patient's arm thanks to an elastic band, see the left side of Fig. 4. This EMG interface system for bio-signals acquisition is designed to be used with dry electrodes and no skin preparation. The board includes a gain knob to tune the amplification of the muscle recording depending on the size and type of muscle. This feature has been used to filter involuntary muscle contractions. The EMG interface board consists of a signal conditioning board and an Arduino Uno that processes the signals. Dimensions and weight of the board are reported in Table I. We have designed the processing unit in order to obtain a trigger signal if the recorded EMG signals exceed a pre-set threshold.

TABLE II
COMMANDS DETECTED THROUGH THE EMG INTERFACE

EMG signal	**Associated action**
one contraction	move/stop
two contractions	change direction
three contractions	change grasp mode

The EMG interface is thus able to detect if the frontalis muscle of the patient is voluntary contracted. Upon this, we have implemented a high level control strategy that is summarized in Table II. With one muscle contraction the patient controls the motion/stop of the finger. When the finger is stopped, two contractions in a time window of 1.5 s switch the motion direction from flexion to extension and viceversa. Finally, when the finger is in its starting position (completely open), the user can change the finger flexion trajectory (power or precision grasp) making three contraction in a time window of 2 s.

C. Device positioning in the patient paretic limb

The position of Robotic Sixth Finger on the patient forearm is an important aspect to take into account. Before deciding where to wear the device, it is necessary to study both the residual mobility of the patient and the ADL we want to accomplish. The Robotic Sixth Finger can be placed in the distal part of the forearm (near, or on the wrist) since the grasp is obtained by opposing the device to the paretic hand. However, the distal positioning of the Robotic Sixth Finger may fail when the post-stroke motor deficit is so advanced that a pathological synergism in flexion has taken place. In this case, the wrist becomes too much flexed and fingers are too much closed towards the palm thus not allowing a successful grasping. When this pathological condition occurs, the Robotic Sixth Finger may be positioned more proximal at the forearm, in a way that the grasp can be achieved by the extra-finger opposition to the radial aspect of the thenar eminence or to the anatomical snuff box. An example of two possible positions for the Robotic Sixth Finger are reported in Fig. 5.

(a) The grasp is obtained at the wrist level.

(b) The grasp is obtained at the hand level.

Fig. 5. The robotic extra finger in two possible configurations on the forearm.

This flexibility in the positioning is achieved thanks to the modularity of the structure and the flexibility of fixing support. Modularity allows to regulate the size and dexterity of the finger according to the position on the forearm and according to the limb characteristic of each patient. The regulation is obtained adding/removing modules on/from the device. The support base of the finger can be translated or rotated along the arm to place the finger on a suitable position and orientation. An elastic band and rubber spacers are used to increase the grip and comfort, while reducing the fatigue during continuous use of the finger.

III. Pilot experiment

In the current proof of concept study, we tested with four subjects (three male, one female, age $48-60$) how the Robotic Sixth Finger can compensate for grasping capability. The aim was to verify the potential of the approach and to understand how rapidly the subjects can successfully interact with the wearable device. In this direction, we performed a fully ecological qualitative test, the Frenchay Arm Test [**?**]. The test consisted of five pass/fail tasks to be executed in less then three minutes. The patient scored 1 for each of the successfully completed task, while he or she scored 0 in case of fail. The subject sat at a table with his hands in his lap, and each task started from this position. He or she was then asked to use the affected arm/hand to:

1) *Task_1* Stabilize a ruler, while drawing a line with a pencil held in the other hand. To pass, the ruler must be held firmly (see Fig. 6).
2) *Task_2* Grasp a cylinder (12 mm diameter, 50 mm long), set on its side approximately 150 mm from the table edge, lift it about 300 mm and replace without dropping (see Fig. 7).
3) *Task_3* Pick up a glass, half full of water positioned about 150 to 300 mm from the edge of the table, drink some water and replace without spilling[1] (see Fig. 8).
4) *Task_4* Remove and replace a sprung clothes peg from a 10 mm diameter dowel, 150 mm long set in a 100 mm base, 150 to 300 mm from table edge. Not to drop peg or knock dowel over (see Fig. 9).
5) *Task_5* Comb hair (or imitate); must comb across top, down the back and down each side of head (see Fig. 10).

When compared with other upper limb assessments, the Frenchay arm test has shown good reliability in measuring functional changes in stroke patients [**?**]. The score ranges from 0 (no one item performed) to 5 (all the items performed).

All the subjects taking part to the experiment have been affected by stroke more than two years before the test. The rehabilitation team has declared that no more functional improvements are achievable with respect to the gained upper limb motor performance. The Robotic Sixth Finger can be used by subjects showing a residual mobility of the arm. For being included in the pilot experiment, patients had to score ≤ 2 when their motor function was tested with the National Institute of Health Stroke Scale (NIHSS) [**?**], item 5 "paretic arm". Moreover, the patients showed the following characteristics: 1) normal consciousness (NIHSS, item1a, 1b, 1c = 0), absence of conjugate eyes deviation (NIHSS, item $2=0$), absence of complete hemianopia (NIHSS, item $3 \leq 1$), absence of ataxia (NIHSS, item $7=0$), absence of completely sensory loss (NIHSS, item $8 \leq 1$), absence of aphasia (NIHSS, item $9=0$), absence of profound extinction and inattention (NIHSS, item $11 \leq 1$). Patients received the Robotic Sixth Finger in the paretic hand, the left hand for two subjects and the right one for the other two. Thanks to the device design, the same prototype can be worn either on the right or on the left arm. Written informed consent was obtained from all participants. The procedures were in accordance with the Declaration of Helsinki.

The rehabilitation team assisted the subjects during a training phase that lasted about one hour. During this phase, the optimal position of the device on the arm according to the patient motor deficit was evaluated. The patients also tried the EMG interface in order to become confident with the extra-finger high-level control. Two patients tried the extra-finger for the first time. After the training, the subjects had three minutes to perform the Frenchay Arm Test. All the subjects performed the test twice, one with and one without the device. The Robotic Sixth Finger was placed on the paretic limb, while it was activated using the EMG interface. In Fig. 6, 7, 8, 9 and 10 snapshots of the execution of the five tasks are reported, respectively. The results of the test are shown in Table III for the four patients. All the subjects selected a precision grasp for the cylinder, while a power grasp was used for the glass. Task 2

[1]Note that for safety reasons we did not use water in presence of electronic components.

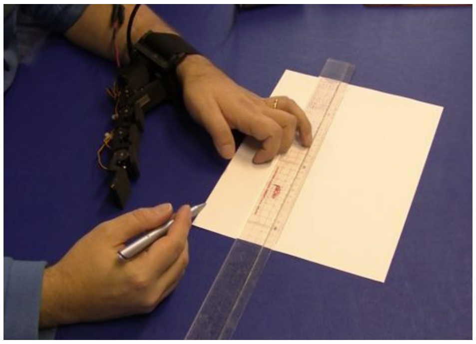

Fig. 6. Task 1: stabilize a ruler, while drawing a line with a pencil held in the other hand. Note that the Robotic Sixth Finger does not interfere with the task execution.

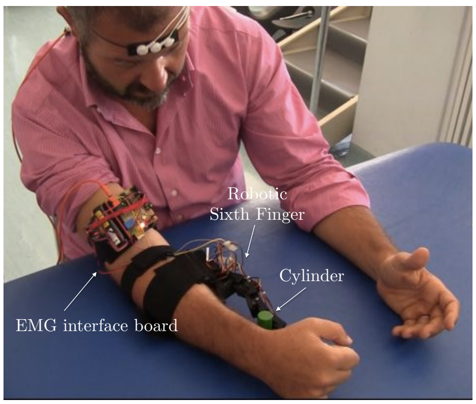

Fig. 7. Task 2: grasp a cylinder (12 mm diameter, 50 mm long). A precision grasp is used.

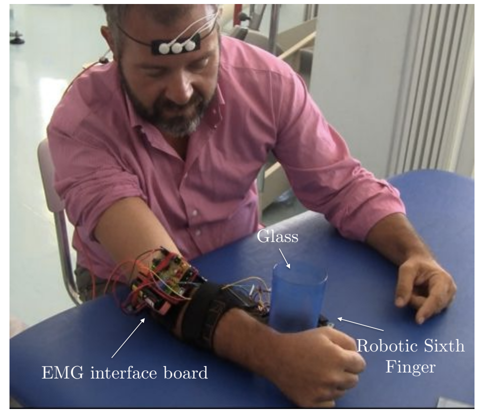

Fig. 8. Task 3: pick up a glass and drink. A power grasp strategy is used to achieve the grasp.

Fig. 9. Task 4: remove and replace a sprung clothes peg from a dowel.

and Task 3 were successfully accomplished by all the patients with the help of the extra-finger. Task 4 and Task 5 involved the grasp of an object and a rather complex manipulation part. Although the patient were able both to grasp the sprung and the comb, the poor residual mobility of the arm caused a failure in the task fulfillment. Task 1 was executed both with and without the device. This means that the device did not interfere with the residual mobility of the paretic limb thanks to its high wearability and portability.

After the Frenchay Arm Test, the patients were asked to fill a questionnaire in order to evaluate the subjective feelings on the ease of use of the device. Results are reported in Table IV. Moreover, the two patients that already tried a previous version of the device with a switch-ring interface declared to prefer the new EMG interface.

IV. Discussion

The exploitation of the Robotic Sixth Finger in post-stroke compensation of hand functions is at an early stage. The device has been built upon the ideas of wearability, ergonomics, safety, ease of use and comfort, while increasing the upper limb functionality of post-stroke patients. Most of the devices designed for hand rehabilitation share the aim of assisting finger motion during an assigned training. Many algorithms for human-robot interaction can be programmed also into simple robotic devices. Lum et al. have classified in [**?**] the main features of different control strategies available in literature. Although our device is not designed for hand rehabilitation but for compensating hand function in grasping tasks, some of the proposed strategies has been taken as guidelines for the design and interface of our device. In particular, we considered: i) adaptation to patient performance; ii) prevention of fatigue and frustration and iii) production of more physiologically accurate movement patterns. The adaptation to the patient performance is obtained considering the versatility of the device to be worn in different parts along the forearm according to patient capability to oppose to the device motion. Moreover, the control of the compliance of the device allows the user to select the tightness of the grasp. To prevent fatigue and frustration on the patient, the motion of the Robotic Sixth Finger is not mechanically coupled with the human limbs. The patients' muscle are not constrained to follow any particular trajectory imposed by the extra-finger. Patients only need to be able to place their forearm in a suitable position, so to let the object be in the workspace of the robotic device. Finally, in case of traditional exoskeletons, precautions need to be carried out

TABLE III
RESULTS OF THE FRENCHAY ARM TEST FOR THE FOUR PATIENTS WITH AND WITHOUT USING THE ROBOTIC SIXTH FINGER (RSF)

Frenchay Arm Test	Patient 1		Patient 2		Patient 3		Patient 4	
	with RSF	without RSF	with RSF	without RSF	with RSF	without RSF	with RSF	without RSF
Stabilize a ruler	1	1	1	1	1	1	1	1
Grasp a cylinder	1	0	1	0	1	0	1	0
Pick up a glass	1	0	1	0	1	0	1	0
Remove a sprung	0	0	0	0	0	0	0	0
Comb hair	0	0	0	0	0	0	0	0

Fig. 10. Task 5: comb hair or imitate.

TABLE IV
QUESTIONNAIRE AND RELATIVE MARKS. THE MARK RANGES FROM "0 = TOTALLY DISAGREE" TO "7 = TOTALLY AGREE". MEAN AND STANDARD DEVIATION (MEAN (STD)) ARE REPORTED.

Question	**Answer**
The EMG interface results intuitive easy to use.	6.75(0.5)
I did not need any particular training to start using the interface.	6(0.81)
I felt confident using the system.	6.25(0.5)
I think that I would need the support of a technical person to be able to use this system every day.	3.25(1.71)
The system was easy to use.	6.25(0.5)
I would imagine that most people would quickly learn how to use this system.	7(0)

in terms of kinematics design and during their use to avoid any abnormal posture that can produce any physiologically inaccurate movement patterns. The use of the extra-finger results to be safer in this regard.

All the patients were able to improve their performance in tasks of everyday activities without the need of any specific training period, thus suggesting that the successful use of the Robotic Sixth Finger is rather intuitive, at least for these very basic activities. This aspect is also confirmed by the answer to the questionnaire in Table IV. The ease of use represents an important point, taking into consideration that a proportion of stroke patients may also complain of some cognitive deficits, possibly limiting their compliance during a demanding learning phase. Now, the challenge is to identify and better understand the different requirements coming from the different application scenarios.

The pathological synergism in flexion is characterized by the arm and the forearm intrarotated, adducted and flexed at their main joints, as well as fingers closed. Patients may show a deficit not only in grasping the object and keeping it, but also in releasing it. This motor pattern is mainly due to two factors: weakness of extensors muscles and hypertonia of flexors. The patients that have tried the Robotic Sixth Finger experienced a new ability in releasing the utilized objects without the aid of the healthy hand, as well as the ability to grasp an object without the help of the contralateral limb.

Compensation process by using extra-finger motivates the patient to use her or his muscles to coordinate with the device for the completion of the task. Thus, the extra-finger acts like an active and motivational assistive device. This approach encourages the patients to effectively use their potential and residual abilities instead of being fully dependent on the motion of robotic devices like passive assistive devices [**?**]. In this view, the use of the Robotic Sixth Finger shares conceptual similarities with the constraint-induced movement therapy (CIMT), a rehabilitative approach characterized by the restraint of the healthy upper limb accompanied by the shaping and repetitive task-oriented training of more affected upper extremity, with the purposes of overcoming the learned nonuse phenomenon of the hemiplegic upper extremity [**?**]. However, the obvious advantage of the Robotic Sixth Finger is that there is no need to immobilize or restraint the healthy limb to favor the (re)use of the paretic hand.

One of the limitation of this approach is the fine manipulation of objects, which however was out of the main purposes of the use of the prototype described here. In fact, the extra-finger and patient limb work jointly as the two parts of a one DoF gripper. Although grasping objects with the paretic limb, without any specific training phase, could already represent a great improvement in everyday life of chronic stroke patients, we are investigating whether the Robotic Sixth Finger can be used also in more complex manipulation tasks.

Another important aspect to take into account is the great variability among patients' capabilities, in terms of type of post-stroke sensorimotor deficit as well as of individual capability in reaching the object to be grasped and in shaping the hand around that. Each patient should be provided with a customized solution in terms of position of the extra-finger along the forearm and in terms of number of modules. We are currently working on a classification procedure to better couple each patient to the best Robotic Sixth Finger setup.

V. Conclusion and perspectives

The latter phase of post-stroke rehabilitation is identified as the "compensation phase". In this phase, functional recovery is based on the learning of newly acquired motor strategies to compensate the neurological deficit. These strategies may sometimes be neither ergonomic nor ecological, or may even increase pathological motor patterns, usually by worsening tonic flexion at the forearm of the paretic limb. In this paper, we presented a robotic compensatory tool that can be used by chronic stroke patients to regain grasping capabilities at the paretic hand. The Robotic Sixth Finger is the result of the synergistic effort of engineers, clinicians and a small group of patients wishing to improve their upper limb functionality. We expect to increase patients' performances, with a focus on objects manipulation, thereby improving their independence in ADL, and simultaneously decreasing erroneous compensatory motor strategies for solving everyday tasks [**?**].

The proposed control of the robotic finger dramatically simplifies the human robot interaction since only the activation of a grasping procedure through the EMG interface is needed. We are currently working on a wireless version of the EMG interface and also exploring other possible solutions based on the reading of bio-signals such as brain electroencephalographic activity driving voluntary actions. We are also investigating the possibility of using our robotic extra-finger in patients affected by other neurological diseases possibly affecting hand grasping, such as Multiple Sclerosis, Amyotrophic Lateral Sclerosis and paresis due to cervical spinal cord lesions.

Basing on the preliminary results presented, the Robotic Sixth Finger might be tested also in the first months after stroke, as an augmentative device, during the intensive rehabilitation period. The early post-stroke performance success in some tasks of everyday life activity (as grasp a cylinder or pick up a glass of water), otherwise not possible without the Robotic Sixth Finger according to current results, might recruit undisclosed internal motivational patients' resources and help to trigger plastic adapting changes at brain level, both favoring functional recovery. In [**?**], it is shown that the presence (or absence) of the voluntary shoulder abduction and fingers extension in the first days after stroke, are the two key factors for favorable or unfavorable prognosis of upper limb functional recovery at six months post stroke. Basing on the presence or absence of one of these two factors, the Robotic Sixth Finger might be used as an augmented-rehabilitative device for improving task-specific activities with the upper limb when voluntary shoulder movements are present, and, when fingers may be voluntary extended, as an augmentative device for hand rehabilitation.

Acknowledgment

Author are grateful to Eng. Giovanni Spagnoletti for his help in developing the EMG interface. The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007- 2013 under grant agreement n° 601165 of the project "WEARHAP".

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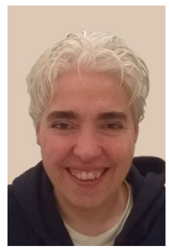

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