Using the Robotic Sixth Finger and Vibrotactile Feedback for Grasp Compensation in Chronic Stroke Patients

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***Abstract*—This paper presents a wearable robotic extra finger used by chronic stroke patients to compensate for the missing hand functions of the paretic limb. The extra finger is worn on the paretic forearm by means of an elastic band, and it is coupled with a vibrotactile ring interface worn on the healthy hand. The robotic finger and the paretic hand act like the two parts of a gripper working together to hold an object. The human user is able to control the flexion/extension of the robotic finger through a switch placed on the ring, while being provided with vibrotactile feedback about the forces exerted by the robotic finger on the environment. To understand how to control the vibrotactile interface to evoke the most effective cutaneous sensations, we carried out perceptual experiments to evaluate its absolute and differential thresholds. Finally, we performed a qualitative experiment, the Franchay Arm Test, with a chronic post-stroke patient presenting a partial loss of sensitivity on the paretic limb. Results show that the proposed system significantly improves the performance of the considered test.**

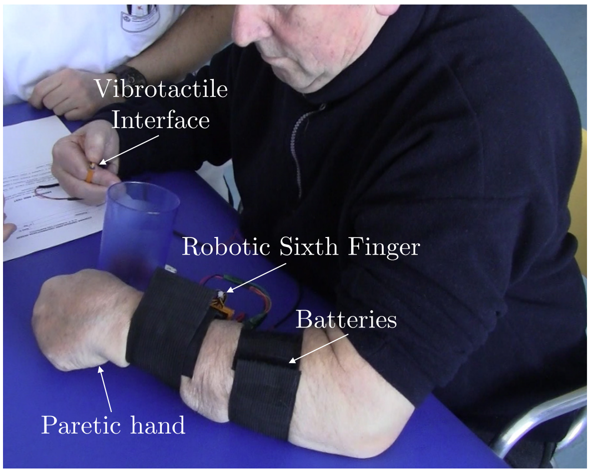

Fig. 1. The robotic extra finger together with the vibrotactile interface ring. The ring provides haptic feedback through a vibrating motor and enable the user to start and stop the finger motion through a switch.

I. Introduction

Stroke is a leading cause of long-term disability, which is often associated with persistent impairment of an upper limb [1]. Studies indicate that only 5% to 20% of stroke patients with a paretic upper limb manage to fully recover six months after the stoke [2], while 33% to 66% show no recovery of upper limb functions after the same period [3], [4]. A key role in functional recovery and better independence in the Activity of Daily Living (ADL) of stroke patients with a paretic upper limb seems to be played by the improvements of the paretic hand [5], [6]. In this respect, robotic-aided therapy represents a novel and promising approach thanks to the possibility of providing high-intensity, repetitive, task-specific, interactive treatments of the impaired limb [7].

In the recent years, several devices for the rehabiliation of paretic hands have been presented in the literature, and some of them have been also tested with post-stroke patients [8], [9]. However, most of these prototypes are neither portable nor wearable, and they are designed to increase the functional recovery in the first months after stroke, i.e., when biological restoring and reorganization of the central nervous system is still possible. Very few have been designed to assist chronic stroke patients, who must thus rely only on compensatory strategies [10].

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In this work, we focus on the compensation of grasping function in chronic stroke patients. We propose to use a robotic extra finger, which we called the Robotic Sixth Finger, together with the paretic hand/arm, to constrain the motion of the object. The device can be worn on the user's forearm by means of an elastic band. The systems acts like a two-finger gripper, where one finger is represented by the Robotic Sixth Finger, while the other by the patient's paretic limb.

A preliminary version of the device has been presented in [11], [12]. In these works, the Robotic Sixth Finger was tested with healthy subjects, by relating the motion of the device to that of the hand the extra finger was coupled with. A dataglove was used to track the hand, while an extension of the object-based mapping proposed in [13] was adopted to compute the robotic extra finger movements. To let the finger be used by patients with a reduced mobility of the hand, we completely redesign the human-robot interaction paradigm. In the version proposed in this paper, the patient can regulate the finger flexion/extension through a wearable switch embedded in a ring worn on the healthy hand, as shown in Fig. 1. Two possible predefined motions can be chosen to obtain either a precision or a power grasp. In addition to the switch, the proposed ring interface also embeds a vibrotactile motor able to provide the patient with information about the force exerted by the device. Vibrotactile haptic stimuli have been proved to enhance the performance of robotic systems in many scenarios. Moreover, vibrotactile motors have an extremely compact form factor with respect to actuators providing other types of haptic stimuli.

Vibrotactile feedback has been successfully employed in teleoperation to provide information about the forces exerted at the remote environment. Schoonmaker and Cao [14], for example, demonstrated that vibrotactile stimulation is a viable substitute for force feedback in minimally invasive surgery, enhancing surgeons' ability to control the forces applied to tissue and differentiate its softness in a simulated tissue probing task. Substituting force feedback with vibrotactile cues has been also successfully used for neuroprosthetic systems. Chatterjee et al. [15] carried out a force-matching grasping task to quantify performance improvements with a pulsing vibrotactile feedback to substitute the grasping force sensed by a myoelectric prosthetic hand, while Cipriani et al. [16] developed a multi-site vibrotactile sensory substitution system for multi-fingered prostheses. In order to understand how to correctly drive the vibrotactile ring to evoke the most effective cutaneous sensations, we ran two preliminary experiments aiming at evaluating the absolute and differential thresholds of our device.

Finally, we set up a pilot experiment involving a patient in a chronic state. The patient worn the Robotic Sixth Finger on the paretic arm and was asked to perform the five tasks of the Frenchay Arm Test [17], while different force information was fed back through the vibrotactile interface. These tests included two manipulation tasks that were successfully accomplished through the proposed robotic extra finger.

The rest of the paper is organized as it follows. Section II describes the robotic extra finger and the ring interface. Section III presents two preliminary experiments aiming at evaluating the absolute and differential thresholds of our vibrotactile haptic device. Section IV deals with the pilot experiment carried out to evaluate the effectiveness of the system, while in Section V conclusion and future work are outlined.

II. The Robotic Sixth Finger system

A. System design

Wearability is the key concept in the design of the proposed system that consists of the Robotic Sixth Finger device and the vibrotactile ring interface. The robotic extra finger can be worn 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 flexion and the hand posture can impede a successful grasp. When this pathological condition occurs, the Robotic Sixth Finger may be placed closer to the elbow, in a way that the grasp can be achieved by the robotic extra finger opposition to the radial aspect of the thenar eminence. This flexibility in the positioning is achieved thanks to the modularity of the structure and to the support base. Modularity makes possible to regulate the size and dexterity of the finger according to the position on the forearm and the characteristic of each patient. The support base of the finger can be translated or rotated along the arm to place the finger on suitable 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.

Each module of the Robotic Sixth Finger consists of a servomotor (HS-53 Microservo, HiTech, Republic of Korea) and a 3D printed plastic part with a total dimension of $42 \times 33 \times 16$ mm. The prototype presented in this paper has 4 Degrees of Freedoms (DoFs), that are obtained by considering four modules in a pitch-pitch connection. These modules replicate the flexion/extension motion of the human fingers. A Force Sensing Resistor (FSR) (408, Interlink Electronics Inc., USA) is placed on each module, as reported in Fig. 2-b. The measured voltages are converted into forces according to the manufacturer datasheet, and are then used to generate haptic feedback as described in Sec. IV. Force Sensing Resistor are resistive polymer elements and, being inexpensive and readily available, are being widely used in haptics and robotics [18], [19].

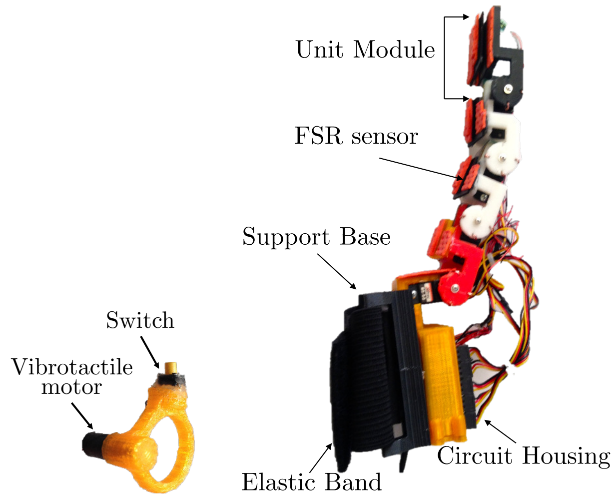
The vibrotactile interface ring is designed to be worn on the index finger of the human hand, as shown in Fig. 1. The ring is equipped with a switch and a vibro motor, as shown in Fig. 2-a. The ring, as well as the plastic modules, is made with a special type of acrylonitrile butadiene styrene, called ABSPlus (Stratasys, USA). The motor used is an eccentric rotating mass vibrotactile motor (Precision MicroDrives, United Kingdom), which does not allow to separately control amplitude and frequency of the vibration. The switch is used to control the finger flexion/extension, as described in Sec. II-B, and move the finger back to the initial grasp position. The vibrotactile motor is used to provide vibrotactile feedback, as explained in Sec. IV. A preliminary version of this vibrotactile interface was presented in [20].

The module actuators and the vibrotactile motor are controlled by PWM signals generated by an Arduino Nano board [21] placed on the finger base. The servomotor position feedback and FSRs signals are interfaced with the analog channels of the Arduino. An external battery is used to provide power to all the circuits.

B. Flexion-extension control

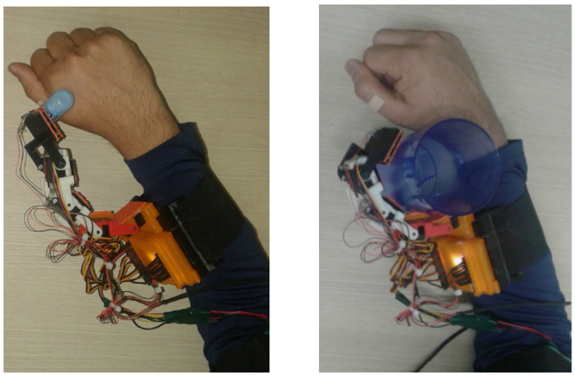
The vibrotactile ring interface embeds a single normally open push button that is used to control the finger motion. In order to grasp object with different size and shape, we considered two possible achievable grasps: precision and power grasp. The two grasps are obtained by imposing different flexion trajectories to the device. In precision grasps, the target is to hold the object between the paretic limb and the fingertip pad, as in Fig. 3-a. To this aim, in the flexion trajectory the fingertip is kept parallel to the paretic limb. In power grasps, each module flexes with a fixed step size in order to wrap the finger around the object as reported in Fig. 3-b. By pushing the button three times consecutively the user can change between the flexion trajectories.

Once the type of grasp is selected according to the object size, the patient can directly control the flexion/extension of the Robotic Sixth Finger. If the button is pressed once and hold at its "ON" state, the finger starts flexing. It keeps flexing until the button is released. To extend the finger,



(a) Ring interface (b) Robotic Sixth Finger

Fig. 2. CAD models of the vibrotactile interface and of the modular finger. Four modules are connected to a wrist elastic band. The ring is equipped with a push button used as an interface with the user and a vibrotactile motor to provide an haptic stimulus.



(a) Precision grasp (b) Power grasp

Fig. 3. The two predefined flexion paths for the robotic extra finger. In (a) the grasp is obtained between the fingertip of the device and the thenar eminence. In (b) the grasp involve the whole device and the user wrist.

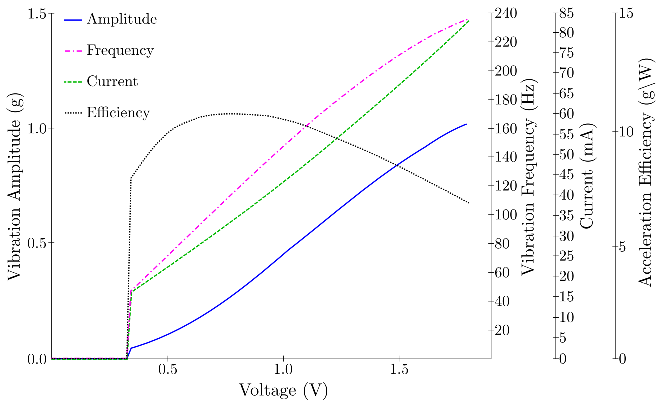


Fig. 4. Typical performance characteristics of the Precision Microdrives 4 mm Vibration Motor (11 mm type).

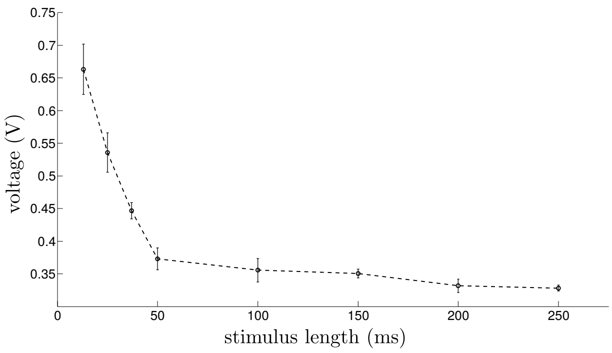


Fig. 5. Absolute threshold. Mean values and standard errors of the mean (SEM) are plotted. The relationship between input voltage, and the amplitude and frequency of the vibration can be found in Fig. 4.

the user presses the button twice consecutively and hold the "ON" state during his second press. As long as the "ON" state is hold, the finger keeps moving for extension.

III. Perceptual Thresholds

In order to understand how to correctly drive the vibrotactile ring to evoke the most effective cutaneous sensations, we ran two preliminary experiments aiming at evaluating the absolute and differential thresholds of our device.

Six healthy subjects took part in the experiment. They were asked to wear the vibrotactile ring on their right index proximal phalanx. Moreover, to avoid providing them with any additional cue, they were blindfolded and wearing noise-canceling headphones.

We evaluated the absolute threshold using the simple up-down method [22]. We used a step-size of 0.08 V, which reduced of 0.02 V at every reversal. We considered the task completed when four reversals occurred. The relationship between input voltage, and the amplitude and frequency of the vibration can be found in Fig. 4. Subjects were required to wear the cutaneous device as shown in Fig. 1 and tell the experimenter when they felt the stimulus. Each participant performed forty-eight repetitions of the simple up-down procedure, with six repetitions for each considered duration of the vibratory stimulus: 13 ms, 25 ms, 37 ms, 50 ms, 100 ms, 150 ms, 200 ms, and 250 ms. Fig. 5 shows the absolute thresholds registered.

We evaluated the differential threshold using again the simple up-down method [22] and the same number of participants. We used again a step-size of 0.08 V, which reduced of 0.02 V at every reversal. We considered the task completed when four reversals occurred. Subjects were required to wear the cutaneous device and tell the experimenter when the two vibrations provided felt different. We calculated the differential threshold for three different vibration lengths: 100 ms, 150 ms, and 200 ms. We did not consider lengths < 100 ms to be sure that everyone would be able to perceive them at all reference stimuli (see Fig. 5). Fig. 6 shows the differential thresholds registered.

More information on the perceptual evaluation of this vibrotactile ring interface can be found in [20].

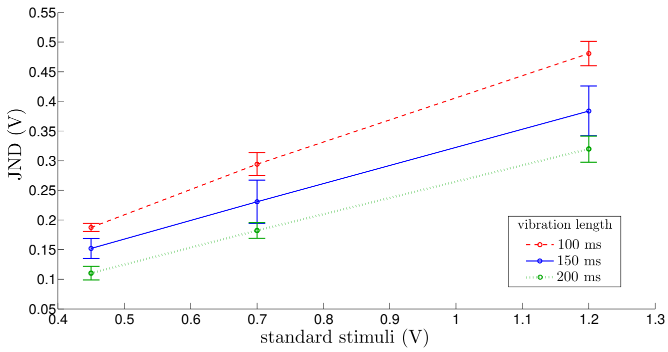


Fig. 6. Differential threshold. Mean values and standard errors of the mean (SEM) are plotted. The relationship between input voltage, and the amplitude and frequency of the vibration can be found in Fig. 4.

IV. Pilot Experiment

In order to evaluate the effectiveness of our extra finger device and the usefulness of vibrotactile haptic feedback, we carried out a pilot experiment with a chronic stroke patient with the objective of compensating for hand function. The patient left upper limb, subsequently to stroke, was affected by mild-severe paresis and hypoesthesia (partial loss of tactile sensitivity). The ring interface was placed on the right arm. The rehabilitation team have declared that no more functional improvements are achievable with respect to the gained upper limb motor performance. Written informed consent was obtained from the subject. The procedures was in accordance with the Declaration of Helsinki. The patient did not present any deficiencies in his haptic perception abilities at healthy hand.

We performed a qualitative test[1], the Frenchay Arm Test [FAT] [17] with different feedback modalities. The experimenter explained the procedures and spent about five minutes adjusting the setup to be comfortable before the patient began the experiment. At the end of the experiments, we asked the subject for a questionnaire related to the overall system.

The FAT is a measure of upper extremity proximal motor control and dexterity during ADL performance in patients with impairments resulting from neurological conditions. It is an upper extremity specific measure of activity limitation. The test consists of five pass/fail tasks to be executed in less than three minutes. The patient scores 1 for each of the successfully completed task, while he/she scores 0 in case of fail. The subject sits at a table with his hands in his lap, and each task starts from this position. He/she is then asked to use his/her affected arm/hand to:

1) Stabilize a ruler, while drawing a line with a pencil held in the other hand. To pass, the ruler must be held firmly.
2) Grasp a cylinder (12 mm diameter, 5 cm long), set on its side approximately 15 cm from the table edge, lift it about 30 cm and replace without dropping.
3) Pick up a glass, half full of water positioned about 15 to 30 cm from the edge of the table, drink some water and replace without spilling[2].
4) Remove and replace a sprung clothes peg from a 10mm diameter dowel, 15 cm long set in a 10 cm base, 15 to 30 cm from table edge. Not to drop peg or knock dowel over.
5) Comb hair (or imitate); must comb across top, down the back and down each side of head.

The patient performed the FAT first without using Robotic Sixth Finger and then by using Robotic Sixth Finger with and without vibrotactile feedback. Two types of vibrotactile haptic cues were provided during the task:

- *threshold feedback:* vibration burst when a predefined force threshold was reached;
- *proportional feedback:* vibrations proportional to the intensity of the force exerted by the robotic finger.

In the threshold feedback condition, the vibrotactile ring provided 200 ms-long vibrations when the force sensed by the robotic finger (we considered the maximum force sensed between the three sensors) was equal to 0.7 times the weight of the grasped object. The weights of the grasped objects were previously measured. In the second condition, the vibrotactile ring provided continuous vibrotactile feedback proportional to the intensity of the force exerted by the robotic fingers. The commanded input voltage v_i, proportional to the mean force sensed on the robotic finger, was evaluated as

$$v_i = \frac{(f_{e,max} + \alpha)}{\beta},$$

where $f_{e,max}$ is the maximum force among those registered by the four sensors on the robotic finger at each instant. The term α was set to 0.3 and the term β to 2.5 according to the experimental results in [20]. The relationship between input voltage v_i and the amplitude and frequency of the vibration can be found in Fig. 4. For example, when $f_{e,max} = 2$ N, the vibrotactile ring provides a vibration of amplitude 0.43 g and frequency 124 Hz .

The Robotic Sixth Finger was placed on the paretic limb, while the vibrotactile ring interface on the index finger on the healthy hand. The extra finger was directly controlled by the patient using the switch placed on the vibrotactile ring. The subject carried out the same test with the three considered haptic feedback, i.e., no vibrotactile feedback, threshold feedback, and proportional feedback. The results of the FAT test is shown in Table I.

Independently from the haptic feedback provided, the patient improved of 2 out of 5 points in the test scale using the Robotic Sixth Finger. The two tasks executed with the help of the Sixth Finger are shown in Fig. 7. Note that the subject was able to stabilize the ruler with and without using our system. This is an additional feature of the device which does not limit the existing dexterity of human limbs. The subject was able to grasp objects of different size by using

[1]A video of the proposed experiment can be downloaded at http://goo.gl/JLLjMo

[2]For safety reasons we did not use water in presence of electronic components.

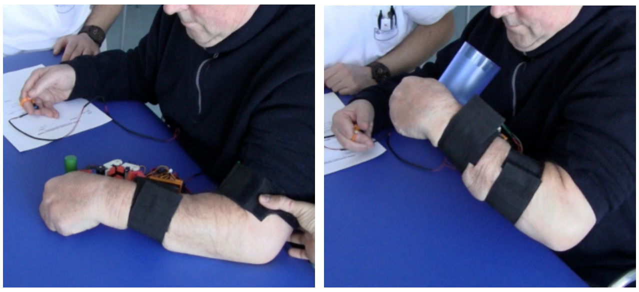


Fig. 7. Two tasks of the FAT fulfilled with the help of the Robotic Sixth Finger.

TABLE I. RESULTS OF THE FRENCHAY ARM TEST WITH AND WITHOUT USING THE ROBOTIC SIXTH FINGER

TASK	No finger	Robotic Sixth Finger
Stabilize a ruler	1	1
Grasp a cylinder	0	1
Pick up a glass	0	1
Remove a sprung	0	0
Comb hair	0	0

TABLE II. QUESTIONNAIRE AND RELATIVE MARKS. THE MARK RANGES FROM "0 = TOTALLY DISAGREE" TO "7 = TOTALLY AGREE"

Question	Answer
I had the feeling of performing better while receiving vibrations from the interface.	7
I did not need any particular training to start using the interface.	7
I felt confident using the system.	7
I think that I would need the support of a technical person to be able to use this system every day.	4
I thought the system was easy to use.	7
I would imagine that most people would quickly learn how to use this system.	7
Which haptic feedback condition did you prefer?	Threshold

power and precision grasp. Particularly, he used precision grasp for the cylinder and power grasp to pick up a glass with the help of the Robotic Sixth Finger.

In order to evaluate the intuitive use of the device and the effectiveness of vibrotactile feedback, the subject was also asked to fill the questionnaire reported in Table II. The subject appreciated the approach of grasping compensation through the Robotic Sixth Finger and found vibrotactile information helpful during the completion of the tasks. Particularly, patient preferred the threshold feedback, i.e., vibration bursts when predefined intensity thresholds of the force exerted by the Robotic Sixth Finger were reached.

V. CONCLUSION AND FUTURE WORK

In this paper we presented the integration of the wearable Robotic Sixth Finger with a vibrotactile ring interface. We introduced a new solution for the grasping phase based on a wearable switch embedded in the ring and a closing policy that let the robotic extra finger adapt to the object shape. In order to understand how to correctly drive the vibrotactile ring to evoke the most effective cutaneous sensations, we ran two preliminary experiments aiming at evaluating the absolute and differential thresholds of our cutaneous device. Results showed that vibrations of 200 ms were perceived at amplitudes as little as 0.1 g, and that two 200 ms-long vibrations need to differ of at least 0.1 g to be perceived as different. After that, in order to evaluate the effectiveness of our extra finger device and the usefulness of vibrotactile haptic feedback, we carried out a pilot experiment involving a chronic stroke patient. The patient was able to improve their performance in 2/5 tasks included in the FAT qualitative evaluation. The patient did not require any specific training period, thus suggesting that the use of the Robotic Sixth Finger is very intuitive, at least in this basic activities. This could represents an important feature also considering that a proportion of stroke patients may also complain of some cognitive deficits, possibly limiting their compliance during a demanding learning phase. The patient participating to the experiment was affected by hypoesthesia so he was not able to perceive the force exerted by the extra finger on the object through the paretic hand. He preferred conditions employing haptic feedback on the healthy hand. In particular, he declared to prefer a distinct signal with respect to a vibration proportional to the force applied to the object by the robotic finger.

We are currently testing the system with other patients, including patients with a fully tactile sensitivity, in order to determine the improvement brought by the haptic feedback. We are also working on making the vibrotactile ring interface completely wireless so to improve the portability and wearability of the system. Finally, we are investigating different types of human-robot interface so to avoid the use of the healthy hand for the extra finger control.

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