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Supernumerary Limbs and Wearable Sensorimotor Interfaces

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Abstract— **The goal of this paper is to describe our studies on the Sixth Finger and present the different solutions available to control and to get haptic feedback from the system. The path toward the final solutions adopted has been paved with different intuitions about the designers and, more importantly, with continuous feedback from patients that tested all the proposed solutions a led us to the final setup. The paper is organised as follows. We will first recall the main characteristic of the Robotic Sixth Finger. Than we will go through the proposed solutions recalling the main results and pointing to the published papers for the details.**

I. THE ROBOTIC SIXTH FINGER

A. Design of the Soft Sixth Finger

The Soft-SixthFinger is a device designed to be used to compensate the missing grasping abilities of chronic stroke patients as presented in [1], [2]. The exploded view of the device and its possible applications are shown in Figure1. The working principle of the device is to replicate the two parts of a simple gripper using on one side the paretic forearm of a patient and, on the other side, a flexible finger that can be worn at the wrist with the help of an elastic band. The Soft-SixthFinger is built with a modular structure. Each module is composed of a rigid 3D printed part realized in ABS (Acrylonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) and a 3D printed thermoplastic polyurethane part (Lulzbot, USA) that acts as the flexible joint.

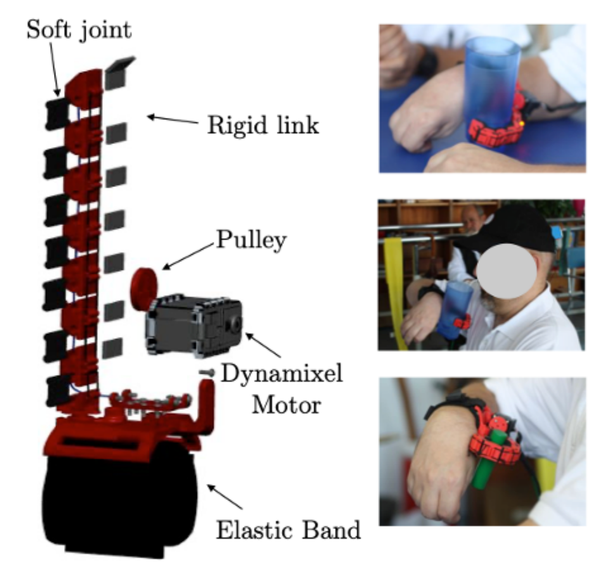

Fig. 1: The Robotic Sixth Finger exploded view and its working principle with paretic hand to compensate its missing abilities.

B. The Double Soft Sixth Finger

Although the soft sixth finger can be used to grasp and stabilize a large set of objects, having a single finger in opposition to the patient arm can result in a limitation in tasks requiring a high payload. We designed the double soft sixth finger to deal with these particular situations [3]. The double soft sixth finger shares with the soft sixth finger the same principle design guidelines related to wearability, modularity, symmetrical structure and underactuation. It is composed of two parts: a support base that allows the finger to be worn at the patient forearm and two fingers. We fixed the fingers in a “V” configuration. The basic idea behind setting the two fingers in this configuration was to keep minimum distance at the base of the fingers while maximizing the fingertips’ distance at a fully extended position with the given length of the finger. The rationale between this choice is the attempt to maximize the distance of the contact points at the fingertips when grasping relatively big size objects. Thanks to the orientation of the finger at the base, when the fingers keep closing so to grasp smaller size objects, the fingertips of both fingers converge one toward the other, hence minimizing the relative distance between them. Thus, this configuration is effective in grasping bigger as well as smaller size objects. The exploded view of the unit module and complete double soft sixth finger is shown in Figure 2. Two tendon wires (one for each flexible finger) and a single actuator control the motion of the device. One end of each tendon wire is fixed to each fingertip, while the other ends of both tendon wires are attached to a single pulley mounted on the shaft of the actuator (MX-28T). When the motor rotates, both tendon wires are wound on the pulley and fingers are flexed to grasp the object. As the motor is rotated in opposite direction, the elastic parts in the joints restore the finger to its extended configuration. The final prototype of the device is shown in Figure 3. the double soft sixth finger can be worn on the arm using the base support and the velcro strips. Both fingers can be shaped into a bracelet through two separate Dovetail locking mechanism when being not used.

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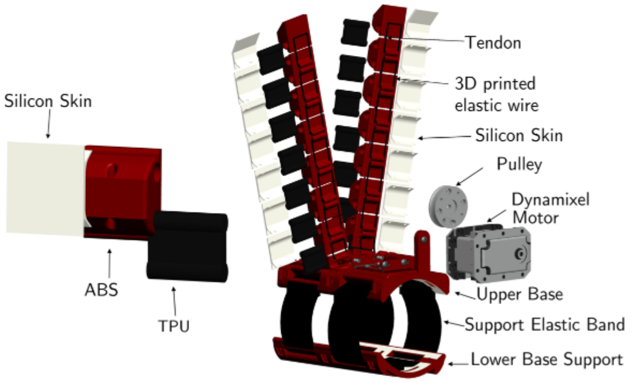


Fig. 2: The CAD exploded view of the double soft sixth finger. On the left unit module with single tendon. On the right, the exploded view of complete double soft sixth finger.

Fig. 3: The final prototype of double soft sixth finger, the device can be worn on the paretic arm through support base and elastic straps. It can be shaped into bracelet when being not used..

II. EMG-BASED INTERFACE FOR THE ROBOTIC SIXTH FINGER

The control interface for patient oriented devices must be intuitive and simple, since chronic patients may also be affected by some cognitive deficits, possibly limiting their compliance during a demanding learning phase. Coordinating the motion of the extra fingers with that of the hand where the devices are worn is not suitable for patients with hemiparetic upper limb since they are not able to control their hand motion. A possible solution could be the involvement of the controlateral hand in the control process. In [4], [5] a ring embedding a push-button to control the motion of an extra robotic finger was proposed. The ring was worn on the healthy hand so to let the user activate it when necessary. However, experiments with patients revealed that these solutions limit the mobility and dexterity of the non-paretic hand and can also cause possible accidental activation of the device during ADL. Patients also confirmed their preference of always having healthy hand free during our tests. To cope with this issue, we have proposed the eCap: an Electromyography (EMG) based wireless interface which maintains the principle of simplicity of a switch without interrupting the patient activities and without the involvement of a healthy hand during task execution. The eCap is a wearable wireless EMG interface where electrodes, acquisition and signal conditioning boards are embedded in a cap, see Figure 4 A preliminary version of the control interface has been presented in [2]. More details on the interface and on its possible applications can be found in [6], [3], [7], [8], [9].

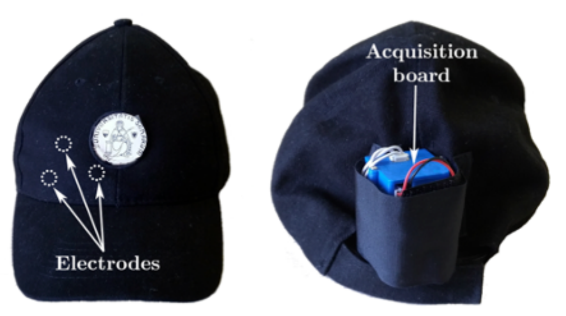


Fig. 4: The eCap interface.

The eCap allows the patients to autonomously wear the interface using only their healthy hand. For chronic patients it is generally difficult to generate repeatable EMG patterns in their paretic upper limb due to the weakness in muscle contraction control. For this reason, we coupled the flexion/extension motion of the robotic device with the contraction of the frontalis muscle. This muscle is always spared in case of a motor stroke either of the left or of the right hemisphere due to its bilateral cortical representation. The user can contract this muscle by moving the eyebrows upwards. The electrodes in the eCap capture the arising EMG signal that is acquired through an EMG signal conditioning circuit and processed by a control algorithm as explained in the following. We used surface EMG electrodes to measure electrical signals associated with the patient's frontalis muscle. In particular, on the inner side of the eCap, we installed non-gelled reusable silver/silver-chloride electrodes, as they present the lowest noise interface and are recommended for biopotentials recording. We designed an EMG signal acquisition board taking into consideration the requirements associated with bandwidth, dynamic range and physiological principles. The motion of Sixth Finger is controlled by using a trigger signal based finite state machine The trigger signal is obtained by using a single-threshold value defined as the 50% of the maximum voluntary contraction (MVC), a level that was repeatable and sustainable for the subject without producing undue fatigue during the use of the device. We set a minimum time (20 ms) in which the EMG signal has to constantly stay over the threshold to generate the trigger signal to prevent false activation due to glitches or to spontaneous spikes. The outputs of the FSM are predefined commands based on sequences of input signals. We consider a finite number of states, transition between those states, and commands. States represent predefined motion commands for the robotic device and transition actions are associated with contractions of the frontalis muscle.

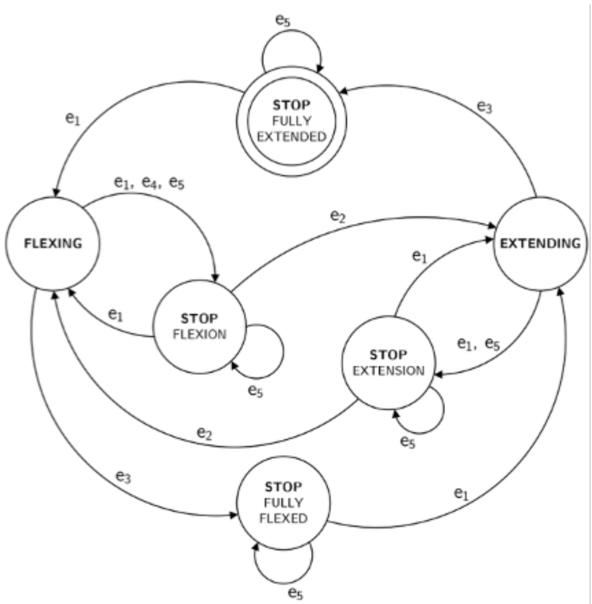


Fig. 5: The proposed finite state machine (fsm) for the motion control of the robotic devices. Events e1 and e2 are generated by the user, while e3 is a software defined event. Event e4 occurs once the object is grasped. Event e5 activates on switching between two proposed control interfaces (eCap or push-button.

The patients control the motion/stop of the finger with a single muscle contraction (event e1). Once the finger is stopped, two contractions (event e2) in a time window of 1 s switch the direction of motion from flexion to extension and vice-versa. The time window length was experimentally selected after the repeated trials with patients. software defined trigger (event e4) stops the actuator's motion once the object is considered as grasped, to avoid a torque overloading situation. The grasp confirmation is detected by continuous monitoring the actuator's shaft position and the exerted torque. During the grasping procedure, if the position does not change in a time window of 2 s and a predefined torque threshold is reached, the object is considered as grasped. The proposed FSM is reported in Figure 5. A LED board is used to provide a visual feedback of the selected commands. In particular, a yellow LED blinks on each trigger signal. When flexion is selected an orange LED is turn on, while a green LED shows the extension. Finally a red LED is turn on when the device is stopped. At this stage, the LED associated to the previous selected state is also turned on to remind the user about the last stage of the device. To provide an additional interface for the user, as well as a recovery mode for possible problem in the eCap communication, we added a push-button on the LED board as further possible control. The eCap has been tested with a total of 15 patients. All the patients have reported a very intuitive usage and could start controlling the finger with practically no training. However, some patients reported that the need of wearing a cap to control the extra thesis may result not very comfortable.

A. Feedback on the eCap

In [7], we have studied the effectiveness of tactile feedback for the acknowledgement of a correct command detection in the eCap, see Figure 6. EMG interfaces are increasingly used in assistive robotics to control robots exploiting the repeatability and robustness of the electromyographic signal. However, in many application a feedback about the correct detection of an input is often missed and the user has to wait for the device motion in order to understand if his/her command has been correctly detected by the system. We demonstrate with a user study involving fifteen subjects, that a vibrotactile feedback on the occipital area of the head can reduce the muscular effort and the time needed to execute a sequence of action commanded by an EMG device. The proposed results could be extended to EMG interfaces designed for other muscles, e.g., for prosthesis or exoskeleton control.

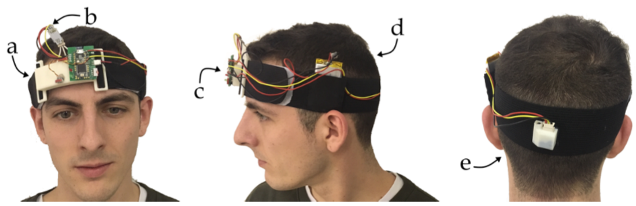
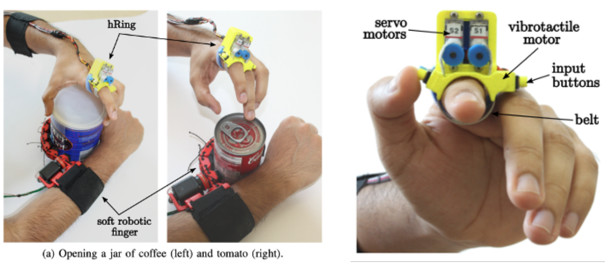


Fig. 6: The Frontalis muscle interface front, side and back view. Arrows indicate: (a), 3D printed electrodes socket with loops for elastic band; (b), EMG conditioning board; (c), sampling and data processing board with Bluetooth module mounted on a custom PCB; (d), Li-Po battery; (e), vibration motor (ERM) for the haptic feedback, embedded in a 3D printed socket.

III. The hRing Interface

We investigated whether providing the patient with information about the forces exerted by the supernumerary robotic finger to the environment would improve the user experience. The first motivation was related to patients suffering from hypoesthesia. For these type of users we firstly design a vibrating ring that could be worn on the contralateral hand and could display a vibration varying its intensity according to the force measured by the robotic sixth finger motor [5]. We then investigated if the haptic feedback would be also useful in patients with an intact sense of touch. We used a cutaneous skin stretch device for the proximal finger phalanx. Wearability, comfort. ease of use, and effectiveness were the main requirements for the design of this haptic device. The hRing is shown in Figure 7.

It is composed of a static part, that houses two servo motors and two pulleys, and a fabric belt, that applies the



(a) Opening a jar of coffee (left) and tomato (right).

Fig. 7: The hRing. a wearable cutaneous finger interface. The picture shows the integrated system used by a patient in Activities of Daily Living (ADL). The hRing is used to control the opening/closing motion of the robotic finger and to provide the wearer with information about the forces exerted by the robotic finger.

requested stimuli to the finger. A strap band is used to secure the device on the finger proximal phalanx. We used two PWM-controlled HS-40 servomotors (HiTech, Republic of Korea). The device weighs 38 g for 30x43x25 mm dimensions. The working principle of the device is simple: When the two motors rotate in opposite directions, the belt is pulled up, providing a force normal to the finger (left side of Figure 5). On the other hand, when motors spin in the same direction, the belt applies a shear force to the finger (right side of Figure 5). These two movements can be combined together to provide at the same time shear and normal stimuli. In Softpro, we mainly used it to apply forces normal to the finger skin. This is mainly due to the fact that we have not added any multi-DoF force sensor on the robotic finger, with the objective of improving its wearability and portability. We estimate the contact force solely from the load of the finger's motor. To demonstrate the effectiveness of our system, we carried out two experiments, enrolling sixteen healthy subjects and two post-stroke patients in pick-and-place and ADL tasks, respectively. Healthy subjects were asked to mimic a paresis on their right hand by closing it in a fist. Results with the healthy subjects showed that the supernumerary finger can significantly help to improve the grasping capabilities of paretic hands. Indeed, no subject was able to complete the pick-and-place task without using the supernumerary finger. Moreover, results also show that providing cutaneous feedback through the hRing significantly improves the performance of the considered pick-and-place task in terms of force applied on the environment and perceived effectiveness. It is worth pointing out that the heavier the object, the larger the improvement of performance when using the haptic feedback. Finally, the two chronic stroke patients found the system very useful for ADL tasks, the hRing easy to use, and the haptic feedback very informative. However, it is also important to notice that the benefits of using the proposed system are not always so evident. In fact, in our task, the only objects that all users were not able to grasp were the small cubes. All the results and the details of this study are reported in [10].

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