Design of wearable robotic extra fingers for human hand augmentation

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***Abstract*—Augmenting the human body with supernumerary robotic extra limbs is a cutting-edge research topic with many potential applications. In this paper we focus on human hand augmentation with robotic extra fingers, used in particular as compensatory and rehabilitation tool for people with upper limb impairments. We designed and developed devices composed of single or multiple extra fingers. Underactuation and compliance are design choices that can reduce the device complexity and weight, maintaining the adaptability to different grasped objects. Each finger is composed of modular phalanges and is actuated with a single tendon. Interphalangeal joints include a passive elastic element that allows restoring the initial reference configuration when the tendon is released. The stiffness of each passive element can be customized in the manufacturing process and can be chosen according to a desired closure movement of the fingers. This paper summarizes the main design principles and the main applications that have been exploited.**

***Index Terms*—wearable robots, robotic fingers, augmentation**

I. Introduction

Wearable robotics is a challenging theme increasingly attracting researchers and engineers: wearable robots are expected to work very closely, to interact and collaborate with people in an intelligent and interactive environment [1]. Traditionally, wearable robotic structures have been mainly used in substitution of lost limbs (e.g., prosthetic limbs) or for human limb rehabilitation (e.g., exoskeletons). However, the progress in miniaturization and efficiency of the technological components is allowing more light and compact solutions, enhancing user's safety and comfort, while opening new opportunities for wearable robot uses. A very challenging research direction is to add robotic limbs to human, rather than substituting or enhancing them. This addition could let the human augment their abilities and could give support in everyday tasks. In this paper we report on the studies that we realised on the augmentation of human hand capabilities by means of supplementary robotic fingers.

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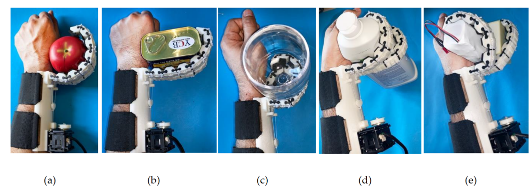

Fig. 1. Grasping objects of Activity of Daily Living (ADL) by means of a modular, underactuated double robotic extra finger.

It is intuitive that the availability of one or more extra fingers enhances the capabilities of the human hand in terms of workspace, and in terms of manipulation capabilities (see Fig. 1). Such technology demonstrated also a significant impact in improving the quality of life for elderly and people with impairments, for example in case of reduced mobility of the hand due to a severe stroke or to rheumatoid arthritis. An extra finger could also be useful in case of thumb severe arthrosis to substitute or help the thumb and reduce pain or in case of finger amputation. Furthermore, from the neuroscientific point of view, the development of this type of devices opens a series of interesting questions on how extra-limbs are perceived by human cognitive system that needs to be investigated.

The first research question that we set was how could we integrate the human hand with an additional robotic finger(s). Such devices could give humans the possibility to manipulate objects in a more efficient way, enhancing our hand grasping dexterity/ability [3]. Together with the design issues related to portability and wearability of the devices, another critical aspect was integrating the motion of the extra–fingers with that of the human hand. We developed a mapping algorithm able to transfer to the extra–fingers a part or the whole motion of the human hand. The algorithm was based on methods previously developed to map human hand motion on robotic hands with non-anthropomorphic structure [3]. In the first phase of the study we developed modular wearable extra fingers with a number of actuators equal to the joints. A smarter and more robust solution was necessary to test the device with users in real applications (Fig. 1). We updated the design by exploiting the emerging results of soft robotics [4]. We designed and prototyped an underactuated version of the finger, named the Soft-SixthFinger, that can be used by chronic stroke patients to compensate for grasping in many

Activities of Daily Living (ADL) [5]. It can be wrapped around the wrist and worn as a bracelet when not used. The light weight and the complete wireless connection with the EMG interface guarantee a high portability and wearability. The Soft Sixth Finger is composed of modular elements, realized with ABS and therefore rather stiff, connected by deformable joints, realized in TPU whose stiffness can be regulated by changing manufacturing parameters. The finger is actuated with only one motor, joint actuation is realized by means of a tendon transmission. By choosing the proper values for joint stiffness we could obtain a controlled closure movement [5].

II. Main sesign criteria and applications

General considerations: Underactuation and modularity are aspects that are investigated to reduce the complexity of the robotic systems and in particular robotic hands by maintaining a suitable level of performance. An an underactuated version of the wearable robotic extra finger has been introduced in [?] to assist patients with limited hand and arm functions for instance after a stroke event. In [6], a pair of soft robotic fingers driven by tendons and servomotors are worn on a human hand and lay on the same plane of the palm, working as two additional thumbs. In applications in which wearable extra fingers are used as compensatory devices, although the availability of a wearable robotic extra-finger opposed to the paretic limb allows the patient a stable hold for a large number of objects, a solution with two or multiple fingers could further help the user when performing some activities requiring higher payloads and grasp stability.

Underactuation: Only one motor is necessary to actuate both the single and multiple finger configurations. This feature limits the weight, complexity of the device, and improve its wearability and user's comfort. Reducing the number of actuated DoFs (Degrees of Freedom) may decrease the overall manipulability properties and the capability to adapt to different shapes and dimensions of grasped objects. For single-finger robotic devices, these properties can be partially recovered by means of compliance, that in the wearable device introduced in has been implemented by passive elastic elements in interphalangeal joints. In devices composed of more than one finger, joint compliance is not enough to guarantee the adaptability to the different shapes of grasped objects. A differential mechanism is necessary in devices composed of multiple fingers actuated with a single motor.

Finger structure: The structure of the fingers is modular at the phalanx level, the same modules can be used both for the single and double finger configurations. The device can be easily adapted to user's specific needs and features. Fingers are composed of rigid phalanges connected by compliant interphalangeal joints, that can be approximated as simple 1-DoF revolute joints. When the motor actuates the differential by pulling the sliding element, both tendons flex the fingers, that assume a configuration that allow them to grasp objects, while when the torque of the motor is released, the passive elastic elements in the joints restore the fingers to their initial extended configuration.

Applications: We believe that the most impactful application of the device presented in this paper is rehabilitation and assistance of patients with upper limb impairments, for example after a stroke [7]. Stroke is a brain attack, affecting 17 million people worldwide each year, it is the second most common cause of death and a leading cause of adult physical disability (http://strokeeurope.eu/). Impairment of the hand, and in particular of its grasping and dexterous manipulation capabilities is one of the common deficits after a stroke. Approximately 60% of stroke survivors suffer from some form of sensorimotor impairment associated with their hand. Supernumerary fingers enable patients to execute grasp and release exercises and practice intensively using repetitive movements.

III. Concluding remarks

Supernumerary limbs provide novel opportunities to recover missing abilities, resulting in improvements of patients' quality of life. The devices were tested with chronic stroke patients through qualitative experiments based on ADL and preliminary results are widely discussed in [9]. The goal of the tests was to evaluate how quickly and easily the patients could learn to use the device in ADL. Different applications were considered (e.g., kitchen scenario, consisting in preparing breakfast and lunch, some tools activities, using the extra finger as an active hook, etc.). The initial tests gave encouraging results; users could complete the tasks reducing the time and with good success rates. A representative application of the robotic sixth finger is available at the following link: https://www.youtube.com/watch?v=02Eu5cbdqGA&t=7s

References

[1] Asbeck, A. T., De Rossi, S. M., Galiana, I., Ding, Y., & Walsh, C. J. (2014). Stronger, smarter, softer: next-generation wearable robots. IEEE Robotics & Automation Magazine, 21(4), 22-33.

[2] Parietti, F., & Asada, H. H. (2014, May). Supernumerary robotic limbs for aircraft fuselage assembly: body stabilization and guidance by bracing. In Robotics and Automation (ICRA), 2014 IEEE International Conference on (pp. 1176-1183). IEEE..

[3] D. Prattichizzo, G. Salvietti, F. Chinello, M. Malvezzi. An Object based Mapping Algorithm to Control Wearable Robotic Extra Fingers. In Proc. IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics, Pages 1563-1568, Besançon, France, July, 2014.

[4] Albu-Schaffer, A., Eiberger, O., Grebenstein, M., Haddadin, S., Ott, C., Wimbock, T., ... & Hirzinger, G. (2008). Soft robotics. IEEE Robotics & Automation Magazine, 15(3).

[5] I. Hussain, G. Salvietti, M. Malvezzi and D. Prattichizzo. Design guidelines for a wearable robotic extra-finger. In proc. IEEE Int. Forum on Research and Technology for Society and Industry, Turin, Italy September, 2015.

[6] Malvezzi, M.; Iqbal, Z.; Valigi, M.C.; Pozzi, M.; Prattichizzo, D.; Salvietti, G. Design of Multiple Wearable Robotic Extra Fingers for Human Hand Augmentation. Robotics 2019, 8, 102.

[7] I. Hussain, G. Salvietti, L. Meli, C. Pacchierotti, D. Prattichizzo. Using the robotic sixth finger and vibrotactile feedback for grasp compensation in chronic stroke patients. In Proc. IEEE/RAS-EMBS International Conference on Rehabilitation Robotics (ICORR), Singapore, Republic of Singapore, 2015.

[8] Mozaffarian, D., Benjamin, E. J., Go, A. S., Arnett, D. K., Blaha, M. J., Cushman, M., ... & Howard, V. J. (2015). Heart disease and stroke statistics—2016 update: a report from the American Heart Association. Circulation.

[9] G. Salvietti, I. Hussain, D. Cioncoloni, S. Taddei, S. Rossi, D. Prattichizzo. Compensating Hand Function in Chronic Stroke Patients Through the Robotic Sixth Finger. Transaction on Neural System and Rehabilitation Engineering.