Towards a Supernumerary Robotic Hand for Upper Limb Assistance and Rehabilitation

Martina Rossero [1,2], Andrea S. Ciullo[1], Giorgio Grioli[1], Manuel G. Catalano[1], and Antonio Bicchi[1,2]

***Abstract*—The effects of neurological diseases (e.g. stroke) can severely affect the subject's quality of life and independence. In the last decades, many robotic devices have been developed to flank standard rehabilitation therapies. Here, we present a new Supernumerary Robotic Hand designed to be used in close coordination with the natural hands, as a "third hand". The SoftHand X system (where X stands for eXtrathesis) is suitable for the assistance of impaired people and is composed of different sub-parts conveniently assembled for the patients' needs. In this paper, the design is described as well as the clinical testing already performed. A first idea to exploit the system in the rehabilitation field is also presented.**

***Index Terms*—Soft Robotics, Robotic Assistance, Supernumerary Robotic Limbs, Rehabilitation Robotics**

I. Introduction

Neurological diseases, such as stroke, are estimated to be the second most common cause of death and the most widespread cause of disability worldwide [1]. Studies have indicated that 20% of stroke survivors need medical institutional care 3 months after stroke (subacute phase), and almost 15–30% of them suffers from long-term disability [2]. Considering the upper extremities, the functional reduction of the hand-arm may drastically compromise the independence of the subject, causing the inability of performing many Activities of Daily Living (ADL) [3]. Moreover, studies demonstrated that the relationship between the use of the hands' function and the ability to perform ADL is stronger than the other limbs [4] [5]. In the last decades, several robotic devices have been developed and used to help during the rehabilitation process [6]. Besides these devices, a new approach has been developed in the robotic field, the Supernumerary Robotic Limbs (SRLs). They consist of additional artificial limbs that work in close coordination with the subject wearing them. A first application in the clinical field can be found in [7] where an additional robotic finger (the Sixth finger) was tested with chronic stroke patients. These assistance activities with rehabilitation purposes are performed with different characteristics related to the clinical phase after the cerebral accident. In the subacute phase, the therapies focus on the prevention of the so-called secondary damage that consists in the insurgence of other clinical problems not directly linked to the stroke [8]. For example, rehabilitation sessions conducted with the purpose to recover the hand abilities are generally limited to avoid the development of spasticity in the wrist flexor muscles, especially when the hypertonus is already present. As a consequence, most patients reach a good motor recovery of proximal upper extremity while rehabilitation of the distal upper limbs is often limited. In these cases, even after years from the neurological accident, daily assistance can be necessary.

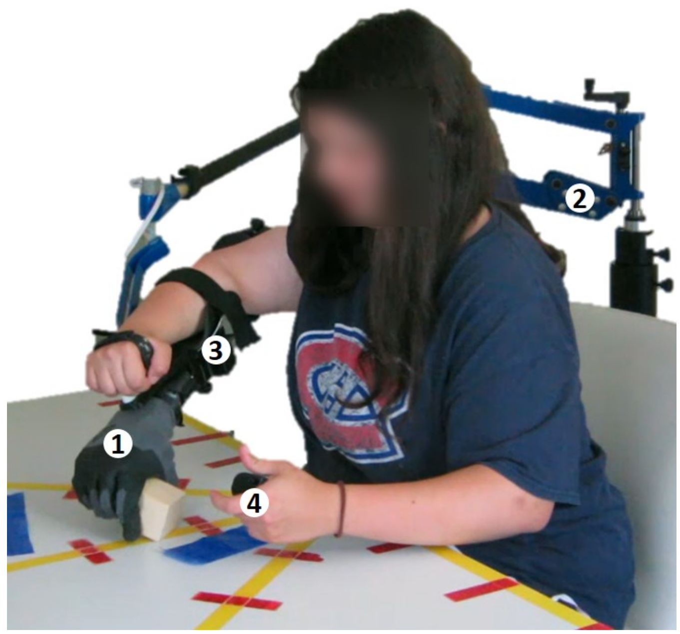


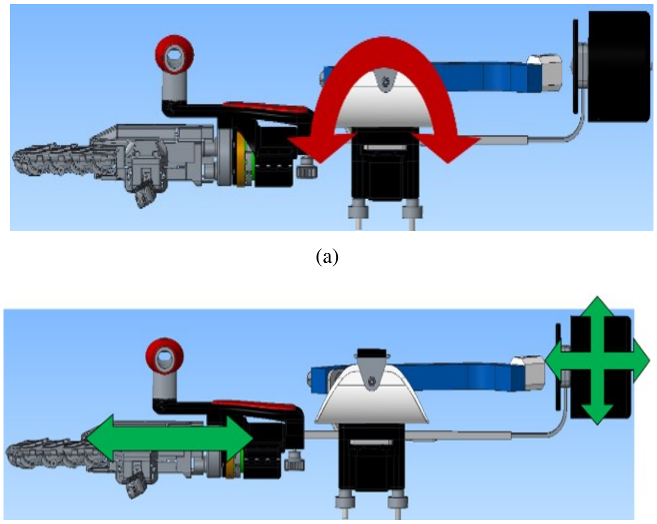
Fig. 1. The figure shows the SoftHand X system worn by a post-stroke patient. (1) is the Pisa/IIT SoftHand acting as end-effector, (2) is the gravity compensator, (3) is the human-arm interface connecting the first two parts and (4) is the input interface.

In this paper, we present the SoftHand X (SHX) system, a new Supernumerary Robotic Hand designed to be used in close coordination with the natural ones, as a "third hand". In Section II, the system and its design are described. Then, in Section III, we show the experiments conducted to find out the optimum position of the robotic hand and to analyze the compensatory movements exploited by subjects using it. In the end, in Section IV the clinical trials already performed are presented together with a preliminary idea to integrate the system within a rehabilitative protocol for sub-acute post-stroke patients.

II. System design

The SoftHand X (SHX) system is a modular robotic system for the upper limb support with anthropomorphic characteristics and inspired by neuroscientific theories of motor control

[1] Soft Robotics for Human Cooperation and Rehabilitation, Istituto Italiano di Tecnologia (IIT), Genoa, Italy
[2] Centro "E. Piaggio" and Dipartimento di Ingegneria dell'Informazione, University of Pisa, Pisa, Italy



(a)

(b)

Fig. 2. (a) shows the mechanical torque generated due to the misalignment and the distance of the robotic hand with respect to the natural one. (b) shows the mechanical possibilities of adjusting the human arm interface to fit different arm's dimensions and the added counter mass.

[9] [10]. As shown in Figure 1, it is composed of single separated sub-parts that are conveniently assembled for the user's needs.

A. End-effector and gravity compensator

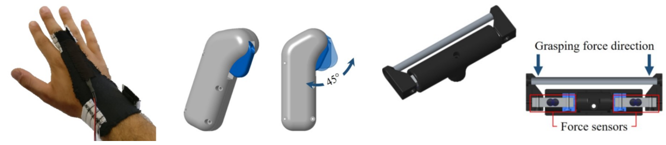
The end effector is a Pisa/IIT SoftHand, an underactuated robotic hand, implementing only one degree of actuation. Thanks to its mechanical design and its softness, it can adapt its shape around objects, thus allowing executing a large number of grasping tasks by activating only a single motor. A gravity compensator is then used to help the patient against the weight of the robotic hand and of his/her own arm.

B. Human-arm interface

The human-arm interface has a wrist-like structure and was designed as additional component with the basic function of connecting the end-effector with the gravity support. As shown in Figure 2(a), the misalignment and the distance of the robotic hand generate additional gravity torques causing annoying rotations. For this reason and to fit the arm dimensions of different patients, the human-arm interface was designed to be adjustable and a counter mass was added in the back (Figure 2(b)).

C. Input interface

The opening/closure of the robotic hand is controlled by the subject with an input interface. The most traditional activation input signal in robotic devices is the EMG signal [11]. Although technically possible to use for the SoftHand X device [12], the EMG signal is not always easily detectable in stroke patients. So, as shown in Figure 3, other input devices have been implemented. A finger glove with a resistive flex sensor allows the robotic hand to open/close proportionally to the flexion of a finger (see Figure 3(a)). Figure 3(b) shows an electromechanical lever mounted into a hand-held trigger. An electromagnetic encoder (Austrian Microsystem) measures the rotation angle of the lever to use this information to control the opening and closure of the robotic hand. Figure 3(c) shows a 3D printed handle embedding two force sensors (Micro Load Cell, Phydgets). With this device, the subject can control the opening/closure of the robotic hand proportionally to the force exerted on the handle. All these input interfaces can be activated both with the healthy hand and with the impaired one. Moreover, other input devices have been developed to allow the activation of the robotic hand with facial muscles or with the feet. In this way, the natural hands are free to move.



(a) (b) (c)

Fig. 3. The figure shows three examples of input interfaces used to activate the robotic hand. (a) shows a resistive flex sensor embedded in a finger glove, (b) shows an electromechanical lever mounted into a hand-held trigger and (c) shows a 3D printed handle embedding two force sensors.

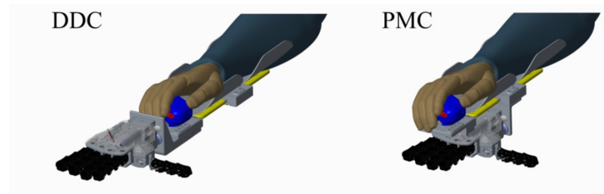


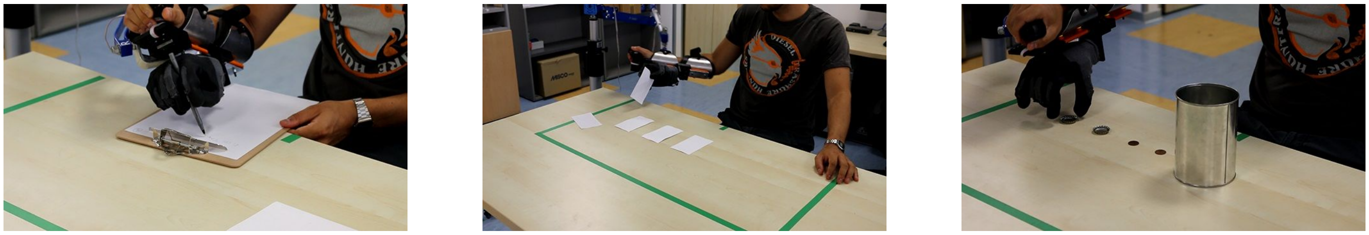
Fig. 4. The figure shows the 2 optimum positions of the robotic hand identified by the workspace and manipulability analysis in [13]. DDC = Dorsal Distal Central, PMC = Palmar Middle Central.

D. Remote control

The system is controlled and monitored by a remote PC. The sensors' signals are delivered to the PC and processed into a Simulink model. Then, the output command signal is sent to the robotic hand. Three different open-loop control strategies have been implemented: (1) the ON-OFF control in which the robotic hand opens/closes completely when the measured input signal is greater than a fixed threshold, (2) the proportional control in which the robotic hand opens/closes proportionally to the magnitude of the measured sensors signal and (3) the integral control in which the hand opening/closure level increases/decreases along the time if the measured sensors signal is over/under a fixed threshold.

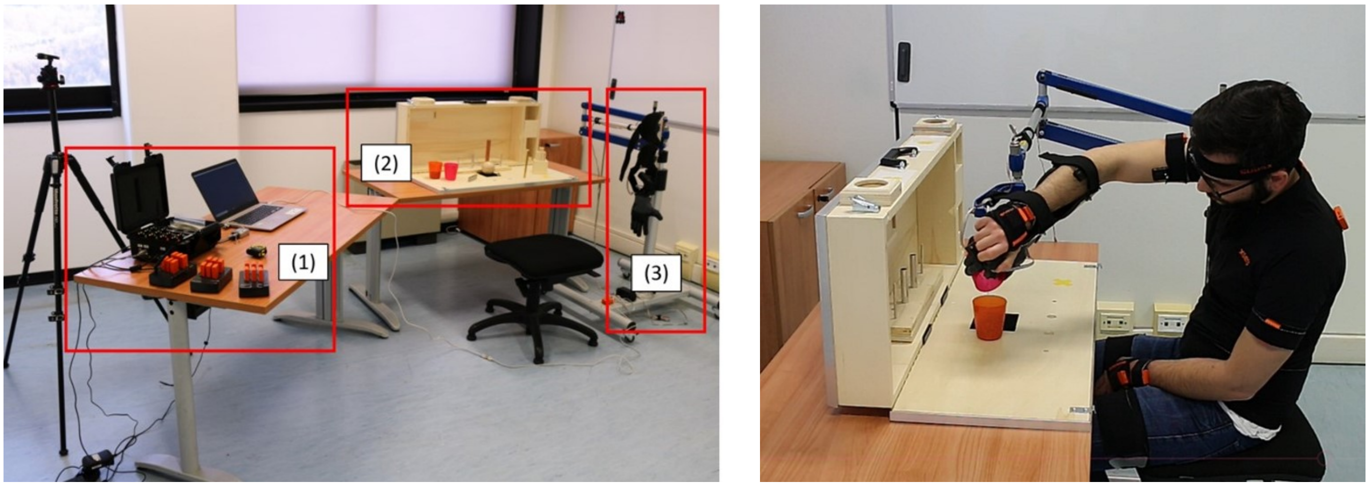
III. EXPERIMENTAL ANALYSIS

Two different experimental sessions have been conducted to find the optimum position of the robotic hand and to understand the effect of the use of the system on the development of compensatory movements.



(a) (b) (c)

Fig. 5. The figure shows a subject executing tasks with the SHX system during the experimental analysis of [13]. From (a) to (c): write a sentence, simulate page turning, lift small objects.



(a) (b)

Fig. 6. (a) shows the setup of the experimental procedure used to analyze the compensatory movements: (1) data acquisition systems, (2) ARAT test case and (3) SHX system. (b) shows an example of trunk and head compensatory movements exploited by a subject.

A. Robotic hand position optimization

Since a supernumerary robotic limb can have different positioning with respect to the subject body some considerations need to be done to find out the optimal placement. In [13], a multivariate optimization was performed to compare 16 different positions of the robotic hand by considering the workspace dimension and the manipulability of the system. 2 optimal positions, shown in Figure 4, have been identified and then experimentally evaluated by 11 healthy subjects performing standard clinical tests. An example of tasks execution is shown in Figure 5. In the experimental scores, both the positions performed similarly and no statistical differences were found. It means that the position can be selected considering the task specifications or the subject's preference, without a significant reduction of performance.

B. Compensatory movements analysis

The use of robotic systems may induce side effects that can be detrimental and worsen patients' conditions. One of the most common is the development of compensatory movements that can limit the recovery of normal movement patterns [14] [15]. Before starting with clinical trials with patients, it is essential to understand if the use of the SHX system may lead to this situation. With this purpose, eleven right-handed healthy subjects were involved within an experimental protocol in which kinematic data of the upper body and EMG signals of the right arm were acquired. The setup of the experiments is shown in Figure 6(a). Each subject executed tasks with and without the robotic system, considering this last situation as reference of optimal behavior. The Action Research Arm Test (ARAT) was used as tasks. The executions with the two optimum positions of the robotic hand, found in the previous study and shown in Figure 4, were also compared to understand if this aspect may affect the compensatory movements. Results demonstrated that the use of the SHX system reduced the range of motion of the wrist, elbow and shoulder, while it increased the range of the trunk and head movements (an example can be seen in Figure 6(b)). Concerning the EMG analysis, the muscle activation was very similar among all the conditions. Results obtained suggest that the system may be used as assistive device without causing an over-use of the arm joints and opens the way to clinical trials with patients.

IV. Clinical Investigation

A. Usability study with chronic post-stroke subjects

To evaluate the usability, the safety and the patient acceptance of the SHX system, a single session clinical study was conducted in collaboration with the University Hospital of Zurich and the Center of Rehabilitation Zurich (Wald, Switzerland) [16]. Ten adult chronic stroke subjects performed the

Fig. 7. The figure shows three patients executing tasks using the SHX system.

experimental tasks of a modified Action Research Arm Test (mARAT) using the SHX system. The whole test was repeated three times, one for each input interface shown in Figure 3. At the end of each of the three phases, the usability was asserted through the System Usability Scale (SUS) questionnaire [17]. Moreover, a clinical evaluation of the subject was conducted by measuring the modified Ashworth Scale [18] before and after the experimental session giving an estimation of the patient's muscles spasticity.
Among the three input devices tested, the usability of the hand-held trigger was rated as "good" while the other two were rated as "ok". 7 patients exhibited a reduction of the mAS although this need to be confirmed statistically. Moreover, 9 patients affirmed that they would use the system frequently, also for home assistance.

B. Rehabilitation approach with sub-acute post-stroke patients

As said in Section I, during the sub-acute phase after stroke (2 weeks-3 months after) hand rehabilitation is generally avoided in situations in which muscular hypertonus in the wrist flexor muscles is already developing. In this case, the SHX system can be used as additional therapy session. Using the finger glove, the robotic hand can be controlled by the impaired one with a particular calibration allowing to open the robotic hand by extending the fingers and close it leaving them at rest. In this way the extensor muscles are trained while the flexor ones are at rest, limiting the increase of spasticity. Future works will explore this possibility and an experimental protocol in collaboration with San Martino hospital in Genova is already under development.

V. Conclusion

In this paper, a new supernumerary soft robotic hand for assistance and rehabilitation is presented. Thanks to the combination of the gravity compensator with the efficient grasping capability of the SoftHand, an impaired subject can successfully complete several tasks. The first results are encouraging both from the point of view of the design, improved thanks to the patients' feedback, and concerning the patients' acceptance of the systems. Indeed, from the usability study 9 out of 10 subjects asserted that they would use the system frequently. Future works will be focused on the rehabilitation application of the system with sub-acute patients.

Funding

This work has received funding from the ERC Synergy grant Natural Bionics (Grant Agreement No.810346).

Acknowledgment

The authors would like to thank Manuel Barbarossa, Michele Maimeri and Mattia Poggiani for their help in the development of the setup.

References

[1] Mozaffarian, Dariush, et al. "Executive summary: heart disease and stroke statistics—2015 update: a report from the American Heart Association." Circulation 131.4 (2015): 434-441.
[2] VanGilder, Reyna L., et al. "C-reactive protein and long-term ischemic stroke prognosis." Journal of Clinical Neuroscience 21.4 (2014): 547-553.
[3] Aluas, Maria, et al. "Disability, human rights, and the International Classification of Functioning, Disability, and Health: systematic review." American Journal of Physical Medicine and Rehabilitation 91.13 (2012): S146-S154.
[4] Dromerick, Alexander W., et al. "Relationships between upper-limb functional limitation and self-reported disability 3 months after stroke." (2006).
[5] Nichols-Larsen, Deborah S., et al. "Factors influencing stroke survivors' quality of life during subacute recovery." Stroke 36.7 (2005): 1480-1484.
[6] Maciejasz, Paweł, et al. "A survey on robotic devices for upper limb rehabilitation." Journal of neuroengineering and rehabilitation 11.1 (2014): 3.
[7] Hussain, Irfan, et al. "The soft-sixthfinger: a wearable emg controlled robotic extra-finger for grasp compensation in chronic stroke patients." IEEE Robotics and Automation Letters 1.2 (2016): 1000-1006.
[8] Provinciali, L., et al. "Trattamento riabilitativo e continuità dell'assistenza." (2007): 427-482.
[9] Della Santina, Cosimo, et al. "The quest for natural machine motion: An open platform to fast-prototyping articulated soft robots." IEEE Robotics and Automation Magazine 24.1 (2017): 48-56.
[10] Santello, Marco, Martha Flanders, and John F. Soechting. "Postural hand synergies for tool use." Journal of neuroscience 18.23 (1998): 10105-10115.
[11] Roche, Aidan D., et al. "Prosthetic myoelectric control strategies: a clinical perspective." Current Surgery Reports 2.3 (2014): 44.
[12] Ajoudani, Arash, et al. "Teleimpedance control of a synergy-driven anthropomorphic hand." 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2013.
[13] Ciullo, Andrea S., et al. "Analytical and experimental analysis for position optimization of a grasp assistance supernumerary robotic hand." IEEE Robotics and Automation Letters 3.4 (2018): 4305-4312.
[14] Levin, Mindy F., Jeffrey A. Kleim, and Steven L. Wolf. "What do motor "recovery" and "compensation" mean in patients following stroke?." Neurorehabilitation and neural repair 23.4 (2009): 313-319.
[15] Carey, Stephanie L., et al. "Compensatory movements of transradial prosthesis users during common tasks." Clinical Biomechanics 23.9 (2008): 1128-1135.
[16] Ciullo, Andrea S., et al. "A Novel Soft Robotic Supernumerary Hand for Severely Affected Stroke Patients." IEEE Transactions on Neural Systems and Rehabilitation Engineering 28.5 (2020): 1168-1177.
[17] Brooke, John. "SUS: a "quick and dirty'usability." Usability evaluation in industry (1996): 189.
[18] Haas, B. M., et al. "The inter rater reliability of the original and of the modified Ashworth scale for the assessment of spasticity in patients with spinal cord injury." Spinal cord 34.9 (1996): 560-564.