A soft supernumerary robotic finger and mobile arm support for grasping compensation and hemiparetic upper limb rehabilitation.

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\textbf{Abstract}

In this paper, we present the combination of our soft supernumerary robotic finger i.e. Soft-SixthFinger with a commercially available zero gravity arm support, the SaeboMAS. The overall proposed system can provide the needed assistance during paretic upper limb rehabilitation involving both grasping and arm mobility to solve task-oriented activities. The Soft-SixthFinger is a wearable robotic supernumerary finger designed to be used as an active assistive device by post stroke patients to compensate the paretic hand grasp. The device works jointly with the paretic hand/arm to grasp an object similarly to the two parts of a robotic gripper. The SaeboMAS is a commercially available mobile arm support to neutralize gravity effects on the paretic arm specifically designed to facilitate and challenge the weakened shoulder muscles during functional tasks. The proposed system has been designed to be used during the rehabilitation phase when the arm is potentially able to recover its functionality, but the hand is still not able to perform a grasp due to the lack of an efficient thumb opposition. The overall system also act as a motivation tool for the patients to perform task-oriented activities.

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rehabilitation activities

With the aid of proposed system, the patient can closely simulate the desired motion with the non-functional arm for rehabilitation purposes, while performing a grasp with the help of the Soft-SixthFinger. As a pilot study we tested the proposed system with a chronic stroke patient to evaluate how the mobile arm support in conjunction with a robotic supernumerary finger can help in performing the tasks requiring the manipulation of grasped object through the paretic arm. In particular, we performed the Frenchay Arm Test (FAT) and Box and Block Test (BBT). The proposed system successfully enabled the patient to complete tasks which were previously impossible to perform.

**Keywords:**
assistive robotics, supernumerary robotic limbs, grasping compensation, Rehabilitation

1. Introduction

Long-term disabilities of the upper limb affects millions of stroke survivors [1]. More than 80% of individuals who experience severe hemiparesis after stroke cannot completely recover hand and arm functionality [2]. The improvement of the paretic hand functionality plays a key role in the functional recovery of stroke patients with a paretic upper limb [3, 4]. Different motor impairments can affect the hand both at motor execution and motor planning/learning level ranging from weakness of wrist/finger extensors, increased wrist/finger flexors tone and spasticity, co-contraction, impaired finger independence, poor coordination between grip and load forces, inefficient scaling of grip force and peak aperture, and delayed preparation, initiation, and termination of object grip [5].

In the last two decades, several rehabilitation teams have started to integrate robotic-aided therapies in their rehabilitation projects. Such treatments represent a novel and promising approach in rehabilitation of the post-stroke paretic upper limb. 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 [6, 7, 8]. Most of the proposed devices for hand and arm rehabilitation are designed to increase functional recovery in the first period after the stroke when, in some cases, biological restoring and
plastic reorganization of the central nervous system take place [9]. However, even after extensive therapeutic interventions in acute rehabilitation, the probability of regaining functional use of the impaired hand is low [10]. For this reason, we recently started investigating on robotic devices for the compensation of hand function in chronic stroke patients. In [11, 12, 13, 14] we introduced a wearable robotic extra finger that can be used as an active compensatory tool for grasping action by chronic stroke patients. The principle of use of the proposed extra finger is rather simple and intuitive. The device can be worn on the paretic forearm by means of an elastic band. The robotic finger and the paretic hand act like the two parts of a gripper working together to hold an object, see Figure 1. This solution represents the minimum robotic complexity necessary to grasp and hold an object. The user is able to control the flexion/extension of the robotic finger through an EMG interface placed on the patient forehead [15]. In [16] we showed how the robotic sixth finger can be used in Activities of Daily Living (ADL) involving common bimanual tasks including opening cans and jars with different closing system and shapes.

In our preliminary experiments with patients, we noticed that 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 assistance device. This approach encourages the patients to use their potential and residual abilities effectively instead of being fully dependent on the motion of robotic device like passive assistive devices. The use of a robotic extra finger also limits the drawbacks of other compensatory strategies [17] that lead to a disuse of the affected arm and hand often lead to the learned non-use phenomenon of the hemiplegic upper extremity [18]. Based on these observations, we started exploring a possible use of the robotic sixth finger as a augmentative device also during rehabilitation in acute and sub-acute phases. In particular, we consider a possible integration of the robotic sixth finger with a mobile arm support (MAS) to compensate for arm weight. Devices for compensating the gravity force of the arm can be used during stroke rehabilitation therapy to increase the quality and quantity of movements and reduce the fatigue made by patients with upper limb impairment [19, 20, 21], especially in the sub-acute post-stroke phases. Supporting the weight of the arm is thought to benefit upper limb rehabilitation primarily by increasing capacity in terms of intensity or volume of therapeutic exercises [22]. In [23] a study on chronic stroke patients reported that gravity supported arm exercises can improve
Figure 1: The proposed system: The Soft-SixthFinger works with the paretic upper limb to compensate for hand grasping functionality. The motion of the device is controlled by a wearable EMG interface embedded in a cap. The Passive arm support compensates the gravity force of the paretic upper limb.

arm movement ability. A MAS counteracts the effects of gravity while facilitating and promoting functional movement. In addition to using a MAS for function, research has shown that gravity compensation devices are also effective for improving motor control, decreasing spasticity and minimizing fatigue [19].

In this work, we present a possible solution for an augmented motor rehabilitation which may increase the paretic upper limb recover of functions thanks to the combination of a robotic extra finger, called the Soft-SixthFinger [16, 24, 25], and the SaeboMAS (Saebo, Charlotte, USA). The aim of the Soft-SixthFinger is not to assist the paretic hand motion of the patient, but rather to add just what is needed to grasp: an extra thumb. The robotic extra finger is worn on the user’s forearm and can accomplish a given task in cooperation with the paretic limb, see Figure.1. The robotic extra finger has been designed to guarantee high wearability and portability with kinematics and actuation inspired by recent works on underactuated compliant robotic hands [26]. In particular, the robotic extra finger is passively compliant due to its flexible joints, so that it automatically adapts to the grasped object, even of different sizes. Only one motor is used to control the device flexion/extension with a tendon-driven actuation. The patient can control the motion of the robotic extra finger through an EMG based interface. Such interface can recognize, through the acquisition of the Electromyography (EMG) signal measured at the frontalis muscle of the patient, when
the patient voluntary moves his or her eyebrows upwards. Frontalis muscle contractions generate events that regulate the finger flexion/extension. The whole system is embedded in a cap. Electrodes can be easily placed on the patient’s forehead just wearing the interface. The proposed system resemble the integration of MAS with active and passive orthoses [27, 28]. To test the proposed system, we set up a pilot experiment where a chronic stroke patient was asked to perform two different tests: a modified box and block test [29] and the Frenchay Arm Test [30]. The purposes of the experiment were to verify the integration of the Soft-SixthFinger with the SaeboMAS and to evaluate with a patient possible exercises useful during rehabilitation.

The rest of the paper is organized as follows. In Section 2 all the parts composing the proposed system are described in details. Section 3 describes the performed experiments, while in Section 4 a discussion on the possible use of the proposed system is reported. Conclusion and future works are reported in Section 5.

2. The proposed system

In this paper, we propose the Soft-SixthFinger to compensate the missing grasping abilities of paretic hand and the mobile arm support to help compensate for the effects of gravity of the impaired arm. Both devices are shown in Figure. 2 and the details of each device are presented in the corresponding sections. In particular, the design and development of Soft-SixthFinger are presented in Section 2.1, while Section 2.2 reports the details on mobile arm support.

2.1. The Soft-SixthFinger

2.1.1. Design guidelines

The Soft-SixthFinger has been designed to compensate the missing grasping abilities of patients with neuromuscular disorder. The device is developed by robotic and rehabilitation teams taking into account the engineering design guidelines which are suitable to clinical needs. In particular, wearability, modularity, lightweight and robustness are fundamental structural features of the device. The wearability concept applied to the design includes also ergonomics and compact size. In addition to that, passive compliance and flexibility for shape adaptation, ease of use, comfort and intuitive user control interface, are from the functional point of view other important features
of the device. The technical details of the Soft-SixthFinger are listed in Table 1. The proposed device consists of two main parts, a flexible finger and a support base, see Figure 3. The flexible finger is based on a modular structure. Each module consists of a stiff part, 3D printed ABS (Acrylonitrile Butadiene Styrene, ABSPlus, Stratasys, USA) and a 3D printed thermoplastic polyurethane part (Lulzbot, USA) that acts as the flexible joint. We selected polyurethane for flexible parts because the high elongation of this material allows for repeated movement and impact without wear or cracking proving also an excellent vibration reduction. Reasons for adding passive elements are manifold, including storing elastic energy, avoiding tendon slackness, passive compliance, the distribution of forces over a large contact area and ensuring the uniqueness of the position [31]. A 3D printed elastic wire is placed on the back side of each module to further tune the stiffness, while a soft neoprene slice at front side of ABS parts increases friction at the possible contact points. The modular structure of the device offers twofold advantages; first the length of the device can be adjusted by choosing the total number of modules; second, the reliability of the device is increased because each module is interchangeable. The modules are assembled by sliding the
<table>
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<th>Table 1: The Soft-Sixthinger technical details</th>
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<tr>
<td>Module dimensions</td>
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<tr>
<td>Support base dimensions</td>
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<tr>
<td>Module weight</td>
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<tr>
<td>SSF total weight</td>
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<tr>
<td>Motor stall torque</td>
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<td>Pulley radius</td>
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<td>Max. current required</td>
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<td>Continuous operating time</td>
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<td>Motor maximum operating angles</td>
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<tr>
<td>Max. non-loaded velocity</td>
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<td>Max. Force at fingertip</td>
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<td>Max. payload</td>
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<td>Max. horizontal resistive force</td>
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thermoplastic polyurethane part in the ABS part. This makes the assembling process easy without the need of any screw or any other passive elements in the joints. The deformation in the joints is regulated by the stiffness of the thermoplastic polyurethane part and the elastic wire. Holes in rigid parts allow the passage of a cable which realizes the tendon driven actuation. The finger flexion is carried out by means of a tendon wire running through the finger and attached to a pulley driven by the actuator. The motor bends the finger through the wire and applies the needed torque while the flexible parts, acting like a loaded spring, bring it back when extension is commanded. The support base of the finger is realized in ABS. It contains the actuator and an elastic band that allows the user to wear the device on the forearm. The flexible finger is connected with the support base through a passive rotatable locking mechanism as shown in Figure 3. The structure of the support base is symmetrical, feature that enables the robotic finger to be worn on both left or right forearms of the patient without modifying the device. The actuator used is a Dynamixel MX-28T (Robotis, South Korea). Principal details on the motor features are reported in Table 1, while for a complete description, the reader is referred to [32]. We use ArbotiX-M Robocontroller [33] to drive the Dynamixel motor. This control solution for Dynamixel motors incorporates an AVR microcontroller, Xbee wireless radio and the motor driver. The extra finger flexion and extension are commanded through the EMG inter-
face described in Section 2.1.2. When flexion command is selected, a desired position (300 deg, which means the extra finger completely flexed) for the servomotor and a desired velocity (33.3 deg/s) are set. When extension is selected, the desired position is set to 0 deg, which results in the finger completely extended, with the same desired velocity. The maximum fingertip force and the maximum payload of the device have been measured by using a dynamometer (Vernier, USA). In order to evaluate the maximum fingertip force, the device has been grounded on a table with the finger perpendicular to the table surface. The initial configuration of the finger was fully extended and it was commanded to close at the maximum torque. The dynamometer measured the force in the vertical direction and its hook was rigidly coupled with the fingertip of the Soft-SixthFinger. The constant applied force value at fingertip is presented in Table 1. To evaluate the maximum payload an operator worn the Soft-SixthFinger on the forearm. The operator’s arm was stabilized on a table while grasping a cylindrical object (diameter=5.7 cm, weight=0.5 kg) with the aid of the Soft-SixthFinger at its maximum torque.
The grasped object was rigidly connected to the hook of dynamometer and it was pulled down using the dynamometer’s utility handle. The maximum pulling force was recorded as soon as the object started to slip. The maximum horizontal grasp resistive force was measured by grasping an object (diameter=65 mm, weight=400 g) with the robotic device and the arm. The object was slowly pulled horizontally by using the hook of the dynamometer. It was noticed that the grasp remained stable till 13 N. The modular finger structure is fitted on the support base through a passive rotatable locking mechanism that allows the device to switch between the rest and working position. The patient can switch between these two positions by using the healthy hand. At rest position, finger can be wrapped around the arm to adapt the shape of bracelet with an elastic band (see figure 4). When needed, the device can be unwrapped and used for rehabilitation activities.

2.1.2. Electromyography (EMG) Control Interface

The devices designed for patients must have simple and intuitive control interface. In this regard, we introduced in [16] the eCap, a wearable wireless EMG interface where electrodes, acquisition and signal conditioning boards are embedded in a cap. In the following we briefly recall the main features and the work principle of the device.

Using the eCap, the patients can voluntary control the Soft-SixthFinger by contracting the frontalis muscle on their forehead. This muscle, due to a bilateral cortical representation, is always spared in case of a motor stroke, either of the left or of the right hemisphere. Activation of the muscle can be achieved by moving the eyebrows upwards. The bipolar EMG electrodes placement inside the cap provides twofold advantages, firstly the electrodes can easily be placed on the patient’s frontalis muscle, secondly the stroke
patients can easily wear the eCap using their healthy hand without requiring any external help. The block diagram of the complete system is illustrated in figure 5. The specifications of the EMG acquisition board are listed in Table 2.

Silver/silver chloride electrodes are used in the eCap as they present the lowest noise interface and are recommended for biopotentials recording [34]. The EMG board was designed according to what is defined in the reference literature and taking into account the technical requirements commonly used in terms of bandwidth, dynamic range and physiological principles. Signals from physiological activity have very small amplitudes (\(<\ 5\ mV\)) and should be amplified (1000 or greater) and filtered before their recording and process-

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>EMG acquisition box dimensions</td>
<td>(3.5 \times 3.1 \times 4.5\ cm^3)</td>
</tr>
<tr>
<td>EMG acquisition box weight</td>
<td>46 g</td>
</tr>
<tr>
<td>Principle</td>
<td>Differential voltage</td>
</tr>
<tr>
<td>Number of electrodes</td>
<td>3</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 – 400 Hz</td>
</tr>
<tr>
<td>Gain</td>
<td>1000</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>100 (GOhm)</td>
</tr>
<tr>
<td>CMRR</td>
<td>110 (dB)</td>
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<tr>
<td>Operating voltage</td>
<td>(Vcc = 3.3\ V)</td>
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ing. A precision Instrumentation Amplifier (In-Amp) INA333 [35], offering high common-mode rejection (110 dB @ \( G \geq 10 \)) and low-noise high speed Operational Amplifiers (Op-Amp) AD869x to perform band-pass filtering and amplification were used in the board.

The motion of the robotic device is then controlled through a trigger signal. The trigger signal is obtained by using a single-threshold value defined as the 50% of maximum voluntary contraction, 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 in order to avoid false activation due to glitches or spontaneous spikes. The trigger detected through the EMG interface is then associated to a determined action. In particular, a single muscle contraction control the flexion extension of the extra finger, while, when the finger is stopped, two contractions in a time window of 1 s switch the motion direction from flexion to extension and viceversa. 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.

2.1.3. Computation of finger flexion trajectory

The Soft-SixthFinger has been designed according to the guidelines proposed in Section 2.1.1. To let the device be able to grasp a wide range of objects it is important to define the finger flexion trajectory once the device structure is defined. To this aim, we took inspiration from the motion of the human hand. In [36] a mapping algorithm to transfer the motion of the human hand onto a robotic extra finger is presented. The mapping algorithm takes advantage of a virtual object to reproduce the motion of a set on reference points placed on the human hand onto the robotic device. In [37] the authors proposed a way to control two supernumerary robotic fingers in concert with the motion of the human hand. The basic idea was to define a new set of postural synergies, called Bio-Artificial Synergies, for an augmented hand that comprises the human hand and the two robotic fingers. Both the solutions can be used when healthy subjects are using extra finger for augmenting human hand capabilities. In the case of a paretic limb, it is not possible to use this kind of controller due to the poor residual mobility of the paretic hand. Our idea is to use a mapping algorithm similar to that propose in [36, 11] only to determine the trajectory of the extra finger.
The flexion/extension motion of the device is triggered using EMG signals as detailed in Section 2.1.2. In the following, we report how we determine the flexion trajectory of the robotic extra finger. The first step is the determination of a reference trajectory obtained mapping human hand synergies onto the robotic sixth finger [38]. We considered a model of a human hand augmented with a model of the extra finger. We simulate using the Matlab SynGrasp toolbox [39] the motion of the human hand according to the first synergy as defined in [40]. We then defined the trajectory of the robotic fingertip using the mapping algorithm presented in [36] whose main equations are reported in the following.

Let us define a reference frame $\Sigma_0$ on the human hand model. The human hand model is that defined by the function $SGparadigmatic$ in the SynGrasp toolbox. Its origin $o$ is in the wrist center of rotation, the $z$ axis is perpendicular to hand palm plane, the $x$ axis is the intersection between the sagittal and the transverse plane, pointing towards the little finger, the $y$ axis is consequently defined. Let us indicate with $p^h_i \in \mathbb{R}^3$, $i = 1, \ldots, n_h$ the coordinates of reference points on the reference human hand, expressed w.r.t. $\Sigma_0$. In this paper we choose as reference points the five fingertips of the human hand model, therefore $n_h = 5$.

Let define as the augmented hand the system composed by the hand with its five fingers and the robotic extra finger, see Fig. 6. Consider also an additional reference point placed at the robotic fingertip. The reference points for the augmented hand are then $p^a_i \in \mathbb{R}^3$, $i = 1, \ldots, n_a$, with $n_a = \ldots$
Let us indicate with $O$ the minimum volume bounding sphere containing all the $n_a$ reference points of the augmented hand. Let $o^h$ indicate its center and let $r^h$ be its radius. Let us define a reference frame $\Sigma_1$ on the virtual sphere, whose origin is in the sphere center and whose axis are, in the reference starting position, parallel to $\Sigma_0$ axis. The reference starting position is arbitrary and do not affect the mapping procedure as detailed in [38].

Let assume the augmented hand in its starting position at time instant $t = t_0$. Assume also that at time instant $t = t_0 + \delta t$ the reference point coordinates $p^h_i$ change due to the motion of the human hand according to the first synergy. Let us indicate with $\Delta p^h_i \in \mathbb{R}^3$, $i = 1, \ldots, n_h$ a vector containing such coordinate variations. This displacement produces a transformation in the virtual sphere, that in this paper we approximate as the combination of a rigid body motion and an isotropic deformation. The rigid body motion can be furthermore represented as the combination of a translation $\Delta o^h \in \mathbb{R}^3$ and a rotation $\Delta \Phi \in \mathbb{R}^3$. The rotation term $\Delta \Phi \in \mathbb{R}^3$ is defined as $\Delta \Phi = [\Delta \phi, \Delta \theta, \Delta \psi]^T$, where $\Delta \psi$ represents the rotation w.r.t. $x$ axis, $\Delta \theta$ represents the rotation w.r.t. $y$ and $\Delta \phi$ represents the rotation w.r.t. $z$ axis. It is worth to recall that, even though the rotations between reference frames are not commutative, and the rotation order is therefore important, if the rotation angles are small, the rotation order is not significant.

The non rigid isotropic deformation can be described by the parameter $\Delta s \in \mathbb{R}$ defined as

$$\Delta s = \frac{\Delta r^h}{r^h}.$$ 

With these assumptions, we can express the displacement of each reference point on the human hand as follows

$$\Delta p^h_i = \Delta o^h + \Delta \Phi \times (p^h_i - o) + \Delta s (p^h_i - o).$$  \hspace{1cm} (1)$$

It is worth to observe that we approximate the transformation that the hand applies to the virtual sphere as a combination between a rigid body motion, described by the first two terms of the right side in eq. (1), and an isotropic transformation (compression or expansion) described by the third term. The third term takes into account the sphere radius variation. In this paper we do not consider other types of transformations for the sake of simplicity, however the method can be integrated to include a non–isotropic transformation, as described in [41], and also shear deformations [42].
Eq. (1) can be applied to all the reference points $p_i^h$, leading to the following linear system

$$\Delta p^h = A \Delta \xi,$$

(2)

where $\Delta p_h = [\Delta p_1^{hT}, \ldots, \Delta p_n^{hT}]^T \in \mathbb{R}^{3n_h}$ is a vector collecting all the reference point displacements, $\Delta \xi = [\Delta o^T, \Delta \Phi^T, \Delta s]^T$ is a $7 \times 1$ vector containing the unknown parameters describing the sphere transformation, including the translation term $\Delta o^h$, the rotation term $\Delta \Psi$ and isotropic deformation term $\Delta s$, finally, $A \in \mathbb{R}^{3n_h \times 7}$ is the linear system matrix, defined as

$$A = \begin{bmatrix} A_1 \\ \vdots \\ A_{n_h} \end{bmatrix},$$

in which each sub-matrix $A_i \in \mathbb{R}^{3 \times 7}$ is defined as

$$A_i = \begin{bmatrix} 1 & -s(p_i^h-o) & (p_i^h-o) \end{bmatrix}.$$  

The linear system in eq. (2) can be solved, to find

$$\Delta \xi = A^+ \Delta p^h + N_A \psi$$

(3)

where $A^+$ denotes a generic pseudo-inverse of $A$ matrix, while $N_A \in \mathbb{R}^{7 \times \nu}$ represents a basis of $A$ matrix nullspace, whose dimension is $\nu \geq 0$, and $\psi$ is an arbitrary $\nu$–dimensional vector parametrizing the homogeneous solution of the system. When $\nu > 0$, the vector $\psi$ can be defined to optimize a cost function that can be defined on the basis of the task, e.g., when a grasping task is performed, we would need to assure grasp stability, maximizing $\Delta s$ magnitude, while in object manipulation tasks, in which the contact forces should be constant, we should maximize $\Delta o$ and $\Delta \Phi$ and minimize $\Delta s$.

Once the sphere transformation parameters have been evaluated we need to generate the trajectory of the robotic extra finger tip. What we impose

\footnote{For any three–dimensional vector $v = [v_1, v_2, v_3]^T$, $s(v)$ indicates the skew matrix associated with vector $v$, i.e.

$$s(v) = \begin{bmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{bmatrix}.$$}

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is that also the reference point of the extra finger moves according to the transformation parameters computed on the virtual sphere. In particular, we consider

\[ \Delta p^r = \Delta o^h + \Delta \Phi \times (p^r_i - o) + \Delta s (p^r_i - o), \]  

(4)

where the parameter \( \Delta o, \Delta \Phi \) and \( \Delta s \) are those computed in eq. (3).

Eq. 4 allows to define a trajectory for the extra finger tip. This target trajectory is the result of the mapping of the first human hand synergy onto the robotic device. Note that this procedure is used only to compute a flexion trajectory of the device. The paretic hand of the patients are not directly involved in the control of the device flexion.

Once a target trajectory is defined, it is necessary to actuate the extra finger so to let the fingertip track it. In [36] a fully actuated finger with four joints was considered. In that case, an inverse kinematic technique was used to set the reference motion for each joint. For the soft robotic structure considered in this work, the computation of the actuation necessary to track the target trajectory is not straightforward. In fact, the proposed device has only one motor that actuates the whole structure through a tendon-driven system.

One possibility to select the trajectory of the robotic finger is that of varying the stiffness of the flexible joints. In fact, an opportune selection of the stiffness of the flexible joint allows to obtain different fingertip trajectory considering the same force pulling the tendon. Let us assume, in general, a compensatory device with \( n_q \) joints, actuated by \( n_t \) tendons.

Let us indicate with \( q = [q_1, \ldots, q_{n_q}]^T \in \mathbb{R}^{n_q} \) a vector containing extra fingers joint rotations and with \( t \in \mathbb{R}^{n_t} \) tendon displacements. From the kinematic analysis of the extra finger, it is possible to relate tendon displacements \( t \) to fingers’ joint configuration \( q \) as

\[ t = Tq, \]  

(5)

where \( T \in \mathbb{R}^{n_t \times n_q} \) is a transformation matrix whose elements depends on tendon routing topology and is independent from fingers posture. By applying the Principle of Virtual Work to the device it is possible to obtain the dual static relationship

\[ \tau = T^Tf, \]  

(6)

where \( \tau \in \mathbb{R}^{n_q} \) represents fingers’ joint torques and \( f \in \mathbb{R}^{n_t} \) is a vector containing tendons’ pulling forces. Considering the structure of the proposed
extra finger, the following relationship between joint torque and finger posture can be set

$$\tau + K_q \Delta q = 0, \quad (7)$$

where $K_q \in \mathbb{R}^{n_q \times n_q}$ is joint stiffness matrix, symmetric and positive definite, and $\Delta q$ indicates a configuration variation evaluated w.r.t. a reference (rest) position of the fingers $q_0$, i.e., $\Delta q = q - q_0$. For the sake of simplicity let us assume $q_0 = 0$.

The problem that we want to solve is: how can we design finger joint stiffness $K_q$ so that, when applying a certain force $F_a$ to the tendons, the configuration vector $q$ assumes a given shape $q_r$ and thus the fingertip follows a desired trajectory? If $K_q$ matrix is diagonal, i.e., if the joints are independent, the problem is straightforward. Eq. (8) can be rewritten, in this case, as

$$\tau + Qk_q = 0, \quad (8)$$

where $Q \in \mathbb{R}^{n_q \times n_q}$ is defined as $Q = \text{diag}(q)$, while $k_q \in \mathbb{R}^{n_q}$ is a vector collecting joint stiffness. Taking into account Eq. (6), the system can be solved as follows

$$k_q = Q^{-1}T^T F_a. \quad (9)$$

The solution is a vector containing fingers joint stiffness values that allows to obtain a configuration $q_r$ of the fingers when the tendons are pulled with a force $F_a$.

Eq. 9 can be used to design the stiffness of the joints so to obtain a predefined position when applying a certain force to the tendon. However, our main goal is to design a finger that, during its flexion/extension motion, follows a given trajectory, defined by the mapping procedure previously summarised. The mapping function gives us a series of goal configurations $q_{ri}$ with $i = 1, ..., t_{tra}$, where $t_{tra}$ is the sampling number. We set as possible goal trajectory the trajectory defined above as the mapping of the first human hand synergy. Following the trajectory generates $t_{tra}$ goal configurations and thus $t_{tra}$ values for the stiffness values $k_q$. To evaluate the stiffness values $k_q$, in this paper we adopted a numerical simulation of the anthropomorphic hand, actuated by synergies and integrated with the kinematic model of the robotic sixth finger. The anthropomorphic hand model has 20 DoF, its details are reported in [43], the mechanical robotic hand is a serial structure, it is composed of 7 modules, connected by 7 revolute compliant joints, as previously described. The overall augmented hand model has therefore 27 DoF. For the evaluation, we adopted SynGrasp [39].
In this simulation environment we imposed to the human hand a closure motion corresponding to the actuation of the first synergy, evaluated with the data described in [40]. We therefore evaluated the corresponding trajectory for the robotic sixth finger, using the procedure previously described and, in particular, eq. 4. Fig. 7 shows the obtained fingertip trajectory. To evaluate the corresponding stiffness values, we then assumed that the trajectory is realised by applying a linear force profile, varying from 0 to 20 N.

We finally evaluated the stiffness values for the robotic sixth finger, necessary to obtain this trajectory of the fingertip, according to Eq. 9. The obtained $k_q$ values are shown in Fig. 8. As it can be seen from the figure, to obtain the desired trajectory we need different stiffness values for each joint, in particular, joint stiffness is harder for the distal joints with respect to the proximal ones. Furthermore, for each joint, the evaluated stiffness is not constant, and depends on the level of synergy actuation, with a nonlinear behaviour. Since: 1) it is not practically feasible to design the stiffness of each joint so that it follows the evaluated curve, 2) the overall stiffness variation for each joint is not very high, 3) the trajectory shape depends on the
Table 3: Mean joint stiffness values.

<table>
<thead>
<tr>
<th>joint n.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>joint stiff. (Nmm/rad)</td>
<td>363.2</td>
<td>423.7</td>
<td>508.5</td>
<td>635.6</td>
<td>847.4</td>
<td>1271.2</td>
<td>2542.3</td>
</tr>
</tbody>
</table>

ratios between the different stiffness values, rather than on their actual value, we then evaluated the trajectory obtained if each joint stiffness is assumed constant, evaluated as the mean of each stiffness curve. The stiffness values are reported in Table 3, while the obtained trajectory is shown in red in Fig. 7, it is clear that the difference with the desired trajectory is practically negligible; in Fig. 9 we reported the difference between trajectories: as it can be seen, its maximum value is lower than 1 mm. We can therefore reproduce the desired trajectory by realising joints with different, but constant, stiffness values.

Figure 8: Joint stiffness values necessary to generate the desired trajectory of the robotic sixth finger tip, evaluated according to Eq. (9), as a function of the corresponding actuation rate of the first synergy.

2.2. The mobile arm support (SaeboMAS)

The SaeboMAS is used for gravity compensation of the impaired upper limb, allowing the patient to perform exercises, as well as self-care activities
demanding a smaller muscle effort. The device can be table-mounted moreover a height adjustable rolling base makes the SaeboMAS mobile for easy relocation throughout user facility. It has an elbow support and a comfortable malleable forearm support with removable liners for infection control. Through an adjustable spring based parallelogram the SaeboMAS can offer various levels of assistance to the user, while a measurable graded tension scale is useful for tracking and documenting progress.

3. Pilot experiments with a chronic patient

In this pilot study, we performed two possible tests to see the effectiveness of the proposed system in performing the tasks with a chronic stroke patient. Fig. 1 shows on the left side the coupling of the Soft-SixthFinger and the mobile arm support with the paretic arm. The Soft-SixthFinger is worn through the support base and elastic straps. The MAS is attached to the forearm through the custom brace and its end-effector support. The forearm is firmly secured to the brace using elasticized fabric wrap. The MAS prevents rotation of the brace in the vertical plane thus ensuring the forearm is always parallel to the table surface. The patient performed the a modified
Box and Block Test and the Frenchay Arm Test. In all the tasks, the subject used the Soft-SixthFinger to grasp the object while he used mobile arm support to support the weight of the arm.

The subject performing the test showed a partial residual mobility of the arm (≤ 2 in the National Institute of Health Stroke Scale (NIHSS) [44], item 5 “paretic arm”). Moreover, the patient showed the following characteristics: normal consciousness (NIHSS, item 1a, 1b, 1c = 0), absence of conjugate eyes deviation (NIHSS, item 2 = 0), absence of complete hemianopia (NIHSS, item 3 ≤ 1), absence of ataxia (NIHSS, item 7 = 0), absence of completely sensory loss (NIHSS, item 8 ≤ 1), absence of aphasia (NIHSS, item 9 = 0), absence of profound extinction and inattention (NIHSS, item 11 ≤ 1). The rehabilitation team assisted the subject during a training phase for each test. During this phase, the optimal position of the devices on the arm, according to the patient motor deficit, was evaluated. The subject did preliminary trails to see his comfort in using the robotic devices and to get familiar with the control interface.

3.1. The Box and Block test

The Box and Block test measures unilateral gross manual dexterity [45]. We slightly modified the test in order to let the patient use the proposed system. In particular, we removed the first compartment of classic setup leaving the cubes free on the table.

The patient was then able to use the arm support plus the extra finger to grasp the cubes and move them inside the second compartment. The subject used the Soft-SixthFinger to grasp the blocks from the table while the arm support was used to assist the paretic arm mobility. The test setup is reported in Fig. 10.

After the training phase, the patient performed the test three times with four different conditions: a) without using any device, b) only MAS, c) only Soft-SixthFinger and d) the complete system. The results of the test are reported in Table 4 and screenshots of the tasks are shown in Fig. 10. On average, patient scored 8 blocks per minute while using the complete system (condition d). On the contrary, he scored 0 while using none of the devices.

3.2. The Frenchay Arm Test

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 or she scores 0 in case of fail. The subject sit at a table with his
Figure 10: The box and block test: The subject grasped the object with the help of the soft-sixthfinger while using passive arm support to assist the paretic arm

Table 4: Results of the Box and Block Test, without using any device, only MAS, only SSF and SSF plus MAS

<table>
<thead>
<tr>
<th>Box and Block Test</th>
<th>None</th>
<th>SSF only</th>
<th>MAS only</th>
<th>SSF plus MAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blocks per minute</td>
<td>0</td>
<td>3</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

hands in his lap, and each task started from this position. He or she is 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.
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.
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
Table 5: Results of the Frenchay Arm Test, without using any device, only MAS, only SSF and SSF plus MAS

<table>
<thead>
<tr>
<th>Frenchay Arm Test</th>
<th>None</th>
<th>SSF only</th>
<th>MAS only</th>
<th>SSF plus MAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stabilize a ruler</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Grasp a cylinder</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Pick up a glass</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Remove a sprung</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Comb hair</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 11: Examples of the Frenchay Arm Test (FAT) fulfilled thanks to the proposed system: on the left comb hair, in the center grasp a cylinder and on the right pick up a glass.

without spilling\(^2\) (see Fig. 11).

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.

5. Task.5 Comb hair (or imitate); must comb across top, down the back and down each side of head.

When compared with other upper limb assessments, the Frenchay arm test has shown good reliability in measuring functional changes in stroke patients [30].

We performed the FAT with a chronic stroke patient using the proposed system to see how it can improve the performance of the subject.

After the training phase, the subjects had three minutes to perform the test. The subjects performed the tasks with four different conditions, without using any device, only MAS, only SSF and SSF plus MAS. The order of tasks was selected randomly. The results of the test are reported in Table 5 and

\(^2\)Note that for safety reasons we did not use water in presence of electronic components.
screenshots of the tasks are shown in Fig. 11.

Patient scored 4 out of 5 while using complete system, on contrary he scored only 1 without using the proposed devices.

4. Discussion

Stroke survivors have to reacquire a very high level of hand motor control before they actually can use the limb in ADL. This might explain why stroke patients that seems to show an adequate movement ability when monitored in the laboratory often do not use the limb into ADL with the expected regularity [46, 47]. With the aid of the robotic finger and of a passive arm support, the patients can better perform rehabilitation tasks and closely simulate the desired motion with the non-functional arm for rehabilitation purposes. The passive arm support can assist patient’s paretic arm in making more meaningful movements during the rehabilitation process, even when proximal arm muscles are still deficitary. It counteracts the effects of gravity to functionally integrate the patient’s affected arm during various tasks. The patient can exercise the impaired arm by positioning the extra robotic finger next to the object and can attempt to use their paretic arm to complete the tasks to the extent of their maximum abilities with minimum assistance from the robotic devices. The level of assistance to paretic arm can be adjusted by setting the stiffness of the MAS after monitoring the patient improvement. The tasks can be completed by the robotic finger and with the help of arm support even if the patient’s upper limb is too weak to do so, thus providing the patient with the motivation to attempt these tasks and minimizing the feelings of defeat that may arise when attempting to complete tasks beyond their current capability. This could help the patient to eventually regain the ability to complete these tasks on their own. The patient may benefit in the short term with increased feelings of independence while simultaneously working toward the long term goals of rehabilitation and healing.

The proposed system aims to assist persons who are not able to make a functional grasp with their paretic arm and hand themselves. The creation of a functional grasp by means of the extra-finger flexion enables patients to execute task-oriented grasp and release exercises and practice intensively using repetitive movements. Repetition is an important principle in motor learning which reflects the Hebbian learning rule that connections between neurons are strengthened when they are simultaneously active (i.e., long term potentiation) [48]. Repetitive task training is a key modality of effective training
in stroke [49]. The proposed dynamic system can be used in goal-directed activities and lowers the threshold for patients to participate in a greater variety of evidence-based treatment programs. In fact, notwithstanding the proven efficacy of classic CIMT [50], the obvious impossibility to perform bimanual tasks in daily living activities may deeply affect patients’ motivation. This issue is overcome by our device, which instead encourages and motivates the patients to fully use their residual abilities, meanwhile possibly acquiring new grasping abilities. For these reasons, we could even say that the MAS plus Soft-SixthFinger device touches in parallel both cognitive and motoric aspects of the rehabilitation process. From the perspective of therapy efficiency and patient satisfaction, the use of an extra finger may be beneficial, because less individual therapy assistance is needed. To date, most clinical studies reporting the use of compensatory tools have been performed in chronic stroke patients. A clinical assumption is that the benefits of such an extra finger may be larger in sub-acute stroke patients, because learned non-use and secondary complications like contractures may be prevented. However, this has not yet been investigated systematically. Obviously, stroke is not the only field of application of the proposed device. All diseases leading to upper limb/arm paresis (myelopathies, amyotrophic lateral sclerosis, multiple sclerosis, muscular dystrophies) may be theoretically a suitable ground of application.

The patients that could take advantage by using our proposed system may be those that show mild upper limb paresis associated with higher hand and fingers weakness in the first weeks after stroke, i.e., during the recovery phase [51]. Although the upper limb paresis is not complete, some of these patients are not able to move the arm against gravity, especially in the sagittal plane and, in addition, the absence of the grasping function makes impossible to perform a real “task-oriented therapy”. For example, Nijland et al. [52] showed that at nine days after stroke some patients showed the shoulder abduction movement, but the fingers extension, which is crucial for the grasping function, is absent. The presence of the shoulder abduction movement is not usually highly correlated with the ability to move the arm against gravity in the sagittal plane in which the most of the ADL take place. In this case report study, we have used the MAS mainly for helping the patient, who was able to perform the shoulder abduction (frontal plane), to better perform shoulder flexion against gravity (sagittal plane) and to grasp objects for solving tasks with the Soft-SixthFinger due to the absence of hand and fingers movements.
5. Conclusion and Future work

In this paper, we presented an approach to use grasp compensatory device and passive arm support in rehabilitation exercise for hemiparetic upper limb where grasping an object and its manipulation through arm is fundamental. We propose the use of our combined system for an “augmenting rehabilitation approach” in addition to the common physical therapy in those patients in which some upper limb movements are present, but an “ecological” and task-oriented therapy cannot be performed. Indeed, there are evidence that better outcome is favored by intensive high repetitive task-oriented and task-specific training during the recovery phase [53]. We presented our preliminary results in combining the Soft-SixthFinger with the zero gravity arm support, SaeboMAS. In our previous works on active tools for manipulation compensation we focused mostly on the grasping part developing an extra-finger that can adapt to different object shapes. However, we noticed that most of the patients testing our devices were still not able to perform basic rehabilitation tests designed for upper limb due to the poor mobility of the paretic arm/shoulder. In this paper we tested the feasibility of the proposed system with one of our same chronic stroke patients. As a result the patient was able to perform the tasks which even needed the grasped object manipulation through paretic arm mobility. The proposed system is a first step toward the realization of an assisting platform when the arm is recovering its functionality, but the hand is still not able to perform a grasp. Currently, we are investigating whether it is possible to introduce the proposed system in early rehabilitation phase. The targeted patients could be who show mild upper limb paresis associated with higher hand and fingers weakness in the first weeks after stroke. Even at this stage, some patients are unable to move the paretic limb against gravity and incapable to fully grasp the objects. This condition makes impossible to perform a real task-oriented therapy. In this regard our system can fully support them to perform accurate rehabilitation exercises. Additional opportunities for these robotic devices include patient monitored rehabilitation training that can be done at home and direct ADL assistance for those with minimal paretic limb functionality. For example, some studies in literature claim that rehabilitation in chronic stages should focus on learning adaptive processes either through more difficult bi-manual activities or through the forced use of the affected limb [54]. In this regard, the patients can use their muscles abilities effectively to complete the bi-manual task, while exploiting only minimal assistance by the proposed
system needed to complete the tasks. Moreover, clinical team could develop new protocols and scenarios for the involvement of such robotic devices, while monitoring the patients improvements on regular basis.

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References


