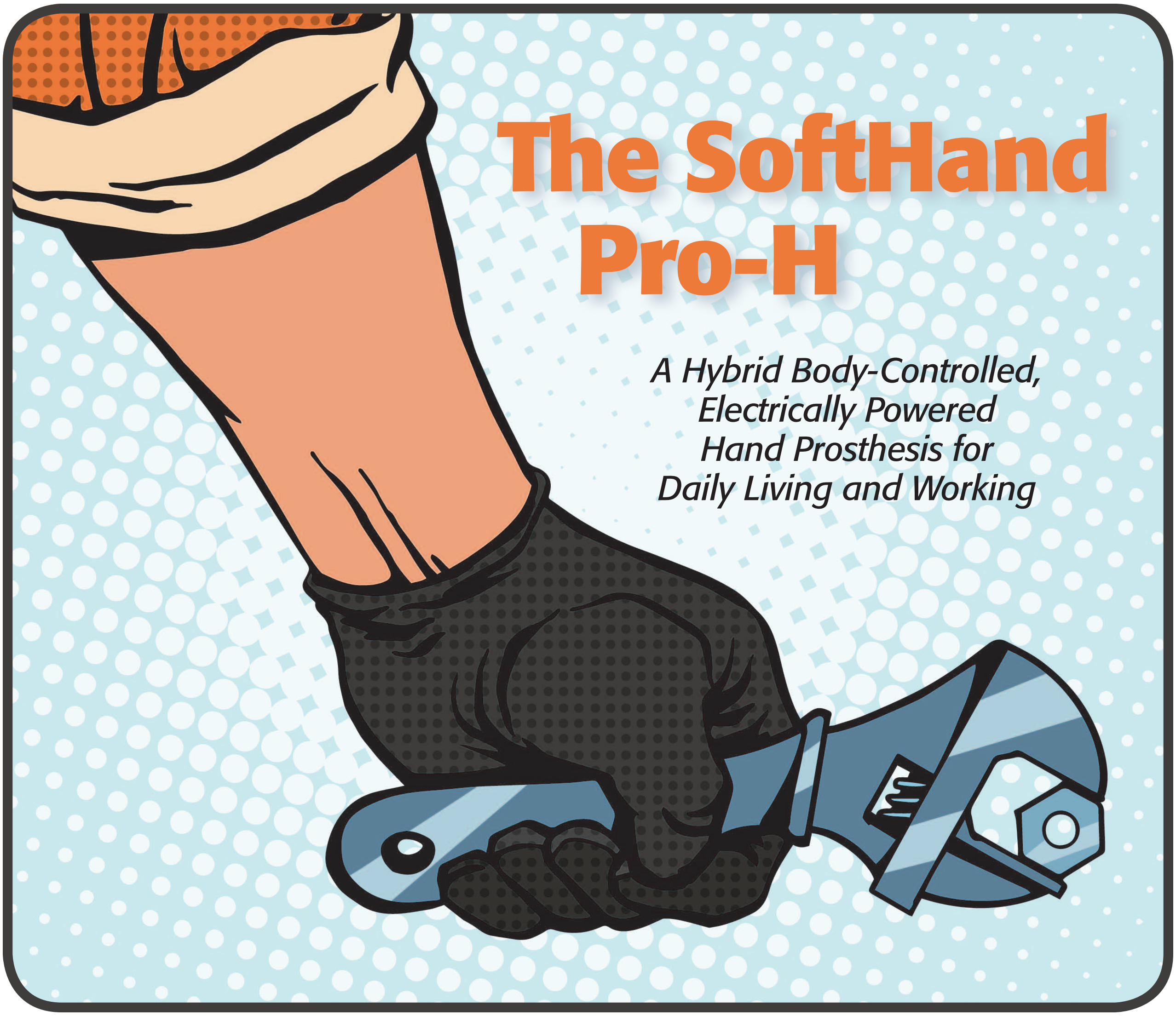


The SoftHand Pro-H

A Hybrid Body-Controlled, Electrically Powered Hand Prosthesis for Daily Living and Working

By C. Piazza, M.G. Catalano, S.B. Godfrey, M. Rossi, G. Grioli, M. Bianchi, K. Zhao, and A. Bicchi

In this article, we study the feasibility of applying the SoftHand technology to a prosthetic device that is suitable for activities of daily living (ADL) and, in particular, some important objectives such as doing work, performing home chores, and participating in hobbies. These applications have specific requirements, such as high grip power; grasp versatility; ruggedness; resilience; resistance to water, dust, and temperature; durability; power autonomy; and low cost. Alternatively, factors like the multiplicity of gestures or aesthetics are less dominant. The intuitiveness of control by the user is a particularly relevant and specific objective of our work. While multiactivation-modalities prostheses use sophisticated myoelectric control to afford versatility and dexterity, most state-of-the-art work-oriented prostheses are body powered (BP). BP prostheses (BPPs) are intuitive to use, have low cost, do not require batteries or motors, and provide useful built-in, sensorless feedback to the user.

In this article, we explore the possibility of realizing prosthetic systems that combine the two worlds, creating a hybrid solution that shares advantages from both, by using inputs from a shoulder harness to control an advanced 19 degrees of freedom (19 DoF), underactuated anthropomorphic, electrically powered hand. We start from an analysis of possible locations of the main components of the prosthesis (the motor, battery pack, and electronics) on the user's body. As a result of this analysis, eight configurations are isolated

Digital Object Identifier 10.1109/MRA.2017.2751662
Date of publication: 15 November 2017

Figure 1. The SHPH and our pilot (SoftHand Pro team) performing the wire-loop task at C-PAPR. (Photo courtesy of ETH Zürich.)

as possible solutions for different requirements. One of these solutions has been implemented in a functional prototype, called *SoftHand Pro-H* (*SHPH*), and used by the SoftHand Pro team in the Cybathlon 2016: Powered Arm Prosthesis Race (C-PAPR) (see Figure 1).

Overview of Prostheses for Upper-Limb Replacement

The loss of an upper limb is a major traumatic event that affects both the personal and social dimensions of an individual in the context of a community. Often leading to a considerable reduction in working ability and personal autonomy, it has a heavy psychological impact on a person's life. In this regard, one of the challenges of modern technology is to enable persons with upper-limb loss to regain their autonomy, e.g., through robotic-enabled aids. The aesthetic appearance and quietness of the device are usually among the most important characteristics that a prosthetic system should ideally exhibit. [1]. However, a robust prosthetic aid that supports the user not only in ADL (an area of fundamental importance) but also in work activities, home chores, and hobbies can play a critical role in psychological well-being as well as social acceptance. For these reasons, we can essentially divide the driving force behind technological advancements of upper-limb prosthetic aids into two goals: 1) the attainment of a realistic aesthetic appearance and 2) the restoration of lost functionality and ability. Functional prostheses are devices that enable users to partially recover the performance of the lost limb by involving, in some cases, the use of actuators. Included in this group are nonanthropomorphic terminal devices, which are not aesthetically pleasing but are preferred because of their robustness, and more visually agreeable anthropomorphic hands; while anthropomorphic devices attempt to replicate the dexterity and appearance of the human hand, it is at the cost of increased mechanical system and control complexity. In recent years, growing medical and engineering interest led to innovative control techniques (e.g., multisurface electromyography regression [2] and machine-learning techniques [3]) as well as surgical solutions (e.g., targeted muscle reinnervation [4] and electrode implantation [5]).

> **Today, many prosthesis users prefer to have two prostheses, one with a predominantly aesthetic role and one with a mainly functional role.**

Unfortunately, the use of these promising solutions is currently mostly limited to research, while the approaches most used in real-life scenarios remain those based on noninvasive techniques. The most prominent among these are myoelectric (one or two channels) and BP control [6]. Figure 2 shows their typical hardware configurations and working principles. Each solution presents advantages and disadvantages (please refer to the "Motivations" section for a detailed comparison), and establishing which best fits the needs of a person with upper-limb loss is not trivial. Despite the technological advances of the past few decades, myoelectric prostheses (MPs) are far from being a valid substitute for their BP counterparts [7]. Moreover, in a systematic literature review [8], Carey et al. state that evidence is insufficient to conclude whether or not the current generation of MPs or BPPs provide a significant general advantage. However, there are some specific domains that show better performance by one type of prosthesis over the other, e.g., MPs tend to be more accepted for low-intensity work, while BPPs are well suited for high-intensity work. As a result, today, many prosthesis users prefer to have two prostheses, one with a predominantly aesthetic role and one with a mainly functional role.

In this article, we explore the possibility of developing a new set of prosthetic configurations that are suitable for transradial amputations and are mainly designed for work-oriented, home chore, and hobby use. The goal is to merge the simplicity (and, in many respects, intuitiveness) of a prosthesis operated via a BP cable with the versatile, dextrous, and aesthetic aspects of modern, multifingered, and electrically powered devices. Our approach moves from the analysis and the enumeration of the possible locations of the main electric components of the prosthetic hand (the motor, battery pack, and electronics) with respect to the other parts of the prosthesis and the body of the user. This work focuses on the integration of such input methods with a specific terminal device, the Pisa/IIT SoftHand [9], a heavily underactuated anthropomorphic robotic hand that uses only one motor to actuate 19 DoF. These characteristics allow highly simplified control of the hand that, together with a high level of robustness and adaptivity, suggest the use of this platform in a range of ADL, with particular focus on work environments, home chores, and hobbies. Among the different configurations isolated (which individually represent solutions for different use scenarios), one layout has been selected, the SHPH, for testing in the specific context of the C-PAPR, where we participated as the SoftHand Pro team.

Motivations

Activities like gardening, woodworking, and housekeeping as well as many other jobs, hobbies, and chores are tough testing grounds for a prosthetic system. Furthermore, strict requirements in terms of grip power, grasp versatility, ruggedness, resilience, resistance to elements (water, dust, temperature), durability, and power autonomy strongly limit the use of traditional MPs in favor of BPPs. However, to take advantage of both types of technologies, it is important to understand the pros and cons; these are grouped by functional areas in the following sections.

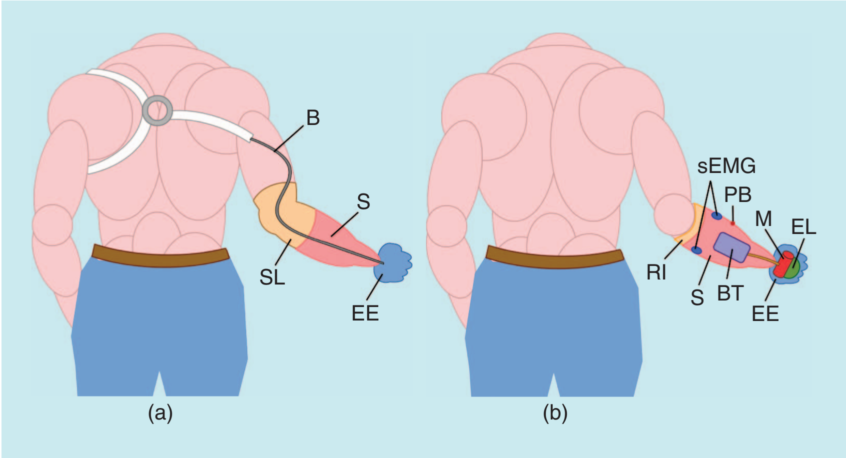


Figure 2. (a) A typical layout of a BPP, where the shoulder harness features a cable control system that runs from the prosthesis, around the back, to the contralateral shoulder. In this configuration, both the input and the mechanical power needed for motion are provided by shoulder flexion. (b) An MP layout equipped with electrically powered actuators, which are typically controlled by surface electromyographic (sEMG) sensors receiving signals from muscles in the residual limb. B: cable control system; EE: prosthetic device; S: socket; SL: soft socket liners; RI: rigid interface; M: motors; EL: electronics boards; BT: battery pack; PB: power button.

Comfort

While there exist specialized myoelectric grippers and hooks targeting work activities, their use is, often, hindered when impurities such as dirt or sweat get between the surface electromyographic (sEMG) sensors and the underlying skin, causing their performance to severely drop. As a consequence of the use of sEMG sensors, a typical MP system requires a rigid socket with an inflexible interface between the prosthetic hand and the residual limb of the user [Figure 2(b)]. Some users find this kind of rigid interface uncomfortable and, especially in the case of short residual limbs, limiting to the range of motion of the user's elbow. However, soft socket liners [Figure 2(a)] can be used more easily with BPPs, as there is no need for any rigid part of the socket to come in direct contact with the skin. Soft liners provide padding and aid the grip of the socket on the residual limb. All of these aspects imbue the system with more comfort and security. BPP function does not suffer from problems related to dirt and sweat, and the contact area with the residual limb can be significantly increased (the liner can extend above the elbow joint, covering part or all of the upper arm). Moreover, the perceived comfort is noticeably improved by the lightness of the overall structure, including the absence of motors and batteries and adoption of simple wrist connections.

Aesthetics

As a drawback, the lack of integration of the harness in the socket and the need of a Bowden cable make BPPs more bulky, less aesthetically pleasing, and much more difficult to wear. Such problems are limited in MP solutions, where sensors and accessories are completely integrated into a single unit that can be easily dressed and managed in everyday use.

Control

MPs also offer other advantages over BPPs. One of the most prominent is the possibility of using multiple actuation units and allowing the control of the hand in multiple postures and shapes. Unfortunately, such abilities imply a more sophisticated control architecture, and sEMG control can sometimes be difficult to master, likely leading to abandonment [10]. People with short residual limbs, in particular, tend to have more difficulty with myoelectric control due to, e.g., limited residual musculature, limited signal intensity, or excessive cocontraction. In these situations, primarily two alternatives are available: BPP configurations or other mechanical input solutions, e.g., linear transducers. Such input devices can be used as an alternative input in substitution of the sEMGs and in combination with a shoulder harness. Conversely, BPPs present a limited range of shapes and input modalities but have the advantage of a good level of intuitiveness, mainly given by the physical perception of the shoulder movement in contrast to the more ephemeral perceived level of muscle effort on the residual limb of an MP solution.

Activities like gardening, woodworking, and housekeeping as well as many other jobs, hobbies, and chores are tough testing grounds for a prosthetic system.

Feedback

BP systems exhibit some level of inherent haptic feedback, which is a highly desired feature among users [1], [11], [12] and is shown to increase the feeling of embodiment of the prosthesis [13]. This feature is nearly nonexistent in myoelectric devices, where users rely on motor noise and perceived level of muscle effort, when possible, to estimate proprioceptive and force information.

Costs

As a consequence of their intrinsic architecture, fitting, training, and maintenance of MPs result in much higher costs for users [14]. This is particularly true if the maintenance and fitting costs of an MP are compared to those of a BPP, where expenses for replacement parts and assistance services are limited and often are activities that the user can manage directly.

Input Force

Operating a BPP requires the user to exert a nonnegligible force with the shoulder harness. This, in turn, tends to engender fatigue and discomfort in the user in the short term and chronic musculoskeletal imbalance and pain in the medium–long term. Furthermore, a person who is unable to generate sufficient force may not be able to operate a BPP. This is particularly true for BP anthropomorphic terminal devices, whose rejection rates can reach up to 80% [16], [17].

Compensatory Motion

In addition to the level of force needed to activate a BPP, another big disadvantage is that wearers may need to make abnormal movements of the shoulder to operate their prosthesis. These movements, called *compensatory motion* [18], [19], and the discomfort they cause have been cited among the main factors influencing BPP abandonment [14]. Such problems are much more limited with myoelectric control or with linear transducers, where the force and activation of the hand is not strictly related to a specific amount of force of the user, and compensatory motions can be reduced with respect to BPPs' systems. To the best of our knowledge, despite the fact that solutions combining BP harnesses, linear transducers, and electrically powered hands are possible, there is limited use of such systems and a lack of literature investigating such hybrid setups.

A hybrid prosthetic system, electrically powered but controlled without sEMG, is likely to have advantages with respect to both BPPs and MPs in many activities.

The SHPH

Approaches

Despite the technological advancements of recent years, a prosthesis that merges aesthetic, functionality, and robustness requirements in a unique device does not currently exist and remains a difficult goal, which is out of the scope and ambition of this article. Regardless, a hybrid prosthetic system, electrically powered but controlled without sEMG, is likely to have advantages with respect to both BPPs and MPs in many activities. First, this is likely to greatly mitigate most of the chronic problems arising from the use of body power to operate prostheses. Inherited proprioceptive feedback of BPPs will be preserved, and, hopefully, the benefits coming from the lower activation force will outweigh the inevitable reduction of exteroceptive feedback. Moreover, the use of this kind of hybrid control, in combination with the grasp versatility possible with advanced anthropomorphic hands, is likely to overcome the need to frequently change task-specific terminal devices, providing the user with greater convenience and ease of use without sacrificing performance. Finally, the adoption of an anthropomorphic hand design can also improve the aesthetic function, which is completely missing in a typical BPP hook, and will likely lead to increased acceptability [20].

To find a proper balance between form and function, different layouts are proposed, analyzed, and discussed. Three main positions with respect to the body of the prosthetic user are considered (the prosthetic hand, socket, and body) for the three main displaceable components (the battery, electronics, and motor). Looking at the resulting configurations, however, not all of them are reasonable or feasible. For this reason, a set of exclusion criteria was defined and used to eliminate infeasible solutions: 1) the battery pack cannot be placed on the hand, 2) the battery pack cannot be positioned distal to the motor, and 3) the electronic board cannot stay in an isolated location. Item 1 is given to preserve the overall hand weight and shape, and items 2 and 3 are provided to reduce excessive wiring and waste of space. Table 1 shows all of the possible combinations of these elements and highlights the most promising solutions (eight in total), selected by applying the previously described exclusion criteria. Table 2 shows the main features of the elements while highlighting their weight and overall dimensions.

Figure 3 shows the graphical representation of each of the eight solutions identified. In general, this approach suggests it could be useful to design a set of modular components to be assembled to match the various configurations. Such modularity could help take into account the relevant constraints for each user and design a personalized solution. Compliance with existing myoelectric and BP socket solutions and commercial components would be provided by solutions in Figure 3(a) and (b), respectively. Solutions where all components are integrated into the hand and socket [Figure 3(a), (c), and (d)] provide the advantage of being less cumbersome and supplying the components with at least limited protection against environmental factors such as dust or liquid. These solutions, however, depend on the length of the residual limb. For longer limb lengths, more components can be placed on the body [such as in Figure 3(f)–(h)], providing additional protection against environmental factors, possibly rendering the system waterproof at the level of the hand or arm. Finally, for scenarios requiring increased grasp strength, solutions such as those in Figure 3(g) or (h) could be used with more

Table 1. A combinatory table of all possible prosthetic layouts, application of exclusion criteria, and isolated solutions (depicted in Figure 3).

	Hand	Socket	External Box	Criterion 1	Criterion 2	Criterion 3	Solution
1	Electronics, Motor, Battery			✗	✓	✓	–
2	Electronics, Motor	Battery		✓	✓	✓	(a)
3	Electronics, Motor		Battery	✓	✓	✓	(b)
4	Electronics, Battery	Motor		✗	✗	✓	–
5	Electronics	Motor, Battery		✓	✓	✗	–
6	Electronics	Motor	Battery	✓	✓	✗	–
7	Electronics, Battery		Motor	✗	✗	✓	–
8	Electronics	Battery	Motor	✓	✗	✗	–
9	Electronics		Motor, Battery	✓	✓	✗	–
10	Motor, Battery	Electronics		✗	✓	✗	–
11	Motor	Electronics, Battery		✓	✓	✓	(c)
12	Motor	Electronics	Battery	✓	✓	✗	–
13	Battery	Electronics, Motor		✗	✓	✓	–
14		Electronics, Motor, Battery		✓	✓	✓	(d)
15		Electronics, Motor	Battery	✓	✓	✓	(e)
16	Battery	Electronics	Motor	✗	✗	✗	–
17		Electronics, Battery	Motor	✓	✗	✓	–
18		Electronics	Motor, Battery	✓	✓	✗	–
19	Motor, Battery		Electronics	✗	✓	✗	–
20	Motor	Battery	Electronics	✓	✓	✗	–
21	Motor		Electronics, Battery	✓	✓	✓	(f)
22	Battery	Motor	Electronics	✗	✗	✗	–
23		Motor, Battery	Electronics	✓	✓	✗	–
24		Motor	Electronics, Battery	✓	✓	✓	(g)
25	Battery		Electronics, Motor	✗	✗	✓	–
26		Battery	Electronics, Motor	✓	✓	✗	–
27			Electronics, Motor, Battery	✓	✓	✓	(h)

= ELECTRONICS = MOTOR = BATTERY

Table 2. The technical specifications of mechanical and electronic components.

	Electronics	Motor	Battery
Model	Custom Electronics [15]	Maxon DCX 22s + GPX22	Parrot AirDrone 2.0
Dimensions	60 × 30 × 12 mm	d = 22 mm l = 80 mm	94 × 66 × 37 mm
Weights	15 g	130 g	202 g
Specifications	Daisy-chain RS485 bus	15-W continuous power	Capacity 1,500 mAh

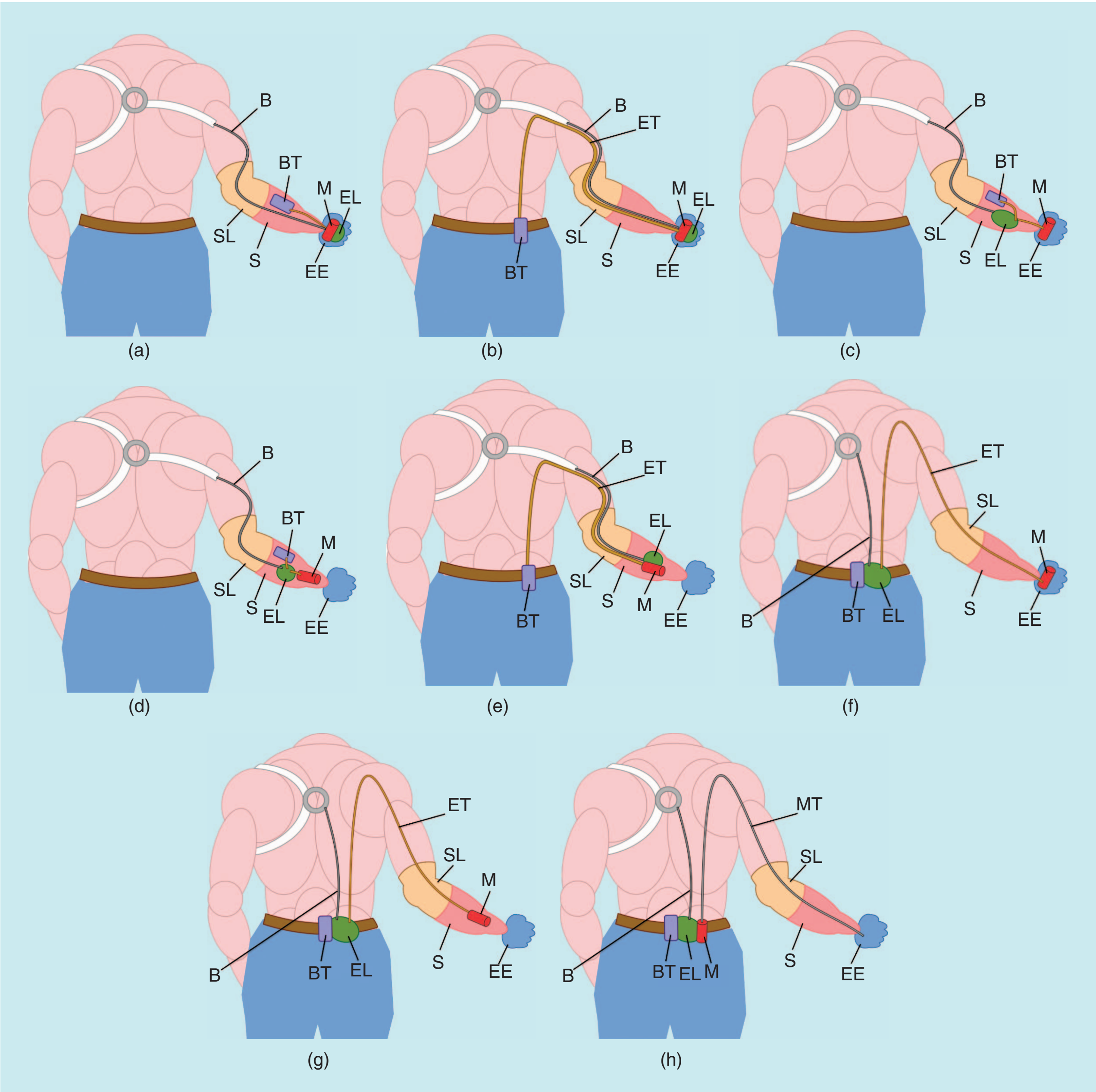


Figure 3. The eight isolated solutions resulting from the combinatory table of the main electric components of an artificial hand (motor, electronics, and battery pack) on the body of a prosthetic user. Solutions (a), (c), (d) have the main components integrated between the hand and the socket, while in alternative solutions as (b), (e), (f), (g), and (h) some components are placed on the body of the user. ET: electrical transmission cable; MT: flexible transmission shaft.

powerful motors. In summary, the selection of a particular solution for an individual should take into account residual limb length, desired weight distribution, environmental factors and constraints, and the need for compliance with existing or commercial components.

Hand Device

Figure 4 shows a first step in the implementation of the hybrid layout conceptually described in Figure 3(b). The proposed system consists of the SHPH covered by a cosmetic working glove, a conventional BP socket, a commercial shoulder harness, and an external battery pack. We chose this layout as the first implementation of the proposed general approach for two main reasons: 1) it is compatible with existing sockets, and 2) our pilot (i.e., the individual with a transradial amputation who competed in the C-PAPR) was a long-term BP user (having used a hook terminal device). It is important to note that we do not claim that this is the optimal solution among those proposed (future work will explore such aspects) but simply that this was the most convenient for the specific application, the C-PAPR.

As mentioned in the "Overview of Prostheses for Upper Limb Replacement" section, the terminal device adopted is an evolution of the Pisa/IIT SoftHand, a soft robotic anthropomorphic hand with 19 DoF and one degree of actuation [9]. Among the different releases of the hand that show improved dexterous capabilities and features (e.g., [21] and [22]), we decided to focus our initial effort on its simplest release. The focus of the work was to realize a simple and effective system, devoting future research activities to developing hybrid systems, likely with higher performance but also higher complexity, where the BP input could be integrated with sEMG signals and much more dexterous hands. In the Pisa/IIT SoftHand, each finger consists of a group of rolling joints connected by elastic ligaments. The elastic bands, fixed on either side of the joint, make the system soft and safe and allow the hand to automatically return to its correct configuration, i.e., after severe dislocations. The transmission system uses one tendon that runs through the entire hand in two levels of pulleys, giving adaptivity to the overall system without a differential gear mechanism. The soft robotic mechanical design gives the hand an overall robustness with the capability of adapting its closure to the shape of objects. Figure 4(g)–(i) shows the hand power grasp and pinch grasp capabilities, whereas Figure 4(a)–(c) shows the main postures the hand can achieve. Moreover, the softness allows large deformations while interacting with the environment, as shown in Figure 4(d)–(f). The current glove used with the SHPH is a commercial work glove that is suitable for working environments. Our approach is to address not only daily activities but also physically demanding work tasks, sports, and hobbies. For this reason, we think that using low cost, commercial gloves (US$5–20) could be a very effective alternative with respect to aesthetically pleasing but very costly prosthetic gloves (US$200–2,000). The selected commercial glove was also valuable for the competition. However, future work will be devoted to investigate the design of a glove customized for the SHPH to increase the grip and allow the system to reach a certain International Protection Marking Code level [28]. Information about the actuation, battery, and electronics board are reported in Table 2. Figure 5(a) shows the mechanical implementation of the SHPH, highlighting the input lever mechanism, motor, wrist interface [Hosmer (Chattanooga, Tennessee) BP wrist], and electronics board.

Figure 4. (a) The SHPH prototype adopted for the C-PAPR and its main components: the hand, the socket, the body power harness, and the battery pack. The main hand postures available to the user include (b) flat hand, (c) grasp closure, (d) and fist. (e)–(g) The soft behavior of the SoftHand and its robustness in several interactions with the environment. (h)–(j) The main grasping capabilities of the hand, highlighting the intrinsic adaptability to object shape.

Input Device

Figure 5(b) shows the detailed, exploded view of the input lever. The support part A, mounted on the hand, is connected with the lever D using two bearings C. The whole system

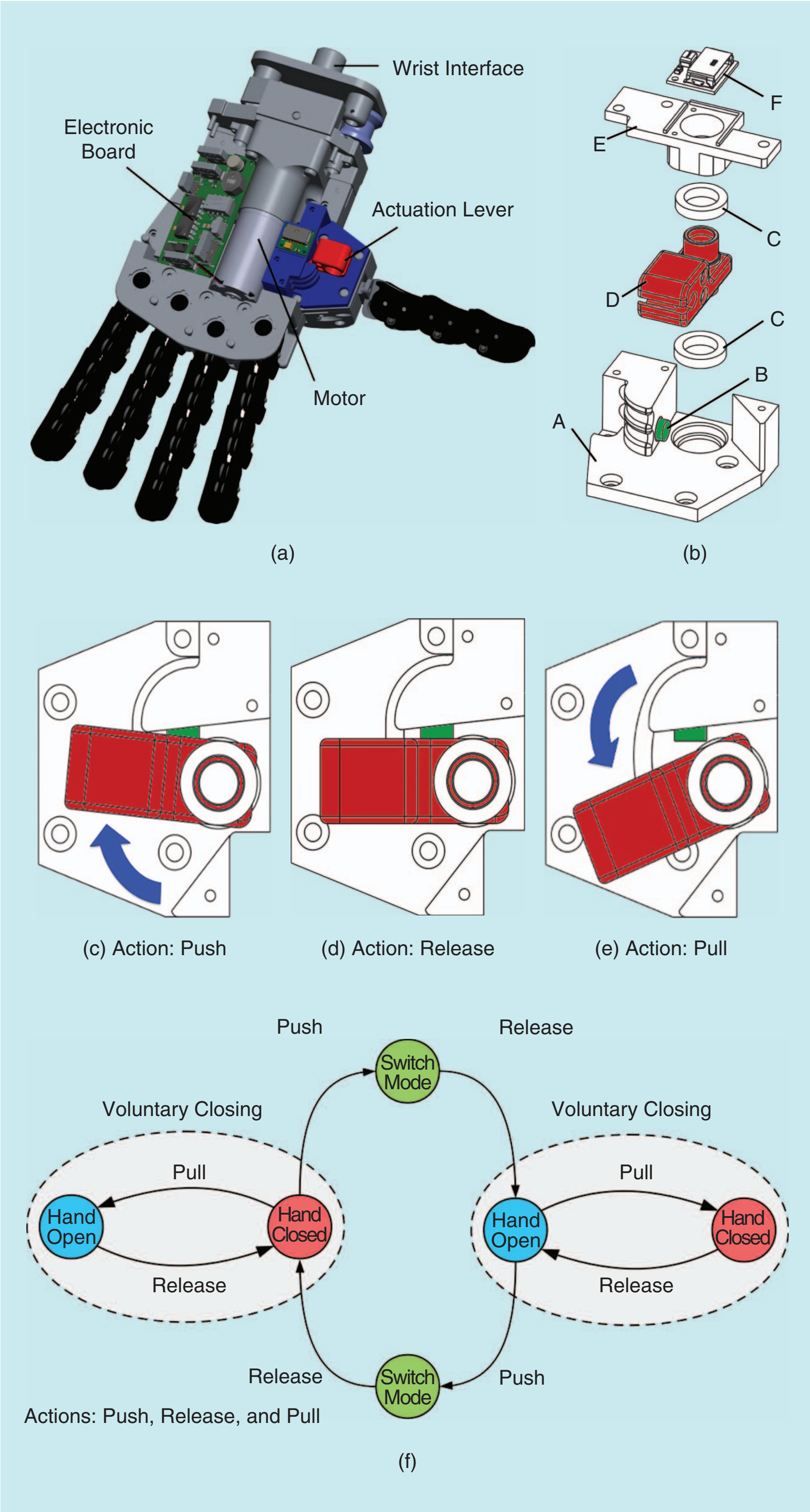


Figure 5. (a) A computer-aided design model of the SHPH. (b) An exploded view of the input lever; the input mechanism consists of A, the support part connected with D, the lever using C, two bearings. B allows switching between different configurations, and E is the cover of the whole system that is mounted to F, a rotary encoder. (c)–(e) The input lever configuration in three different control situations: (c) pushing the lever to switch modes (from VO to VC and vice versa), (d) releasing the lever to enter rest mode, and (e) pulling the lever to activate the hand. (f) The logic of the input control algorithm behind the mechatronic system.

is covered by part E, on which a rotary encoder F is mounted. The lever has a small groove to house the end of the Bowden cable of the shoulder harness. Shoulder movement pulls the lever down and activates the hand [see Figure 5(e)]. The lever returns to the rest position thanks to an elastic band connected to the upper part of the mechanism. This system allows for the translation of the Bowden cable movement into a motor command with a considerable effort reduction compared to commercial BP devices (see Table 3). An upgrade to this system, implemented following the Cybathlon, was the introduction of a switch B between two different modalities with a working principle similar to the one presented in [23]. It is possible to switch between a voluntary opening (VO) and a voluntary closing (VC) mode by pushing the lever. The logic schema behind the switching mode is depicted in Figure 5(f). It is possible to manage the force (acting on the lever spring) and shoulder movement (acting on the encoder range) that are needed to activate the system. These features can reduce shoulder pain for the user but also allow the system to adapt to different users' needs. Setting the force or the movement needed for the activation allows the system to provide some kind of exteroceptive and proprioceptive feedback to the user, in a way similar to that of conventional BP systems but decoupled from the grasp and functional needs of the mechanical device (see the "System Performance" section).

System Performance

Table 3 highlights some features of the SHPH in comparison to two commercial BPPs [Ottobock (Austin, Texas) Hook and Hosmer Soft VO hand]. As shown, the SHPH needs a significantly lower level of force for the activation than the other two solutions. Empirical data show that the level of force required to obtain a minimum opening is ten times less than the Ottobock Hook and 16 times less than the Hosmer hand. Such reduction becomes higher (14 times and 21 times, respectively) in a condition of maximum opening. Moreover, despite the fact that the needed activation force is low, the magnitude of the grasping force is similar for pinch grasp [measured with a JTECH (Midvale, Utah) Commander Echo Pinch Dynamometer] and becomes much higher in with power grasp (measured with JTECH Commander Echo Grip Dynamometer). This is particularly true for grasping widths that are near 60 mm. As a consequence of this input force reduction, the hybrid approach will result in a decrease of exteroceptive and proprioceptive feedback, but, as previously shown (see the "Input Device" section), a proper setup of the system can be made to restore this feature. Future work will explore such tuning and will extensively compare it with other approaches that are explicitly designed to restore a specific haptic feedback (as, e.g., [24] and [25]).

Although BPPs do not require the use of batteries, the autonomy of the SHPH system is not an important limit for the setup. Preliminary experimental acquisitions show that the current release of the SHPH (with the current battery) can perform around 3,500 opening/closing cycles in 4 h. Considering a typical use of roughly 300 cycles per day [26], plus power consumption while not in use and during holding phases, the SHPH is estimated to comfortably provide one to two days of autonomy with typical work use. One limitation of the current solution is the overall weight of the SHPH, between 73% and 82% heavier than the other two solutions. This problem could be partially circumvented through the use of alternative solutions, distributing the total weight of the system along the body of the user. This approach is proposed in the "Approaches" section and could significantly help decrease the weight of the hand, especially in solutions where both the battery and the motor are placed on the waist area. Figure 6 shows the SHPH performing tasks related to work, sport, and hobby activities. As shown, the use of a robust hand together with a common working glove and a simple (and mechanical) activation system allows the user to perform tasks in different contexts, e.g., to use a saw in a garage [Figure 6(b)], to ride a bike [Figure 6(e)], or to play guitar [Figure 6(g)].

Table 3. A comparison between the SHPH and two BP terminal devices, Ottobock Hook model 10A81 [tested in two different spring preload settings, a) minimum spring preload; b) maximum spring preload] and Hosmer Soft VO hand.

	 Ottobock Hook Model 10A81	 Hosmer Soft VO Hand	 SHPH
Weight	285 g	300 g	520 g *
Maximum opening width	100 mm	63 mm	120 mm
Required activation force			
Minimum open	a) 29 N, b) 34 N	54 N	3.3 N
Maximum open	a) 49 N, b) 98 N	147 N	6.7 N
Pinch gripping force	a) 17 N, b) 29 N	13 N	20 N
Power gripping force			
l1 38 mm	a) 17 N, b) 35 N	17 N	40 N
l2 51 mm	a) 17 N, b) 40 N	22 N	53 N
l3 63 mm	a) 17 N, b) 40 N	26 N	63 N
l4 76 mm	a) 14 N, b) 40 N	–	76 N
l5 89 mm	a) 14 N, b) 40 N	–	76 N

*Battery not included.

Cybathlon: Trials and Race

We tested the effectiveness of the SHPH by competing in the C-PAPR. The race consisted of six tasks varying from abstract tasks, aimed to challenge different aspects of the pilot's control and the prosthetic technology itself, to practical tasks mimicking ADL, aimed at testing the functionality in real-world situations. The Cybathlon was scored first on a point system based on the number of tasks completed and difficulty of tasks. For teams that completed the same tasks successfully, as was often the case, time was the determining factor in the scoring process and, thus, is presented along with the total score in the following results. Seven months prior to the competition, our pilot participated in a five-day training session; immediately preceding the competition, our pilot had five additional days of training to refamiliarize himself with the device. A breakdown of SHPH strengths and limitations in the six tasks and the results are presented in the following sections. Task description, rules, and the main skills required are reported in Table 4.

Puzzle

The ability of the SHPH to fully open (to a flat hand, thus maximizing the grasp aperture) facilitated the grasp of larger objects, such as the sphere and large cone [Figure 7(a) and (c)]. The flexibility of the fingers can be challenging to novice users, but, with training, it can become an advantage, e.g., both the key and cord can be lifted with a prosthetic hand with a pinch grasp, although the user must ensure a large enough force and be precise in placing the grasp to avoid slippage. With the SHPH, our pilot could more roughly grasp the object and, with a slight twist, bend the fingers, essentially locking the grip and preventing accidental drops [Figure 7(d)].

Wire Loop

The wire-loop task aims at evaluating the pilot's capabilities in the coordination of his arm's DoF and highlights

Figure 6. The SHPH is used several types of activities, including: physical labor, e.g., (a) handling an axe, (b) using a saw, and (c) lifting a wheelbarrow; sports, e.g., (d) handling a climbing rope, (e) riding a bike, and (f) paddling; and hobbies, e.g., (g) playing the guitar, (h) painting, and (i) throwing a ball.

the potential benefits of the presence of active joints in the overall prosthetic setup. The task itself does not require hand dexterity but rather wrist, elbow, and shoulder coordination. There are two important aspects that could be highlighted from the execution of this task: the capacity of the user to control the hand in the presence of strong compensation movements (e.g., avoiding false activations) and the possibility to have grasps where the object is in line with the main axis of the user's forearm (to minimize compensation movements). Most of the hands at the competition did not have a powered wrist and, thus, required compensatory movements to navigate the course. Because of the flexible closure of the SHPH, our pilot was able to grasp the handle of the wire loop between the index and middle fingers, allowing the wire-loop handle to be in line with the rest of his arm, thus minimizing awkward compensatory movements [Figure 7(e)–(h)]. Moreover, the normally closed modality of the hand allowed our pilot to effectively grasp the wire-loop handle and attend not to the grasp stability but to the precision and joint coordination in the execution of the task.

Shelf and Tray

Two steps in this task were particularly challenging: removing silverware from a drawer organizer and screwing in a light bulb. For the former, the narrow drawer opening and size of the hand (which approximates a large male hand) made it difficult to comfortably reach into the drawer. This difficulty was partly ameliorated by the flexibility of the fingers, e.g., allowing the ring and pinky fingers to bend out of the way while the others picked up the silverware [Figure 7(i)]. For the latter, our pilot removed the bulb from its box by turning it upside down into his partially opened SHPH, then set the bulb in the socket and secured it by turning at the shoulders and waist. Our pilot, after securing the bulb [Figure 7(l)], tended to make a fist and twist the bulb into the socket by touching the fist to the bulb and pulling his arm toward himself.

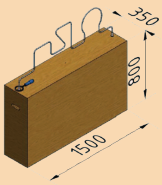
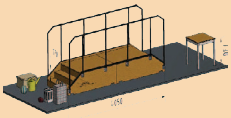
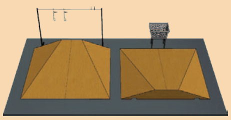
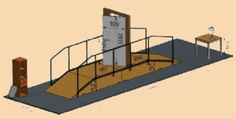
Breakfast Table

Two subtasks of particular interest were cutting the loaf of bread and opening the can. For the former, our pilot made a fist, placed it on top of the loaf of bread, and used the flexible wrist to secure the loaf [Figure 7(m)] while cutting a slice with his other hand. The can opener proved challenging for many pilots, in part because it required the continuous exertion of downward force from the stabilizing hand (most pilots used their prosthesis) while the active hand turned the lever [Figure 7(o)]. Our pilot struggled with this subtask on the qualification round but performed well in the final race.

Hang Up

Two components of this task of particular interest were engaging and closing the zipper and manipulating the clothespins. Our pilot chose to lay the zippered jacket on the floor, holding the bottom stop with the SHPH and engaging the zipper pull with his other hand. To increase speed and stability, he held the jacket in place with the SHPH in a fist [Figure 7(q)]. In practice sessions, our pilot trained in grasping the clothespins in two

Table 4. The task description, main rules, required skills, and scores of the six tasks composing the C-PAPR. (Photos/images courtesy of ETH Zürich.)

	Scheme	Task Description	Main Rules	Required Skills	Points
Puzzle		• Transfer a 3 × 3 grid of square wooden bases from one puzzle frame to another. • Handles have different shapes.	• The pieces could only be lifted by the handle. • The handle could only be manipulated using the prosthetic terminal device.	• Adaptivity • Grip force • Manipulation	115
Wire Loop		• Move a wire loop from one end of a metal wire course to another. • The wire loop is conductive.	• Any contact with the wire course resulted in a task failure. • The start and finish were safe zones.	• Stability of the control signals • Precision • Compensation ability • Wrist, elbow, shoulder, and trunk coordination	102
Shelf and Tray		• Transfer items from shelves and drawers onto a tray. • Carry the tray over a ramp. • Open a door and continue down a ramp. • Reach a table and screw a light bulb into a table lamp.	• The bowl, plate, coffee cup, cutlery, and light bulb could only be handled with the prosthetic device.	• Adaptivity in real environment • Ability to use the prosthesis during movements	130
Breakfast		• Open a water bottle and a jar. • Unwrap a sugar cube. • Cut a loaf of bread. • Use a can opener.	• The task could be completed using either hand.	• Bimanual tasks • Power • Compensation ability • Wrist	104
Hang Up		• Pin a T-shirt onto a metal line by manipulating pins. • Close (buttons and a zipper) and hang two jackets using the hangers.	• The clothespin could only be manipulated using the prosthetic terminal device.	• Bimanual task • Precision	108
Carry		• Carry bags, parcels, and balls over flat ground. • Carry the items up and down stairs and place them on a table.	• The pilot could make as many trips as desired. • Objects varied in weight from 0.4 to 5 kg.	• Force • Control signal • Robustness	101

positions: hanging freely below the line (pointing down and able to swing) [Figure 7(s)] or stably placed on the line (pointing up) [Figure 7(t)]. In both orientations, he found the most stable and easy-to-use grasp to be between the pinky and ring fingers and the palmar surface without needing to adjust the wrist orientation (assuming a neutral wrist starting orientation).

Carry
Our pilot had practiced stacking all items onto the large box and lifting the stack by the box handles using his natural and prosthetic hands [see Figure 7(u)–(x)]. During the final race, however, he chose to make two trips, slightly increasing his time on this task.

C-PAPR Results
Total scores and time (in seconds) for each task and each team admitted in the final race of the C-PAPR are reported in Table 5. The results are split by prosthetic hardware type into BP (one team), single-grasp powered (one team), and multigrasp powered, regardless of control mode (five teams), and compared to results of the SoftHand Pro team. A breakdown of the time to task completion of the teams in the finals can be found in Figure 8(a). However, in cases where more than one team used similar prosthetic hardware (as was the case for multigrasp-powered prostheses), the mean plus-or-minus-one standard deviation is presented. As shown in Figure 8 and Table 5, the SoftHand Pro team's results were highly competitive. Our pilot

Figure 7. The SHPH training on C-PAPR tasks: the (a)–(d) puzzle, (e)–(h) wire loop, (i)–(l) shelf and tray, (m)–(p) breakfast, (q)–(t) hang up, and (u)–(x) carry.

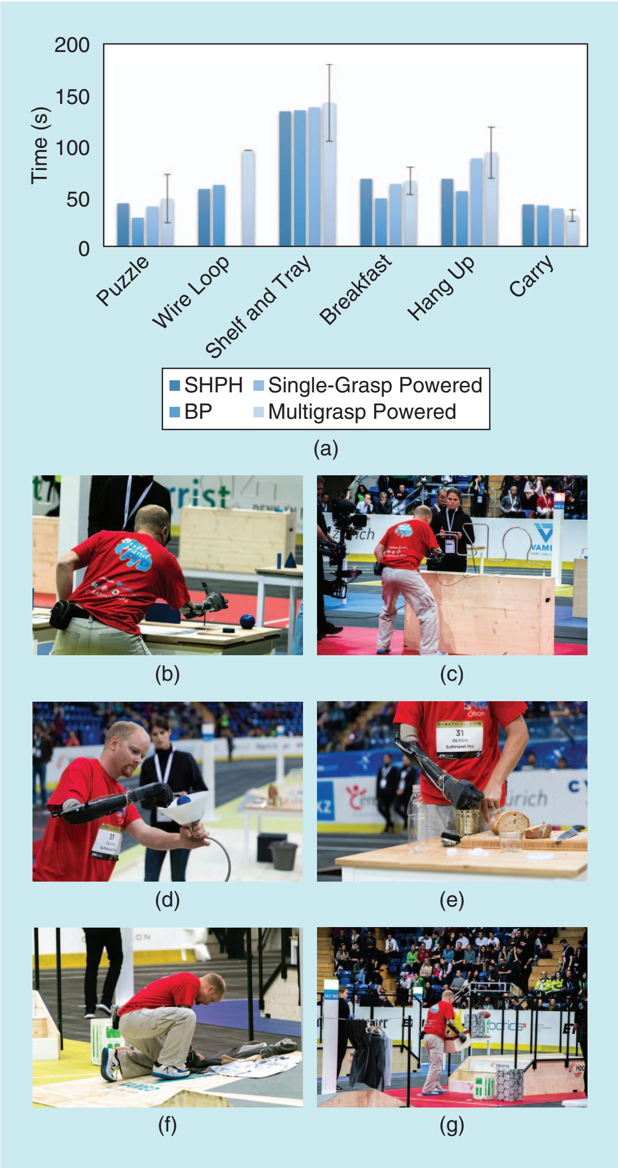


Figure 8. (a) The breakdown of the C-PAPR finals results organized by prosthetic device: SHPH; BP (one team); single-grasp powered (one team); and multigrasp powered (five teams). The highlights from the final race: (b) puzzle, (c) wire loop, (d) shelf and tray, (e) breakfast, (f) hang up, and (g) carry. (Photos courtesy of ETH Zürich.)

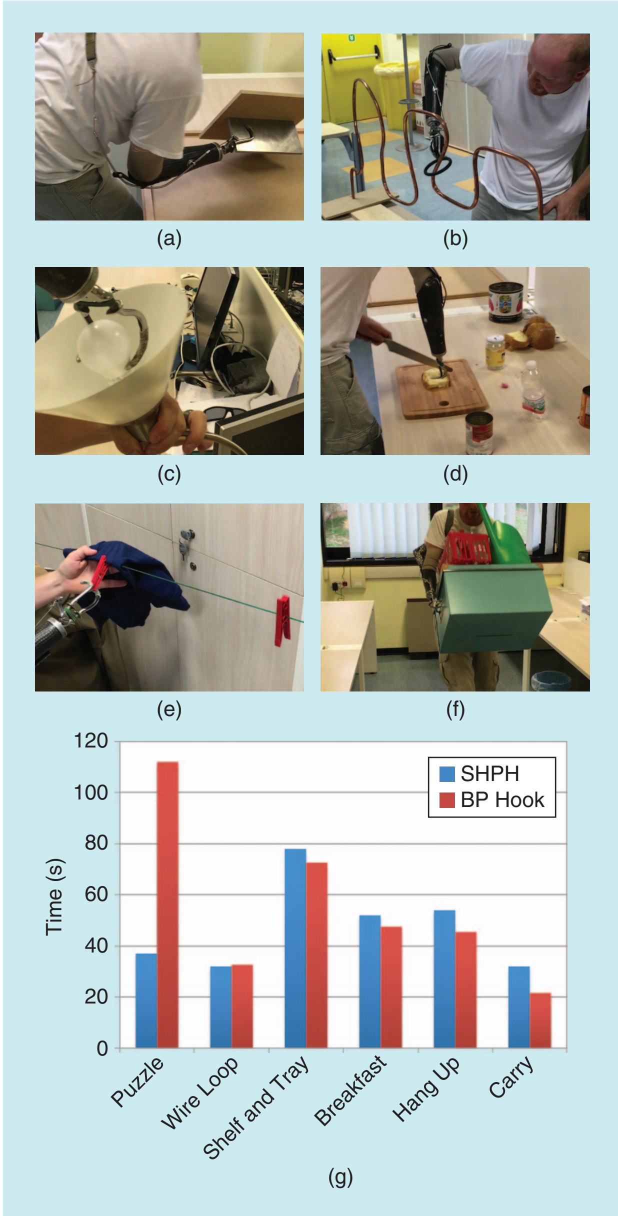


Figure 9. A BP commercial hook on C-PAPR tasks: (a) puzzle, (b) wire loop, (c) shelf and tray, (d) breakfast, (e) hang up, and (f) carry. (g) A comparison, for each task, between the SHPH and BP hook performance.

Table 5. The total scores and time (in seconds) for each task and each team admitted into the final race of the C-PAPR.

		Puzzle	Wire Loop	Shelf and Tray	Breakfast	Hang Up	Carry	Total Score
SHPH		42	56	132	66	66	41	660
BP		28	60	133	47	54	40	660
Single-grasp powered		39	0	136	61	86	37	558
Multigrasp powered	Team A	33	0	91	53	70	33	558
	Team B	74	0	135	80	101	28	558
	Team C	33	0	152	47	73	30	558
	Team D	0	94	195	70	0	37	437
	Team E	0	0	130	70	123	22	443

performed times in line with the average on all tasks, with the exception of a slight delay in the carry task, as explained previously. Furthermore, our pilot was one of only two competitors to complete all six tasks. An element that had great influence on our pilot's performance was the emotional factor. The Cybathlon challenges both pilots and their technologies, but pilots are not trained athletes, so the emotional component should be evaluated. In the first race, our pilot also had difficulty with the can opener task that was performed better in the second race. The C-PAPR results, especially in light of the pilot's limited training with the device, illustrate the utility and intuitiveness of the SHPH system.

Comparison with a BP Hook

The training performed for the preparation of our pilot for the Cybathlon 2016 tasks allowed us to conduct a brief comparison between our pilot's performance with his own prosthetic system (a Hosmer hook) and the SHPH. Figure 9(a)–(f) shows some grasps performed by our pilot with his prosthesis. The execution time for each task for both devices is reported in Figure 9(g). Data were collected during a single session of experiments. Figure 9(g) shows that the major advantage of the SHPH system is in the execution of the puzzle task, where the time-to-task completion is almost double with the hook. The main reason behind this result is the improved grasping capabilities of the SHPH, as it is possible to see from a comparison between, e.g., Figure 7(b) and Figure 9(a) or Figure 7(l) and Figure 9(c). Looking at the other results, the SHPH performs better in the wire-loop and breakfast tasks but has some delays in the shelf and tray, hang-up, and carry tasks. This comparison, as well as the results of the C-PAPR, taking into account the limited training time that our pilot had with the new prosthetic system with respect to his own hook, shows encouraging results for the development of the proposed system. For an extensive comparative analysis with more details on the use of the SHPH system during the Cybathlon race and user feedback, see [27].

Conclusions

In this article, we studied the feasibility of applying the SoftHand technology in a range of ADL, with particular attention focused on work-oriented environments. Among the many requirements needed by these applications, we can cite high grip power, grasp versatility, resilience, and power autonomy as the main design parameters, whereas factors like aesthetics or silent operation are less dominant. Of particular relevance and a specific objective of our proposed work was the control interface with the user. Virtually all work-oriented prostheses are operated via a BP cable, which is very easy to use, has low cost, and does not need batteries, motors, or sensors. Conversely, multiactivation-modalities prostheses have sophisticated myoelectric control and electronics, affording greater versatility, dexterity, and aesthetics. In this article, we explored the possibility of realizing a prosthetic system that combines the two, creating a hybrid system with shared advantages from both fields, adopting a typical BPP input (a shoulder harness) in combination with an electrically powered multifinger anthropomorphic hand. In particular, the adopted hand has intrinsic features that enable the above-mentioned qualities, such as robustness, adaptiveness, and resilience.

Our approach to the problem started from the analysis and the enumeration of the possible locations of the main electric components of the prosthetic hand (motor, battery pack, and electronics) with respect to the other parts of the prosthesis and the body of the user. As a result of this analysis, eight configurations have been isolated, one of which has been implemented in an operational prototype, the SHPH, and used in the C-PAPR by the SoftHand Pro team. Future work will focus on the implementation and comparison of some of the proposed layouts and verifying with users their relevance, effectiveness, and level of acceptance. The Cybathlon competition provided us with the opportunity to test and explore the potential of the first release of the system. Moreover, the effectiveness of the system and the extremely positive preliminary results in the use of our hybrid approach both encourage our ongoing research studying systems where a BP input is also integrated with multiactivation hands and sEMG signals.

Acknowledgments

This work was supported by the European Commission project (Horizon 2020 research program) SOFTPRO 688857, the European Research Council under the Advanced Grant SoftHands "A Theory of Soft Synergies for a New Generation of Artificial Hands," ERC-291166, and the Proof of Concept Project SoftHand Pro-H, ERC-2016-PoC 727536. We thank Samuele Batazzi, Fabio Bonomo, Alberto Brando, Andrea Di Basco, and Alessandro Raugi for their valuable support in the development of the hardware prototype.

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