The *SSSA-MyHand*: a dexterous lightweight myoelectric hand prosthesis

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***Abstract*— The replacement of a missing hand by a prosthesis is one of the most fascinating challenges in rehabilitation engineering. State of art prostheses are curtailed by the physical features of the hand, like poor functionality and excessive weight. Here we present a new multi-grasp hand aimed at overcoming such limitations. The *SSSA-MyHand* builds around a novel transmission mechanism that implements a semi-independent actuation of the abduction/adduction of the thumb and of the flexion/extension of the index, by means of a single actuator. Thus, with only three electric motors the hand is capable to perform most of the grasps and gestures useful in activities of daily living, akin commercial prostheses with up to six actuators, albeit it is as lightweight as conventional 1-Degrees of Freedom prostheses. The hand integrates position and force sensors and an embedded controller that implements automatic grasps and allows inter-operability with different human-machine interfaces. We present the requirements, the design rationale of the first prototype and the evaluation of its performance. The weight (478 g), force (31 N maximum force at the thumb fingertip) and speed of the hand (closing time: <370 ms), make this new design an interesting alternative to clinically available multi-grasp prostheses.**

***Index Terms*—Artificial Hand, Geneva Mechanism, Grasping, Prosthetics, Upper limb amputation.**

I. Introduction

THE human hand, as well as being one of the principal agents of motor activity, is the chief organ of the fifth sense, touch, and part of our communication system. Its anatomical complexity, richness and variety of sensory receptors combined with its intimate communication link with the brain, make the replacement of a missing hand by a prosthesis one of the big challenges in rehabilitation engineering and applied neuroscience.

State of art myoelectric prostheses suffer from a number of limits like: poor/difficult controllability, lack of sensory feedback, poor functionality and *cosmesis*[1] as well as wearing discomfort (too heavy, too warm or too cold) [1], [2]. While controllability and sensory feedback mainly pertain to the interface between the individual and the prosthesis, namely the human-machine interface (HMI), functionality, cosmesis, and wearability are issues mostly related to the physical features of the hand. The latter are of interest for this work.

Conventional myoelectric hands, clinically available since the 70s [3] are relatively simple devices: a thumb opposes four fingers and all digits move simultaneously in order to form a tri-digital grip. Although they partially restore some of the lost motor functions, their functionality is severely curtailed by the limited degrees of freedom (DoFs), and in particular by the lack of three components, that are: (i) thumb abduction/adduction, (ii) independently driven digits and (iii) wrist flexion/extension. In unimpaired grasping these three components and their combination are pivotal to allow a wide range of prehensile and non-prehensile grasp patterns and postures, in a wide range of arm orientations; with a conventional 1-DoF prosthesis this versatility is prohibited.

In an attempt to overcome such limitations new multi-articulated anthropomorphic hands, reflecting different design approaches, were proposed in the last decades [4]-[9] (for a detailed review refer to our previous work [10]). Most of the past designs attempted to match the *grasping function* of the hand rather than its individual movements, by combining a reduced number of commercially available motors together with differential mechanisms and/or underactuated digits. This was the case for the SVEN [4], the MANUS [5], the SmartHand [7], the Vanderbilt [8] and the DEKA hands [11], to cite a few, which were purposely designed in order to perform grasps and gestures useful in activities of daily living (ADLs). The principle of underactuation was taken to an extreme level in the Pisa/IIT SoftHand [9] in which a single actuator drives 19 joints, taking inspiration from postural synergies in the human hand [12]. The opposite design approach was pursued within the DARPA flagship programme “Revolutionizing prosthetics 2009”, the (financially) largest research programme focusing on upper limb prosthetics in the last decades. The programme’s objective, namely to match the individual movements of the natural hand in the artificial hand, was remarkably met by technicians and researchers, which fitted 15 custom–made

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[1] Cosmesis is the term used in prosthetics to describe how a particular device looks. A device is considered to be cosmetic in appearance if it is aesthetically pleasing and looks like the limb it seeks to replace in both its lines and color [13]. Static or dynamic cosmesis refer to the appearance of the prosthesis while in fixed position or while moving.

motors and drivers inside the palm and digits [6]. The result was a hand prototype potentially able to perform fine manipulation of objects, albeit this opportunity was achieved at the detriment of weight, reliability and cost [6].

Besides these research/academic endeavours, new five-fingered prosthetic hands became clinically available as off-the-shelf components, in the recent years. Among these the *iLimb* (by Touch Bionics Ltd, UK), the *BeBionic* (by RSL Steeper Ltd, UK), the *VINCENTevolution2* (by Vincent Systems GmbH, Germany) and the *Michelangelo* hand (by Ottobock GmbH, Germany) are the most advanced. The *iLimb* and *BeBionic* are five-fingered hands with independent flexion/extension of all the digits (i.e. five independent actuators). In these hands the thumb abduction/adduction movement is passive: the user must rotate the thumb manually in either the opposition (thumb facing the fingers as to perform a power grasp) or the reposition configuration (thumb facing the lateral aspect of the index as to perform a lateral grasp – the key grip). Although the movement was automatized in the latest version of the *iLimb* hand (the *iLimb ultra revolution*) and in the *VINCENTevolution2* hand, this was made possible by further increasing the number of actuators (to a total of six), hence the power consumption and, importantly, the weight of the device. However this is in contrast with the well-known fact that the one of the most important concerns for myoprosthesis users is wearability, that is associated to the device mass, which should be significantly reduced [1], [13].

The *Michelangelo* hand follows the opposite philosophy, being actuated by just two motors [14], [15]. One motor is devoted to the abduction/adduction of the thumb, while the other allows for the simultaneous (mechanically coupled) flexion/extension of all the digits. This feature prevents certain non-prehensile and prehensile patterns, which are useful to perform common ADLs: for example it is not possible to flex the index when the flexion of the thumb (or middle finger) is locked, as required to pull the trigger of a drill while holding it. For the same reason it is not possible to take the index apart the last three fingers, as required to press buttons. These functions instead are possible with the *BeBionic* and *iLimb* hands due to their independent digits. In short, although the newly clinically available myoelectric hands represent an enormous breach in a market niche which has been substantially frozen for 50 years, such devices still demonstrate several functional limitations that preclude a substantial added value with respect to the hands of the previous generation besides being 10-40% heavier [14] and – remarkably – three to four times more expensive[2].

In this work we propose a design of an anthropomorphic mechatronic hand sought to overcome the functionality and weight issues of currently available myoelectric prostheses. To address this objective we developed a novel transmission and a mechanical architecture which allows to perform most of the grasps and gestures useful in ADLs, using only three actuators. Moreover, in an attempt to include artistic constraints in the design process, the aesthetics of the hand was jointly conceived by industrial designers and engineers, with the underlying objective of developing a device that could draw attention rather than try to be unnoticed: a robot-cartoon looking-like hand. This paper presents the design rationale, the developed prototype as well as the evaluation of its performance, compared with those of commercially available multi-grasp prostheses [14].

II. Requirements of the SSSA-MyHand prosthesis

Low cost and robustness were the pivotal requirements for the design of the *SSSA-MyHand* prosthesis. All other requirements related to functionality, anthropomorphism, cosmesis, and target performance were identified after reviewing the state of the art of robotic/prosthetic hands [10] and taking into considering the feedback from the users [1], [17], together with the experience gained by our group in developing functional robotic hands for research [7], [18], [19] and in testing them in realistic scenarios [20], [21], [22], [23].

A. *Motor functions of the hand*

A prosthetic hand should allow amputees grasping objects and performing motor tasks useful in ADLs. This rather general, qualitative statement was quantified with a list of motor functions already deemed fundamental in a number of studies [7], [13]. The list comprises of: *i)* the power (or cylindrical) grasp (used in 40% of ADLs), *ii)* the precision grasp (used in 30% of ADLs), *iii)* the lateral grasp (10% of ADLs), *iv)* pressing keyboard keys/buttons (7% of ADLs), and *v)* forming a neutral position (used during ~40% of the day time) (percentages estimated by Zheng and colleagues [24]). The latter is desirable from an aesthetic perspective (when the prosthesis is not grasping anything, it should mimic a hand at rest) and from a functional point of view: when donning/doffing a coat or a shirt it is necessary that the hand assumes a small form factor.

B. *Anthropomorphism and cosmesis of the hand*

The hand was conceived as a self-contained trans-radial prosthesis, eventually mountable onto a wrist. A target size of roughly the 50th percentile male (or equivalently roughly the 95th percentile female according to the hand anthropometry by Greiner [25]) was deemed a suitable trade-off: it is small enough to be clinically exploited by a wide audience of below-elbow amputees but large enough to ensure a proper grip aperture and –importantly– to allow the integration of its functional components at affordable costs [26]. Notably, the 50th percentile male is roughly the size of current clinically available multi-grasp hands [14]. A desirable target mass was ~400 g which corresponds to the average mass of the human hand [25]. The human model surely represents a gold standard, however, since in most cases prostheses are anchored to the body through a suspension system (and not directly through the skeleton) their perceived weight is larger than the actual one. Hence, a lower mass is even a more desirable design target [13]. Moreover, it is a well-known fact that heavy prostheses, combined with exaggerated compensatory movements required by patients to manoeuvre them in order to compensate for their

[2] Personal conversations with representatives of manufacturers.

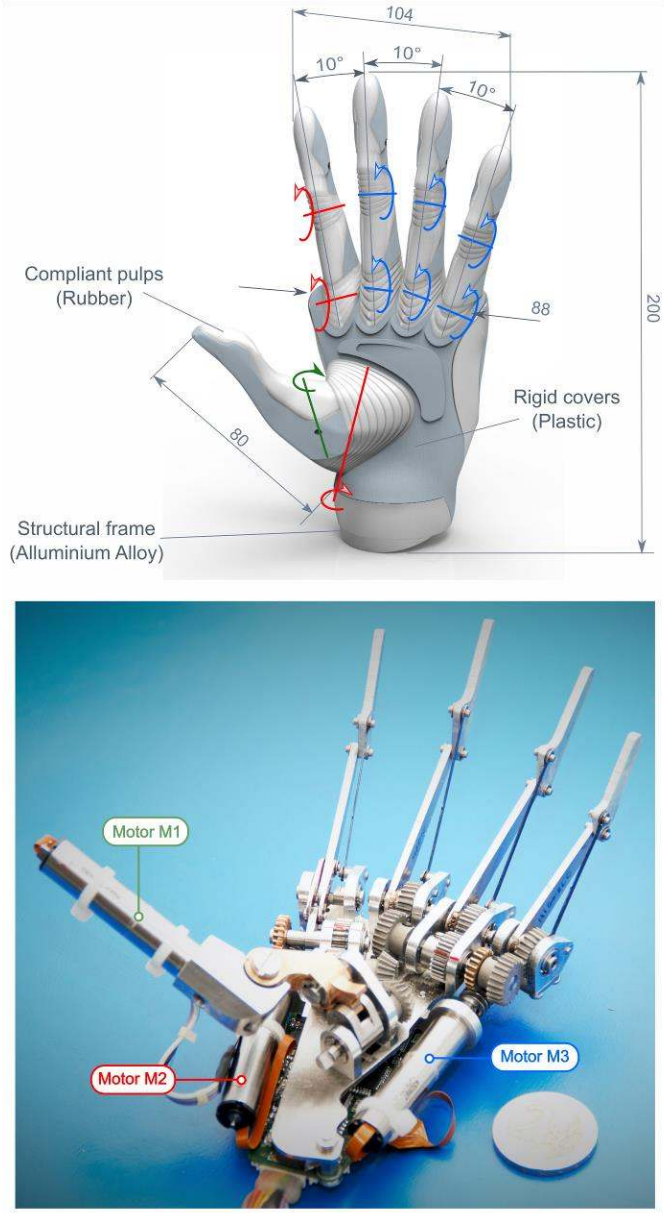

Fig. 1 Dimensions, actuation units and joints of the *SSSA-MyHand* prosthesis. The hand includes 10 joints actuated by three motors (M1-M3): M1 is housed in the body of the thumb and drives its flexion-extension; M2 is housed inside the palm of the hand and alternatively drives the flexion/extension of the index finger and the abduction/adduction of the thumb; M3 also housed within the palm, drives the middle, ring, and little fingers. Dimensions are in mm.

limited DoFs and controllability, are the main causes for complications like overuse syndromes [27], [28].

As regards the range of motion (RoM) of the joints in the prosthesis, we chose as the target values those observed in the human hand, in order to improve the dynamic cosmesis of the hand and to enable use of common tools and instruments (ergonomics). The RoMs of the human thumb are approximately between 45° and 60° for the basal joint (palmar and radial abduction movements), 90° for the inter-phalangeal (IP) joint, and 65° for the metacarpo-phalangeal (MCP) joint. Normal RoMs of the long fingers fall between 70° and 130° for the flexion of the distal and proximal IP and MCP joints.

The design of the visible parts of the prosthesis was a crucial step. The conventional approach based only on functionality and engineering principles was not pursued; instead, architectural elements and features were included, in order to develop an aesthetically enjoyable hand. In particular, in countertrend with commercially available silicone gloves or myoelectric prostheses and with the actual definition of static cosmesis [13], we opted for a manifest non-human-like design concerning the covers, thus deliberately moving away from the *uncanny valley* [30].

C. Performance of the hand

Desirable performance of a prosthetic hand can be inspired by the natural hand: average physiological speeds for everyday pick-and-place tasks have been found to be in the range of 3 to 4 rad/s (170-230 °/s), while most ADLs require prehension forces in the range of 0-65 N [29]. The natural hand is also able to sustain, in a power grasp, very large weights that can easily reach 30-50 kg (e.g. large suitcases). Concerning the power consumption, any myoelectric prosthesis should ensure a full-day operation without battery recharging. While ideal figures can always be used as design targets, the experience gained by working in this field has taught us that available engineering approaches are impractical and require extreme simplifications of the system. In general, trade-offs among desired performance, prehension capabilities and anthropomorphism are mandatory, given a certain budget [11], [13], [18], [26]. Indeed, reliable actuators with power density similar to the human muscles still do not exist for robotic applications [10], and low-efficiency electrical motors are still today the most effective choice.

III. Design of the SSSA My-Hand prosthesis

The cost and robustness requirements motivated us to design a device based on a reduced number of parts, and wherever possible using low-cost manufacturing processes (like laser cutting) and commercial off-the-shelf components, including commercial actuators. We reduced the complexity of the system by designing a five-fingered anthropomorphic hand based on three identical motors (M1, M2, M3 in Fig. 1) and on a Geneva drive transmission [30], in order to fulfil the functional requirements in a size equal to the 50^{th} percentile male hand. The actuation architecture comprised: *i)* an independent flexion/extension of the thumb (using M1), *ii)* a semi-independent abduction/adduction (ab/ad) of the thumb and flexion/extension of the index finger (using M2 and the Geneva drive), and *iii)* a simultaneous/synchronous flexion/extension of the last three fingers (using M3). This architecture allows performing all the grasps and gestures listed in the requirements (cf. paragraph IV).

The long fingers were designed with two joints each: a proximal joint (equivalent to the MCP in humans) and a more distal one, here referred to as IP (inter-phalangeal) joint. Conversely, the thumb was designed with no IP joint; it could flex/extend around an equivalent MCP joint and abduct/adduct around an equivalent trapezio-metacarpal (TM) joint. The three identical motors are 8 W brushless DC motors (EC10, Maxon Motor, Switzerland) with integrated planetary gearheads (64:1 reduction ratio) and Hall-effect sensors. The motion of the three

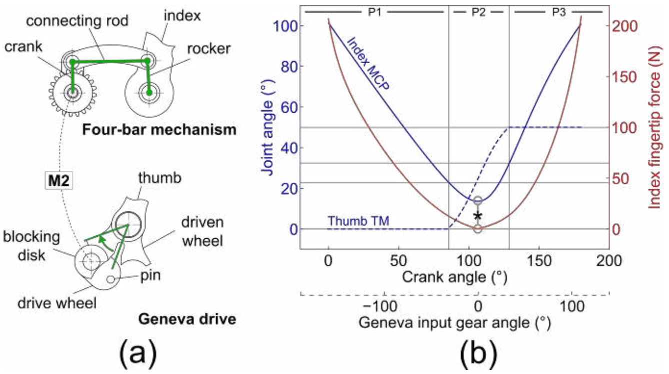

Fig. 2 Thumb abduction/adduction, Index flexion/extension Semi-Independent Transmission (TISIT). a) Motor M2 actuates the four bar mechanism (connected to the flexion/extension of the index finger) and the Geneva drive (connected to the abduction/adduction of the thumb). b) Synchronization of the TISIT: the thumb switches its opposition plane (dashed blue curve) when the index finger (blue solid curve) is close to full extension (cf. asterisk). This point corresponds to the dead point of the four-bar mechanism, i.e. the configuration at which the output force is null (red curve). P1, P2 and P3 indicate the three phases of the TISIT.

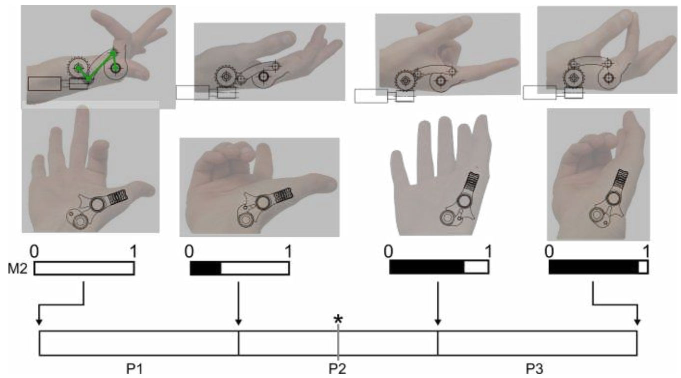

Fig. 3 Graphical representation of the three phases (P1-P3) of the TISIT vs. the rotation of the input drive (motor M2) as indicated by the progress bar. P1: the index finger extends. P2: the index finger reaches its maximum extension (cf. asterisk) and the thumb switches its opposition state. P3: the index finger flexes again.

motors was made non-back-drivable by including one worm gear on the output shaft of each gearhead, similarly to the design by Gow [32] and Puchhammer [15]. This solution was a necessary design constraint introduced to prevent power consumption from the battery while grasping [13].

A thin plate at the *metacarpus level* holds all functional components, including the motors M2 and M3 (M1 was contained in the body of the thumb), the mechanical transmission, the control electronics and a mechanical wrist (Fig. 1). Such assembly is enclosed into a 3D-printed metallic mainframe (aluminium alloy) inspired by the Möbius strip [33] and into plastic covers protecting the internal components. The latter were moulded using materials which stiffness was based on the specific role of the component in the hand (structural components moulded in stiff materials, others in soft materials) and shaped with round curves in order to increase the sense of affinity of the users with the device. In particular, the finger pads were designed so to replicate the mechanical features of the human skin taking inspiration from our previous work [34]. The hand includes a sensory system both for automatic grasp control and for future integration with a HMI able to provide sensory feedback to the user [20], [35], [36]. The sensory system, also dictated by robustness constraints, comprises position sensors (Hall-effect sensors in the motors), touch sensors (FSR sensors for future integration in the fingertips of the thumb, index and middle fingers) and motor current sensors (via shunt resistors). The electronic board implements a grasp controller based on the control inputs (analogue inputs or commands sent over a serial port) and is ruled after a finite-state machine. Each functional component is described in the following sub-sections.

A. Mechanical design

1) Thumb abduction/adduction-Index flexion/extension Semi-Independent Transmission (TISIT)

The *SSSA-MyHand* prosthesis includes a novel transmission mechanism that implements a semi-independent actuation of (i) the ab/ad of the thumb and (ii) of the flexion/extension of the index, by means of a single actuator (in this case M2) [30] (Fig. 2). We dubbed this TISIT (Thumb-Index Semi-Independent Transmission): it combines a Geneva drive and a four-bar mechanism, which are both driven, in parallel, by a worm gear mounted on the shaft of the actuator (Fig. 2a). In particular, the input of the TISIT is connected to both the drive wheel of the Geneva drive and the crank of the four-bar mechanism. The output of the Geneva drive is used to rotate the opposition plane of the thumb between two positions (ab/ad of the thumb), whereas the output of the four-bar mechanism (i.e. the rocker) is used to flex/extend the index finger (in particular its MCP joint) in a continuous fashion (trajectories in Fig. 2b).

A Geneva drive is a gear mechanism that translates a continuous rotating motion of the drive wheel (input) into an intermittent rotary motion of the driven wheel (output). The drive wheel has a pin that reaches into a slot of the driven wheel advancing it by one step for each turn of the drive wheel. The drive wheel also has a raised circular blocking disc that locks the driven wheel in position between steps (a comprehensive textbook on intermittent mechanisms was published by Bickford [37]). The driven wheel of the Geneva drive was designed in order to move the thumb between two positions (i.e. the thumb opposition or reposition configurations/states) with the two steps being separated by 50° (Fig. 2).

The four-bar mechanism was designed so that the rocker could complete two oscillations per turn of the crank (crank-rocker configuration fulfilling the class I *Grashof* condition) (Fig. 2a). This implies, in general, two dead points in the mechanism (dead point is defined as the geometrical configuration at which the linkage loses its mobility); such points are out of phase by 180° and are both characterized by having (i) the crank aligned with the connecting rod and (ii) the rocker inverting its motion. In the TISIT we modified the conventional four-bar mechanism: in particular we limited the mobility of the crank to less than one turn (in particular, 180°) in order to reach one dead point (where the index finger is fully extended - cf. asterisk in Fig. 2b) and to inhibit the reaching of the second dead point. As a result of the design the index finger starts from fully flexed and, as the crank rotates, it fully extends (crossing the dead point) and flexes again (Fig. 2b). Notably,

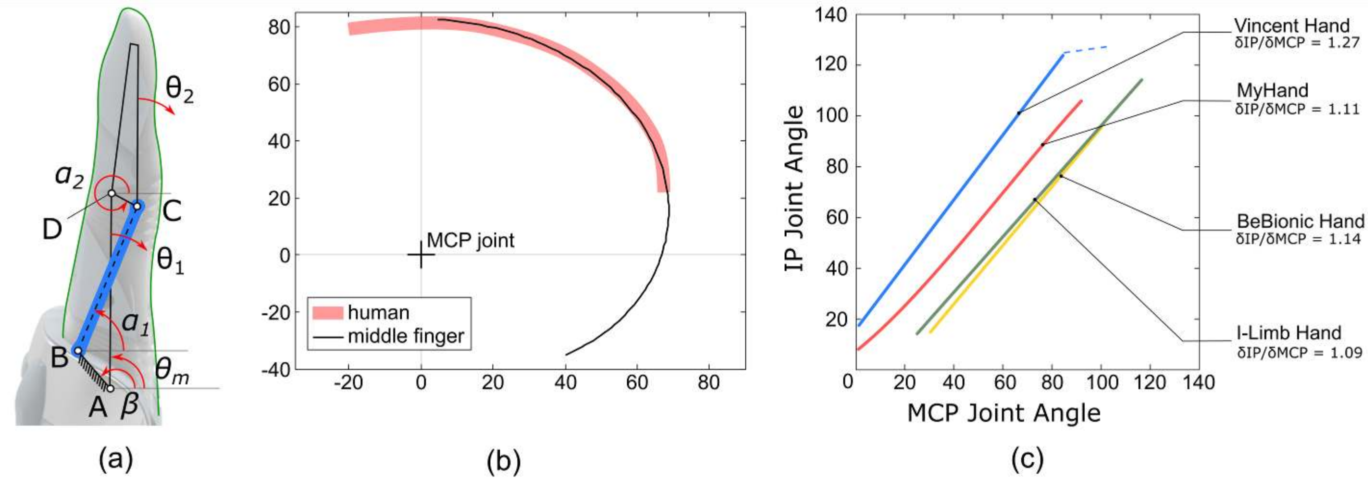

Fig. 4 Finger kinematics of the *SSSA-MyHand* prosthesis. (a) Schematization of the inverse four-bar mechanism of the fingers. (b) Trajectory of the middle fingertip compared with human data (adapted from [39]). (c) Relationship between the IP and MCP joints in the SSSA-MyHand and other commercial prostheses (as calculated by Belter et al. [14]).

having a dead point corresponding to when the index is fully extended is not only the only *possible solution* but also the *optimal* one. Indeed, during normal use of a hand prosthesis, a digit is not expected to apply any grasp forces while fully extended.

The operation of the TISIT can be divided in three phases (Fig. 2b and Fig. 3). Phase 1: the index finger starts from fully flexed and, as the crank rotates, it extends. Phase 2 (switching phase): the index reaches its maximum extension, the thumb switches its opposition/reposition state. Phase 3: the index flexes again until complete flexion. In particular, the Geneva drive was synchronized with the four-bar mechanism in a way that the driven wheel switches between steps (traced curve in Fig. 2b) when the four-bar mechanism is close to the dead point; in other words the thumb switches between the opposition and the reposition state configurations when the index is close to full extension (Fig. 3). This choice was critical for the design of the TISIT because it implied that, during normal operation of the prosthesis, the thumb could be opposed/reposed only when the index finger is totally extended. We argue that this constraint is acceptable as the resulting operation actually mimics natural grasping (indeed the thumb is opposed/reposed during the reaching phase, i.e. when the digits are extending [38]). Nevertheless, this choice causes the index to perform a small oscillation while the thumb switches its state (Fig. 2b). To conclude, the TISIT was designed in order to maximize the RoM of the index flexion and to ensure proper RoM of the thumb ab/ad DoF, while preventing an evident (unattractive) oscillation of the index. An acceptable trade off was achieved by admitting a RoM for the index MCP of 80°, while fulfilling the other specifications.

2) Kinematics of the long fingers

The design of the long fingers of the *SSSA-MyHand* prosthesis was based on an inverse four-bar mechanism (ABCD in Fig. 4a) in which the rotation of a proximal phalanx (AD) around an MCP joint (pivoted in A) is coupled with the rotation of a distal phalanx (in-built with CD) around an IP joint (in D). AD is actuated by the motor (and thus considered the input of the system) while CD moves under the constrains of the kinematic chain. This architecture is known for its robustness and is the same used in state of art prostheses [14]. The kinematics of the mechanism is described by the following system (cf. Fig. 4a):

$$\begin{cases} \overline{AB}\cos\beta + \overline{BC}\cos\alpha_1 = \overline{AD}\cos\theta_m + \overline{CD}\cos\alpha_2 \\ \overline{AB}\sin\beta + \overline{BC}\sin\alpha_1 = \overline{AD}\sin\theta_m + \overline{CD}\sin\alpha_2 \end{cases} \quad (1)$$

where $\overline{AB}, \overline{BC}, \overline{AD}, \overline{CD}$ are the lengths of the links whereas $\beta, \alpha_1, \theta_m$ and α_2 are their angles relative to the reference system (for the sake of simplicity, in this example it is taken as the horizontal line). In particular, β is the offset angle of the frame, θ_m is the angle of the proximal phalanx (connected to the motor) and α_1, α_2 are the system variables (the angles of BC and CD, respectively). A more compact system can be obtained by linearly combining the equations in system (1) and using the exponential form:

$$\begin{cases} \overline{BC}u - \overline{CD}v = z \\ \dfrac{\overline{BC}}{u} - \dfrac{\overline{CD}}{v} = \bar{z} \end{cases} \quad (2)$$

where:

$$z = (\overline{AD}\cos\vartheta - \overline{AB}\cos\beta) + i(\overline{AD}\sin\vartheta - \overline{AB}\sin\beta),$$
$$u = e^{i\alpha_1}, \qquad v = e^{i\alpha_2}$$

and i is the imaginary unit. By solving the first equation of system (2) in u and substituting the result in the second one, we find:

$$\overline{CD}\bar{z}v^2 + (|z|^2 + \overline{CD}^2 - \overline{BC}^2)v + \overline{CD}z = 0, \quad (3)$$

which, as a quadratic equation in v can be easily solved to find $\alpha_2(\theta_m)$ [and, simply by substitution in system (1), $\alpha_1(\theta_m)$]. The rotations of the proximal (θ_1) and distal (θ_2) phalanxes can then be calculated using the following equations:

$$\theta_1 = 90° - \theta_m$$
$$\theta_2 = \alpha_2(\theta_m = 90°) - \alpha_2 \quad (4)$$

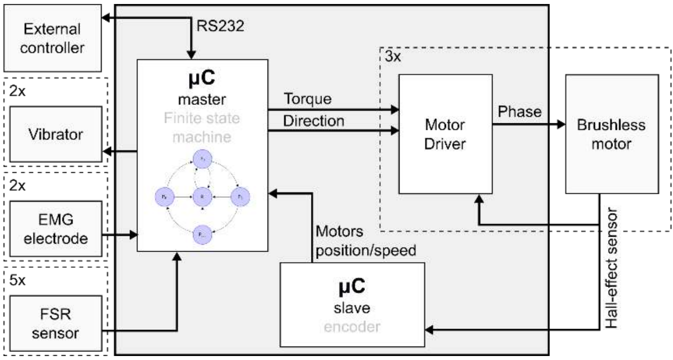

Fig. 5 Embedded control architecture of the *SSSA-MyHand*.

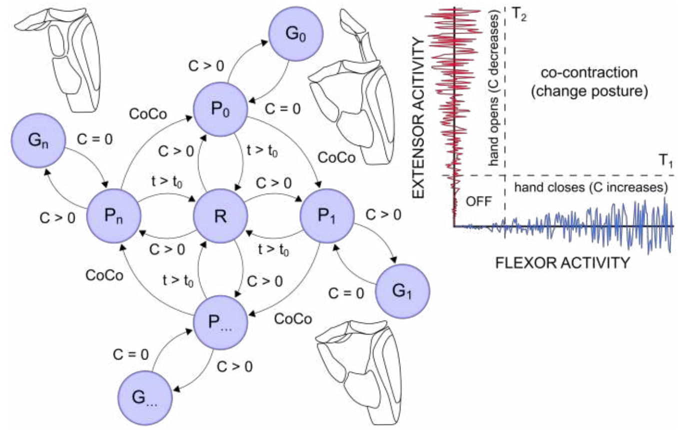

Fig. 6 Finite-state machine of the *SSSA-MyHAND*. The main states correspond to the preshape postures (P_i) relative to the grasp/functions physically achievable by the hand: lateral, bi-digital, power (or cylindrical), hook, pointing up and pointing down. These are sequentially selected by means of EMG co-contractions (CoCo). Once in a preshape state P_i, the hand can enter in a grasp state G_i, and is controlled following the well-known two-state amplitude-modulated myoelectric control scheme with noise thresholds (T_1 and T_2) [41] (sampling frequency 100 Hz). When in a state P_i, the hand returns in a rest position (state *R*) if the EMG activity is below threshold for a certain time t_0.

We simulated the kinematics of the finger using different configurations (i.e. different lengths of the links and different values for β), in order to find the optimal configuration that would (i) be compatible with the dimensions of the 50th percentile male and (ii) mimic the trajectory of the human fingertip during grasping (Fig. 4b) [39]. The kinematics of the chosen configuration resulted similar for all fingers, and showed to be compatible with other state of art prostheses (Fig. 4c) [14].

3) Actuation of the flexion/extension of the thumb and of the last three fingers

The thumb designed for the *SSSA-MyHand* acts as a curved opposition post with no distal joints. The body of the thumb hosts motor M1 (used to flex/extend it), with the output shaft oriented towards the palm (Fig. 1). A worm gear transmission directly connected to this output shaft forms the non-back-drivable joint akin to Gow's digit [32].

The last three fingers use the inverse four-bar mechanism described in the previous paragraph (Fig. 4a). As for the other digits their transmission includes a non-back-drivable worm gear on the motor shaft (M3); the three digits are mechanically coupled by means of spur gears, which means that they all synchronously flex and extend together, akin to our previous design [7]. However, in the current design there are no differential mechanisms, hence no adaptation of the last three fingers during grasp can be achieved.

B. Embedded controller and sensory system

The design of the embedded controller of the hand aimed at ensuring flexible operation and connectivity with a variety of different HMIs. In particular, the architecture was designed to support: (i) the identification of external commands, (ii) the implementation of automatic (stereotypical) motor functions, (iii) the real time acquisition/processing of the internal sensors (in-hand), and (iv) the potential delivery of sensory feedback to the subject through appropriate HMIs. To this aim, a master-slave configuration based on a pair of 8-bit microcontrollers was chosen for the controller, akin to our previous designs [18], [7] (Fig. 5).

The printed circuit board we developed handles an insulated serial port (RS232) which can be used to interface the hand with an external myocontroller (e.g. the Coapt pattern recognition system [40]) or a sensory feedback system, and up to nine lines which can be programmed to be a combination of either digital inputs/outputs (DIOs) or analogue inputs. In the current implementation two lines are used as analogue inputs to acquire external EMG sensors used for control, five lines are used as digital inputs for future integration of FSR touch sensors on the fingertips, and two lines are used as digital outputs for future connection with a vibrotactile sensory feedback interface [35], [36].

The master microcontroller acquires the EMG signals, communicates with the external world via the serial port and the bus of DIOs, implements the finite-state machine that rules the operation of the hand (Fig. 5) and controls the brushless motors using dedicated integrated circuits. In particular, the master controls the actuators using torque, speed and position PID algorithms. The slave microcontroller is used to compute the actual position and speed of the motors – by sampling their internal Hall-effect sensors – and passes such information to the master controller. In the current implementation a simple finite-state machine was modelled after the sequential control scheme available in state of art multi-grasp prostheses (e.g. the *iLimb* or *BeBionic* hands) (Fig. 6).

IV. Performance Analysis

The developed *SSSA-MyHand* prototype is compatible in size with the healthy hand of a transradial amputee and is able to perform all the motor functions listed in paragraph II.A and even more (Fig. 7a). The total weight is close to the natural hand and to conventional 1-DoF prostheses: 480 g. This figure includes a standardized quick wrist disconnect unit (QWD, ~60 g), the metallic 3D printed Möbius strip (80 g), and the aesthetic covers (115 g) Fig. 7b); it excludes the batteries (which are usually hosted in the prosthetic socket, proximally to the residual limb). The time series in Fig. 8 demonstrates a representative operation of the hand while grasping an object using a power grasp (100% torque, 30% speed). At the beginning (t=t_0) the hand is in the rest state, with the thumb in the reposition state, and the digits assuming a small form factor.

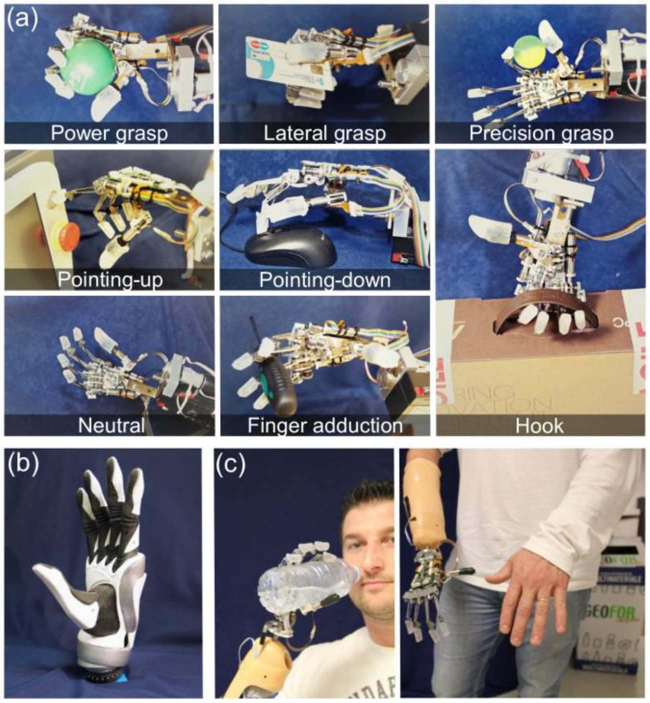

Fig. 7 The *SSSA-MyHand* prosthesis. A) Postures and grasps achievable by the hand. B) The external covers developed for the hand. C) Hand mounted on a prosthetic socket fitted on a right-hand transradial amputee.

Once the grasp command is received ($t=t_1$) the hand exits the rest state and moves towards the power grasp preshape: the motor M2 starts moving in order to oppose the thumb, while M1 and M3 extend the thumb and the last three digits respectively in order to increase the grasp aperture properly. During this phase the current that flows into M2 is relatively low because the torque required to switch the Geneva drive is relatively low (estimated: 0.18 Nmm). Starting from $t=t_2$ all the digits start to flex until they all grasp the object. When they can no longer move a torque balance is reached ($t=t_3$, the current is steady), which depends on the desired grip force. At this point, if the grasp command is stopped ($t=t_4$) the current in the motors drops to zero, even though the torque is maintained by the non-back-drivability of the transmissions, which also keeps the digits firmly in place; in other words, the prosthesis holds the object without draining additional energy from the battery.

The technical features of the *SSSA-MyHand* are comparable

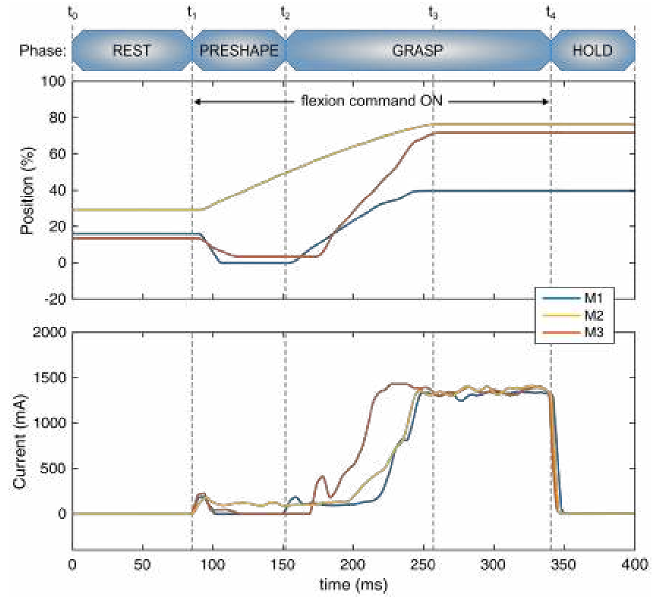

Fig. 8 Time series of position and current for all digits during a stereotypical power/cylindrical grasp.

with those of clinically available multi-grasp prostheses (as published by the manufacturers on their websites or assessed by Belter and colleagues [14]), as summarized in Table I. Notably, by weighing only 478 g, the *SSSA-MyHand* is lighter than all clinically available multi-grasp prostheses. Relevant performance of the prototype including power consumption, individual fingertip force and speed were also evaluated as described in the following paragraphs.

A. Power consumption

The power consumption of the control electronics is roughly 0.5 W (45 mA @ 12 V); this coincides with the instantaneous power required to maintain the hand in a fixed posture or grasp. The energy required to perform the main prehensile movements and grasps was measured under different load conditions (Table II). Overall the consumption is acceptable and could yield to a full-day operation; it was estimated that a 12V battery with 1 Ah capacity could ensure 2300 power grasps (and 2300 re-openings) divided as derived from [24] (48% power/cylindrical, 32% precision, 12% lateral, and 8% index-pointing). Such capacity could be ensured by a small sized (20 x 34 x 50 mm),

TABLE I
GENERAL FEATURES OF THE SSSA-MYHAND AND OF COMMERCIAL MULTI-GRASP PROSTHESES

Name (year) [developer]	Weight (hand + QWD + Glove) (g)	Overall size (height x width x thickness) (mm)	Number of joints	Degrees of freedom	Numbers of actuators	Actuation type	Joint coupling methods
MyHand (2016) [SSSA]	478	200 x 84 x 56	10	4	3	DC Brushless motors – Worm gear	Four bar mechanism and TISIT
Vincent eveolution2 large size (2010) [Vincent Systems]	509	163 x 80 x N.A.	11	6	6	DC Brushed motors – Worm gear	Linkage spanning MCP to PIP
iLimb Ultra medium size (2010) [Touch Bionics]	563	182 x 80 x 42	11	6	5	DC Brushed motors – Worm gear	Tendon linking MCP-PIP
BeBionic v2 large size (2011) [RSL Steeper]	682	200 x 92 x 50	11	6	5	DC Brushed motors – Lead Screw	Linkage spanning MCP to PIP
Michelangelo (2012) [Ottobock]	572	200 x 80 x 50	6	2	2	DC Brushless motors – planetary gear head	Cam design with links to all fingers

QWD: Quick Wrist Disconnect unit (which is ~60 g); cosmetic glove, *Realistic Prosthetics Ltd, U.K.* (which is ~84 g)

TABLE II
AVERAGE ENERGY CONSUMPTION TO GRASP

	No-load grasping (100% speed, minimum torque)	Power grasping (100% torque, 30% speed, stiff object)
Power	4.2 J	19.5 J
Bi-digital	3.3 J	13 J
Lateral	4.2 J	10.8 J
Index-pointing	3.4 J	-

lightweight (~60 g) commercial lithium-ion polymer battery.

B. *Fingertip force*

For the fingertip force we followed the testing procedures described by Belter and colleagues in order to allow for comparison with other clinically available prosthetic hands [14]. In particular, the force generated by each digit without covers was measured by using a calibrated load cell (NANO17, ATI Industrial Automation Inc., USA) rigidly fixed on a base placed on the top of the tested fingertip, with the finger fully extended. Notably, in this condition the force transferred to the fingertip is the lowest possible as the moment arm is maximum. The digit was then driven to flex at full power. The holding force recorded after impact was recorded; this procedure was repeated 15 times for each digit. The average force exerted by the single digit at the fingertip was 31.4 N for the thumb, 11.7 N for the index, and ranged between 9.4 N and 14.6 N for the middle, ring and little fingers. It is worth to recall that the last three fingers are driven by the same motor, hence they cannot generate those forces simultaneously. Although the measured forces were lower than those produced by healthy subjects [29], they are comparable with those of multi-grasp prostheses commercially available [14] (Fig. 9).

C. *Speed of the digits*

The speed was retrieved experimentally through video analysis of the digits during prehensile movements and automatic grasps performed in free space (i.e. without obstacles). Individual digit flexion/extension speeds were measured about the MCP joint without covers. During the movements the digits were given a 100 % command signal for the entire duration of motion. The measured speeds resulted 160 °/s (thumb) and 170 °/s (index and last three fingers). The time to switch the thumb from the opposition to the reposition state was found to be 200 ms (equivalent to 250 °/s). The time to complete a grasp starting from the rest position was found to be 270 ms for the lateral grasp and 370 ms for the cylindrical and bi-digital grasps. When compared to the commercially available multi-grasp hands the *SSSA-MyHand* results as the fastest (Fig. 9).

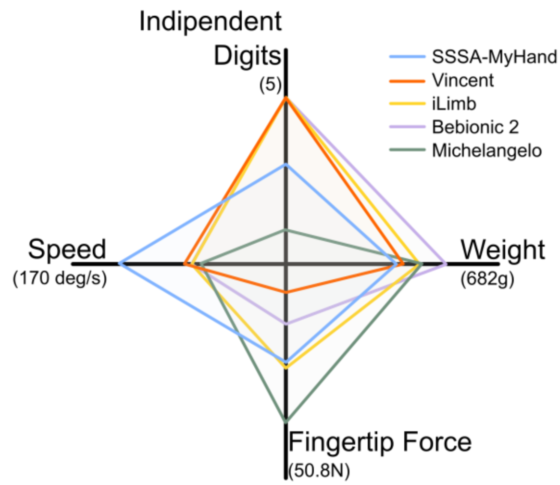

Fig. 9 Comparison between the *SSSA-MyHand* and other commercial prostheses as assessed by Belter, Segil and colleagues [14]. W, FF, S and ID indicate weight, fingertip force (defined as the maximum fingertip force among the digits), digit flexion speed and number of independent digits, respectively. Speed and fingertip force were measured without covers/glove. Maximum value for each index reported within round brackets.

V. DISCUSSION

The *SSSA-MyHand*, with only three electric motors and a transmission that exploits an intermittent mechanism is physically capable to perform most of the grasps and gestures useful in ADLs, akin commercial prostheses with up to six actuators, albeit it is as lightweight as conventional 1-DoF prostheses. The main innovation that entailed these performance is the TISIT (Thumb abduction/adduction, Index flexion/extension Semi-Independent Transmission) which allows semi-independent actuation of the abduction/adduction of the thumb and of the flexion/extension of the index finger. We argue that the TISIT is rather an elegant solution because, although it disables arbitrary configurations of the digits, in particular arbitrary rotations of the thumb about its TM joint, it enables –using just a single actuator– those two crucial configurations which are required to perform power/precision grasps (thumb opposed) and lateral grasps (thumb reposed), i.e. the majority of grasps of ADLs. The TISIT inhibits in-hand fine manipulation, however this cannot be deemed as an urgent need in upper limb prosthetic devices, today [1], [42]. The two DoFs of the TISIT are not independent but it looks as if they were, as long as the thumb opposition is rotated at the very beginning of the grasp (i.e. before flexing the digits); remarkably this behaviour mimics natural grasping in humans [38], hence having one actuator less can pass unnoticed. In addition, since the Geneva mechanism *engages/disengages* the kinematic chain of the TISIT, the two DoFs are rigidly connected only when the thumb rotates (a movement that was designed to be very fast), meaning that when the DoFs are disengaged the index can freely flex/extend regardless of the external constrains or forces applied to the thumb (this is a known issue in the *Michelangelo* hand where the transmission is always engaged). In fact, the abduction/adduction of the thumb is likely the most critical DoF to design when developing any artificial hand [43], and the TISIT represents an interesting trade-off between mobility, complexity, weight and functional outcome.The *SSSA-MyHand* prototype matched the low-cost requirement. This was made possible by: the reduced number of motors, the design approach, the use of off-the-shelf components and their optimization in terms of variability of components (e.g. only one model of ball-bearing and of worm-gear were used) (estimated cost for one prototype < 3000 €). Still, the prototype demonstrated interesting performance, albeit there is space for improvements and this work invites further studies. The weight of the *SSSA-MyHand* is largely affected by the aesthetic covers, fingertips and the Möbius strip. A less-conceptual and more engineering-grounded design of these components, including the selection of appropriate materials, could allow reducing the weight of the hand by 30%, for a target weight of less than 350 g. Moreover, while the declared objective was to use the *SSSA-MyHand* with non-human like covers, it is recognized that a significant amount of amputees, might still prefer to have a conventional cosmetic glove. The latter should not impede the functioning of the mechanism too much. Furthermore, the comparison with commercial multi-grasp prostheses revealed that the *SSSA-MyHand* is the fastest but among the weakest ones (Fig. 9); this suggests that a better match between speed and digit force could be reached in the future by increasing the transmission ratio between the motors and the digits. Finally, the four-bar mechanism used for the long fingers which inhibits adaptive grasps like under-actuated tendon-driven digits [10], could be improved by introducing compliant linkages or differential mechanisms in the last three fingers. Nevertheless its use in commercial prostheses (*iLimb, BeBionic* and *Vincent*) suggests that it is a very robust/reliable solution.

Compared to previous authors' work the *SSSA-MyHand* was purposely designed and developed to be a reliable and easy to maintain prosthesis aimed at sustaining long-term home studies, rather than a laboratory device for short-term neuroscientific experiments [7], [18]. For this reason during the development of this project, every subassembly was evaluated and the design continuously reviewed in order to enhance the performance and reliability of the final prototype. The next goal of this work is to finalize the development of the cosmetic covers in order to fit the prosthesis to selected transradial amputees and to assess its performance away from the laboratory.

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