Adaptable Poly-Articulated Bionic Hands Enhance Both Performance and User’s Perception in Bilateral Amputation: A Case Study

P. Capsi-Morales, Member, IEEE, M. G. Catalano, Member, IEEE, G. Grioli, Member, IEEE, L. Schiavon, E. Fiaschi, and A. Bicchi, Fellow, IEEE

Abstract—This article evaluates and compares the performance and perception of prosthetic devices based on different design principles, a traditional rigid gripper and an adaptable poly-articulated hand, in a pre- and post-training protocol with an individual with bilateral amputation. As a representative of the first class, we use commercial hands (Ottobock’s MyoHand VariPlus Speed), which is a widely adopted model by prosthesis users worldwide. We compare these with two SoftHand Pro hands, which are experimental prototypes exhibiting 19 articulations actuated by one single motor, and are inspired by human hand motor control models. Results show that the individual with bilateral amputation, who was a non-expert myoelectric user, achieved better performance with adaptive poly-articulated hands. Furthermore, the acceptance, satisfaction and perceived functionality of the user were considerably higher for the SoftHand Pro. An observational analysis of the patient’s behaviour by experienced therapists suggests that adaptable poly-articulated hands reduced compensatory movements and cognitive load. Using soft technologies may be especially advantageous for individuals with bilateral amputation, who present a very limited residual mobility and can largely benefit from the active use of their artificial arms in everyday life.

Index Terms—Prosthetic hand, neuroprostheses, soft robotics, clinical trials, assistive technologies.

I. INTRODUCTION

PERSONS with bilateral upper-limb amputation suffer from a very strong limitation in performing their daily activities and from a distorted body image [1]. Artificial limbs open up the possibility of restoring some lost capabilities. However, most clinical studies only include unilateral amputations. Only few report cases have addressed the uncommon situation of individuals with bilateral upper-limb amputation (e.g. [2], [3], and [4]).

Persons with unilateral upper-limb amputation can live independently without the use of a prosthesis [5]. Most of them typically convert most activities into one-handed performance (with a supportive role of the prosthesis) [6]. This usual situation increases the difficulties in obtaining information about the artificial hand capabilities. Sometimes experimenters are forced to ask for particular actions to be performed by the subjects, which may not be otherwise naturally intended, and thus negatively affect their performance and perception. On the contrary, individuals with bilateral upper-limb amputation have no other option but to actively use their prostheses for most activities of daily living (ADLS), unless they fall back on external help. Even though these do not represent the majority of persons with limb deficiency, their condition accentuates the importance of providing them with the appropriate level of perceived functionality that may prevent abandonment. Moreover, studies with bilateral prosthesis users permit a better understanding of meaningful factors in the development of assistive technologies.

Bilateral patients usually report discomfort in the fit, excessive weight, difficulties in operation, and poor functional improvement as reasons for the abandonment of their myoelectric prostheses [2]. Because of the difficulties in delivering suitable prosthetic devices, especially for individuals with bilateral amputation, a common strategy is to provide utensils [2] or modified aids [3], both in their prostheses and in the environment, to ease the performance of specific activities at home or work. Even though this is a practical method, we promote the design of adaptable and dexterous prostheses, rather than the modification of the environment or the hands for the execution of a particular task (i.e. only with a functional purpose). Furthermore, prosthesis users also reported the desire for social integration, improved self-image, and improved aesthetics [7].

In agreement with the previous idea and towards more anthropomorphic solutions, we propose the SoftHand Pro (SHP) as a powerful but simple prosthetic that explores compliance for patients with this condition. Designed after
Fig. 1. The subject with bilateral amputation uses two SoftHand Pro (SHP) systems during prosthetic training. The user is capable of proportional and simultaneous control of both systems without support.

the soft synergy model of hand motor control on humans [8], this hand, with only one degree-of-actuation (DoA), allows the adaptation of the grasp pattern in response to the object being grasped and the surrounding environment. Findings from previous research testing the SHP in unilateral patients (e.g. [9] and [10]), demonstrate the potential of adaptable poly-articulated systems to regain independence and recover part of users’ hands functionalities (including social integration).

This article evaluates the benefits of an adaptable poly-articulated hand for an individual with a transradial bilateral amputation, compared to a commercial myoelectric prosthesis (MyoHand VariPlus Speed, Ottobock [11]) with rigid fingers. Both prosthetic solutions present 1 DoA controlled by the user’s muscle signals. Authors hypothesize positive results regarding the user’s perception and functional satisfaction through the exploration of compliance. Moreover, successful outcomes in rehabilitation can be attributed to patient-direct prosthetic training [12]. Therefore, we investigate the effect of training correlated with the device being used and its mechanical properties (soft or rigid).

This investigation has a very episodic nature, essentially motivated by the rarity of people with bilateral upper-limb amputation. To compensate for the lack of statistically valid generalization ambitions, we present also an overview of the needs of people with bilateral upper-limb amputation, together with the specific results recorded from the subject. Note that the focus of the paper remains the comparison between using soft prosthetic hands and traditional rigid prostheses.

II. MATERIAL & METHODS

The experimental protocol compares the performance and user-perception of two myoelectric prostheses with distinct design features in an individual with bilateral amputation for pre- and post-training conditions.

A. Ethics Statement

This study was authorized by the local Ethics committee of Area Vasta Nord-Ovest (CEAVNO), Tuscany (Italy), protocol n. 7803. The clinical trial was conducted in the Operational Unit of Recovery and Functional Rehabilitation, USL Tuscany Nord-Ovest (Italy). The patient gave his written informed consent under the Declaration of Helsinki.

B. Prosthetic Solutions

During the experiments, both robotic hands were connected to the same passive rotational wrist (from Ottobock) and two customized sockets implementing two sEMG sensors each (13E200 MyoBock electrodes). This was considered appropriate as, among powered prostheses, myoelectric hands are especially useful to reduce the physical effort required to control the device. The MyoHand is a commercial 1-DOF prosthesis with rigid fingers (available in Ottobock [11]). In this article, we termed the combination of the MyoHand and the passive rotational wrist [13] as MyoBock. The SoftHand Pro (SHP) is an articulated soft robotic hand of 19 DOF controlled by only one motor (1 DoA). Designed with the concept of human hand synergies, it results in a simple yet useful solution with adaptable capabilities for multiple object manipulation and human interaction [14]. Find a more detailed description of the SHP in [9].

The choice of the baseline hand to use as a comparison with respect to the SHP was driven by two factors. A first, we considered using a multifunction hand with poly-articulated fingers, since its kinematics and function exhibit more similarities with the SHP. However, its use demonstrated to be excessively complex for the subject, due to their muscle condition and to the prostheses weight. Therefore, together with the therapist, we opted for using a simple and commonly accepted device, which was also the subject’s previously prescribed system, the MyoBock. We acknowledge that this limits, in part, the strength of our conclusions, and demand comparisons with another poly-articulated hand to future studies.

C. Patient’s Medical Condition

A 57-year-old man with a bilateral upper-limb amputation joined the experimental protocol. His past medical history includes interstitial nephritis, which led to a chronic renal failure, forcing the patient to start a hemodialysis treatment in 2007. Raynaud’s Syndrome\(^1\) was the cause that led to the loss of the patient’s limbs. In September 2015, the patient had transient ischemia in the lower limbs. Two months later, a second and more severe episode of ischemia occurred, resulting in the amputation of all the patient’s upper and lower limbs. The amputation level in the upper limbs was at the distal third of both forearms, leading to a stump length of 27 cm on the left and 26.5 cm on the right arm (measured from the elbow joint). The participant presents right-hand dominance pre-amputation. After the amputation surgery, the patient was admitted to a rehabilitation center and treated with Hyperbaric Oxygen Therapy to promote the healing of the stumps. Initially, the patient was provided with lower-limb prostheses (which he currently uses). Then, the subject visited his general practitioner to get the prescribed upper-limb prostheses and selected the control parameters with an Ottobock technician. A pair of myoelectric-controlled MyoHand Variplus Speed prostheses from Ottobock were fitted in February 2017 by a therapist that gave initial training to the patient.

\(^1\)Raynaud’s phenomenon [15] is a reversible and episodic vasospasm of digital arteries, pre-capillary arterioles and cutaneous arteriovenous shunts in response to cold or stress. These result in pallor, cyanosis, and occasionally subsequent ischemia.
According to the patient, he abandoned the UL prostheses soon after the training session and did not exercise with them or any other prostheses (neither active nor cosmetic) from February 2017 until our tests, executed in December 2019. The reason for the abandonment of the prescribed system was poor interfacing, both in the comfort of the socket and the capacity for control. As a consequence, we describe the subject of our experiments as a non-expert myoelectric user. At the moment of admittance to the Recovery and Functional Rehabilitation (ASL Tuscany Nord-Ovest) for the tests, the patient was in good clinical condition and in pharmacological therapy with low molecular weight heparin, proton pump inhibitor and trisectiman hemodialytic treatment.

The SoftHand Pro parameter configuration and setup were done at the beginning of the experimental campaign in December 2019 by a USL Tuscany Nord-Ovest therapist in collaboration with a technical team of the Italian Institute of Technology and University of Pisa (the institutions where the prosthesis was developed and the prototypes realized). During the setup, we observed undesired co-contractions when moving the right arm in space. This muscle condition suggested using FDS-based proportional position control (PPC) instead of the more commonly adopted proportional velocity control (PVC) [16].

D. Experimental Protocol

After recruitment, the protocol included two experimental sessions interspersed with a week break. Each session focused on one system and comprised two consecutive working days. The intermediate resting days had the purpose of reducing the learning effect between systems. Nonetheless, the user tested first the SHP and then the MyoBock systems to, if anything, favor the commercial system, in particular about the learning effect and the risk of fatigue related to the control type. Moreover, to prevent the risk of fatigue from excessive use, we divided the therapeutic training into two working days. The design of the experimental protocol was guided by an occupational therapist, who was involved also during the experimental sessions. Usually no more than 2h of training (daily) are given to new prosthesis users with prescribed devices [12]. Because of the discrepancies in literature about prosthetic training, we defined the duration of treatment based on the patient’s clinical features to assure an acceptable level of expertise. Fig. 2 shows a diagram of the protocol and the selected outcome measures.

We started with a screening of the involved systems during Day 1, followed by the enrollment of the patient at the medical center. A therapist supervised this process to control the state of the patient and his medical history. No detailed information was given about the capabilities of the new system, not to influence its perception and not to create unrealistic expectations, as suggested in [12]. The user answered a survey about general preferences.

Day 2 started with the system training (e.g. calibration) and a short familiarization, named system setup in Fig. 2. The thresholds and gains inside of the control loop were customized and adjusted. Later, a pre-training testing phase was conducted to obtain the baseline performance. The user performed 2 standard assessments accounting for the hand functionality: the Box and Blocks test (BBT) and the Assessment of Capacity for Myoelectric Control (ACMC). After the testing, the user does 2h of training with a trained therapist. Prosthetic training is a dynamic process that includes orientation, control and use training, and ultimately, the execution of ADL [5]. This latter step especially encourages subjects because of the direct application to common activities.

On the Day 3, we inverted the process, starting with 2h of training and continuing with the level reached the day before. Then, the protocol was followed by the post-training testing. These results will be compared to their corresponding baseline values. At the end of the second session for each system, the user responded to three standard outcome surveys (SUS, TAPES-R* and DASH) accounting for user-perception to complete the evaluation of the system.

After a week of rest, Day 4 and Day 5 consisted of the same process described for Day 2 and Day 3, but for the other system under study.

1) Hand Functionality Assessment: We include two common and well-accepted tests for the evaluation of hand functionalities.

The Box and Block Test (BBT) measures unilateral gross manual dexterity [17]. It is a quick and simple test used with a wide range of populations (i.e. not specific for prosthetics). The BBT is composed of a wooden box divided into two compartments by a partition and 150 blocks. The user moves the maximum number of blocks, one by one, from one compartment to another within 60 seconds. We repeated the experiment 3 times per hand. BBT was chosen as this is a well-known standard method, and time-based metrics are commonly used to evaluate the functional success of prostheses. However, it is a less complete functional outcome. For this reason, we added the ACMC, which is a more novel measure but includes interesting items related to activities of daily living and a more relaxed environment to evaluate natural use.
The ACMC is an observational-based assessment that measures a person’s ability to operate a myoelectric prosthetic hand when performing ordinary life activities [18]. This is the first outcome assessment specific for myoelectric upper-limb prostheses. The ACMC evaluates hand functionalities through the assessment of different aspects of manipulation: the need for external support, grip force and opening width, coordination of both hands, different positions and in motion (with timing), repetitive grasp and release, and the need for visual feedback. It is important to keep the subjects motivated and create environments as natural as possible. The test comprises 22 items (ACMC version 3.0) scored on a 4-point rating scale (from not capable to extremely capable) by a trained observer. Items differ in movement and level of difficulty. All items can be found and evaluated in the following tasks: (1) the patient performed the setting of a table in the pre-training sessions and (2) the packing of a suitcase post-training. The minimal detectable change (MDC) indicates whether a change between ACMC scores is due to measurement error or an actual change. The MDC is 2.5 ACMC units for the same rater and 3.1 ACMC units for different raters.

2) User Self-Assessment: Large changes in manual dexterity skills can have different effects on client-rater measures. For this reason, it is fundamental to measure different aspects of the self-evaluation part of an experiment [19]. As mentioned in Fig. 2, we asked the user to reply to SUS, TAPES-R* and DASH surveys. The system usability (SUS) [20] gives information about the acceptability and usability of a system. TAPES-R [21] is a survey related to the quality of life of the user obtained through the use of the device. This method has been widely used in lower-limb amputees. Since this study involves a complex case of a naïve and bilateral user, we considered only the subsection regarding perceived satisfaction, which provides complementary and important information in the user self-assessments, and this is evidenced by an asterisk in the article. Note that the explored subsection of TAPES-R only allows a maximum score of 12. DASH [22] evaluates the hand functionalities perceived by the user, commonly used for upper-limb disabilities. The user is asked to evaluate how good could it be at performing several actions with the use of the system proposed. This test even includes 2 optional sections to detect additional issues concerning work and sport/music abilities.

3) Observational Analysis: Apart from quantitative measures, additional aspects were visually evaluated by the therapist, especially during the training sessions. Sec. IV-B reports our findings about two common aspects of the evaluation of UL prostheses, that are the amount cognitive load required to operate the prosthesis and the presence and entity of compensatory movements. Those aspects are commonly quantified through the execution of specialized tasks, e.g. in actions that combine manipulation and cognitive activities for the cognitive load, or through the measurements of body segment angles for compensatory motions. However, such a systematic and quantitative evaluation was not possible during training nor while testing of our system.

Therefore, we report a recollection of visual evaluations performed by the therapist. More in particular, where compensatory motions are reported about directly, we report about cognitive load by breaking the aspect down in observations about control usability, effective usage of the prosthesis and in-hand manipulations. We report and discuss about the execution times, rates of failures and retrials, the amount of visual feedback required, or quality of conversation flow with the therapist while training.

III. Results

The user reported the sockets, which are fundamental for the good use of the prostheses, as the most important aspect during the survey about general preferences, answered before starting with the protocol. Sockets were followed by human-likeness appearance, being useful for work activities and hobbies, and the importance of the wrist in ADL. He finally reported disagreement in the need for a dexterous hand with several grasp patterns, and in the preference for a more mechanical system than a human-like hand. Moreover, he rated seven aspects from high- to low-priority:

1) Aesthetically human-like
2) Intuitive use
3) Anthropomorphism
4) Mechanical robustness
5) Possible control of the wrist

![Box and Blocks test (BBT)](image-url)
Fig. 4. Scores for the Assessment of Capacity for Myoelectric Control (ACMC). Individuals with bilateral amputation require two scores per experiment, accounting for the functionality presented at each arm. See three horizontal dashed lines to classify the scores into the clinical scale evaluation.

6) Possible control of individual fingers movements
7) Grasp reliability

Concerning hand functional assessments, Fig. 3 presents results from the BBT tests with average scores (±SD) on the left, and the 3 repetitions during pre- and post-training sessions for each hand on the right. The y-axis presents information about the patient’s muscle condition in parentheses and the arm (left or right) used. BBT scores proved an improvement with training for all systems except for MyoBock (right hand) with 14 and 10.33 boxes, pre- and post-training, respectively. Initially, the right hand performed better than the left hand for both prostheses, with 14 (MyoBock) and 12.33 (SHP). However, the left hand presents a higher functionality after training for both prostheses, with 16 (MyoBock) and 17 (SHP).

Fig. 4 shows the scores from the ACMC test, which included more functional tasks and the manipulation of different objects. When assessing individuals with bilateral upper-limb amputations, the rater should only focus on one hand at a time to define two scores from the same experiment, corresponding to the expertise of each arm. The ACMC scores suggest a consistent improvement after training in both SHP hands of around 8 points, but a considerable difference between hands is visible for the MyoBock condition. Indeed, MyoBock (right hand) is the only condition in which there is no difference with training, with 34.8 (pre) and 35.6 (post), which does not pass the MDC of 2.5 ACMC units. These results agree with what we observed in the BBT scores. Between prostheses solutions, a higher performance (i.e. clinically considered somewhat capable) is obtained with the soft hands as a baseline score (i.e. pre-training condition) with 42.1 (left arm) and 45.4 (right arm). In agreement with the ACMC scores, DASH results suggested a higher perceived functionality of the SHP, except for sport/music abilities, where both prostheses rated with the same value.

IV. DISCUSSION

A. Hands Assessment

Standard outcome measures help the researchers and developers to improve prostheses under users’ preferences or requirements [19]. Regarding the performance of BBT, the major cognitive load during the MyoBock testing was on the trajectory planning, observed when the flow of the movement is slightly interrupted, probably because of the less intuitive grasping approach from many proximal joint positions. The rigid properties of the hardware force the execution of compensatory movements, visually inspected by the therapist,
Fig. 5. Scores for each item during the Assessment of Capacity for Myoelectric Control (ACMC). The upper x-axis specifies the corresponding item, while the lower x-axis shows the value relative to the difficulty level of such action. Vertical dashed lines separate the items into the 4 manipulation phases: grasping, re-adjusting, holding and releasing.

Fig. 6. On the left side, the scores about acceptability and satisfaction surveys rated by the client. The higher, the better. On the right, the scores about the quality-of-life improvement (DASH). The lower, the less difficulties are perceived by the user to perform those activities and the better hand functionality.

to approach successfully the boxes (see an example in Fig. 7). The kinematic approach to grasping reported in Fig. 7 shows the combined results of two different aspects. On one side, we observe that the rigid hand uses its fingertips to grasp the boxes, where the SHP permits the contact of the palm before the closure of the fingers, leading to a completely different approach in grasping, that mainly depends on the softness of the hand fingers. On the other side, we appreciate also that the passive wrist flexion of the SHP makes the subject arm approach the boxes more similarly to how a person with intact arms would do. Note however, that this second feature is not exclusive of the SHP, indeed would the MyoBock hand have used the Motion Control multiflex wrist, its orientation should have been closer to that of the SHP. Although the rigid hands obtained more precise grasps (i.e. contact with the fingertips), the excessive and tiring compensatory movements can hinder users’ dexterity. On the contrary, the SHP allows for the exploration of the environment with a more natural body posture. Despite this, the lack of sensory feedback and hand soft properties resulted in a higher uncertainty about grasping success. Indeed, results from BBT do not prove a substantial improvement concerning the system used (see results post-training at the left arm with 16 and 17 boxes for MyoBock and SHP, respectively). Nonetheless, differences in improvement after training for the right hand (where the patient presents limited muscle independent control) depend-
for both hand functional assessments (i.e., BBT and arm dominance) at pre- and post-training testing sessions. This suggests a more suitable control solution [16] of the SHP, correspondent to the patient’s muscle condition. However, note that proportional position control is not exclusive to the technology proposed. Moreover, this muscle problem is also highlighted in the left arm results, where the improvement post-training for both robotic hands is considerably larger. Besides, the time-based nature of the BBT presents limitations in evaluating other important aspects of the hand functionality and of manipulation such as naturalness. Therefore, the ACMC provided valuable information.

Likewise, both artificial systems present improvement in ACMC after training for the same experimental conditions, which reinforces the previous statement about the more suited control algorithm for the SHP. Furthermore, the SHP provides the user with greater functional capabilities in ADL and a better adaptation to different requirements, considered generally capable in the ACMC clinical scale (see Fig. 4). Note that with MyoBock, in its best condition (post-training, left arm), its score (42.5) is only equal to the baseline functionality of the SHP for both arms (i.e., somewhat capable), with 42.1 (left) and 45.4 (right). Although the soft poly-articulated hand presents a larger initial dexterity, with 4h of training the patient is capable to improve its score so that to change to a higher clinical condition (i.e., generally capable), as occurred for MyoBock (left arm). This outlines the idea that, having both artificial systems with 1 degree-of-actuation, the learning to use a 19-DoFs hand could be clinically analogous to the learning of 1 DoF.

Even though the right arm presents a more limited muscle condition, we observed functional differences between arms (i.e., arm dominance) at pre- and post-training testing sessions for both hand functional assessments (i.e., BBT (Fig. 3) and ACMC (Fig. 4)). This occurs probably because of the user’s preferences and expectations, as he was right-handed before the amputation, which could affect the baseline outcomes. However, after training, the user considerably improves his performance with the left arm for both robotic systems tested. The condition in which the right arm still performs better than the left arm, even after training, does only happen for the SHP at the ACMC test, which represents a more practical and complete outcome measure.

Finally, the ACMC in [18] proved to be sensitive enough to detect the difference in ability, especially for new prosthetic users. This sensitivity can be extremely useful for therapists providing prosthetic training, as suggested in [18]. The therapist could use ACMC to assess the initial ability of a new prosthesis user, set relevant training goals at an appropriate ability level, do the training, and use ACMC to evaluate the results from the training. The previous claims reinforce the validity of our experimental protocol and previous conclusions.

The SHP obtained high acceptability and satisfaction scores during the self-evaluation surveys. Indeed, Fig. 6 shows that the SHP got a score (92.5) much larger than 68 (the average score in literature to consider a device accepted). On the contrary, the MyoBock obtained a very low score (37.5), highlighting its poor usability. Note that weight, fit, and comfort are items that are scored inside of TAPES-R*. Initially, the user reported the sockets (physical interface) as the most important aspect for the good use of prostheses in the general preferences survey, which weight, fit, and comfort strongly relate to. In TAPES-R*, the subject reported satisfaction (scored with 2 or 3) towards those three items for the SHP and not satisfied (scored with 1) for the MyoBock, emphasizing a more appropriate interfacing perceived with the overall SHP system. About DASH results, in the work subsection, the user indicated that he only works at home, while he reported his wish to do some gardening, play with the dog and paint for the sport/music part. The equal response for sport/music abilities in Fig. 6 could occur because the user perceived no difference in performing such tasks, or because of a very strong limitation that does not allow the user to imagine himself in those situations. Finally, recall that the subject has also a bilateral lower-limb amputation, the combination of both upper- and lower-limb amputations is considered the most severe physical disability for an amputee [23]. Therefore, he has very limited mobility and minimal progress in ADL performance is considered a big help in his quality of life. The perception of the SHP is considerably better than the one for the MyoBock in all surveys, evidencing the potential of compliant prostheses in individuals with bilateral amputation.

B. Observational Results - Therapeutic Training

The training sessions with the therapist were registered and reviewed. Although no rating or objective measures were performed, prosthetic training highlighted several aspects that are worth mentioning.

1) Compensatory Movements: If prosthesis users do not have the degrees of freedom to compensate during the grasp or release action (as happens usually in individuals with bilateral amputation, or in narrow spaces for unilateral amputations), the collaboration between hands can be fundamental for the proper orientation of the object. The adaptability of the SHP allows an easier and more natural collaborative work of the prostheses. Moreover, this collaboration with rigid hands usually is not related to the active use of the hands, but to the use of the socket+hand as an extension of the stump.

Another important aspect is the wrist rotation, in which, due to the bilateral condition, the user cannot passively rotate the hands by himself. Note that active wrist rotation would not be possible because of the poor quality of the user’s right arm muscles. In this context, rigid prostheses performed larger
compensatory movements (e.g. Fig. 8(a)), and sometimes they prevent the execution of a task. Contrarily, the grasp compliance embedded in the SHP fingers results crucial for the grasping success of many objects without the active help of the therapist (for the wrist rotation).

2) Control Usability: During the MyoBock sessions, the user had several difficulties keeping the hand closed while moving the right arm in the space because of the partial coupling of his muscles. Instead, the control selected for the SHP sessions provides the user with greater security of the hand motion that allows the user to control both hands simultaneously without visual feedback. Fig. 8(b) presents an example of bimanual manipulation, where the user is looking at the glasses and not directly at the hand. The major problem with PPC occurs when controlling both hands simultaneously in different manners, which requires concentration and expertise. Nevertheless, the patient does not present any risk of fatigue after the protocol with the SHP, visible in the testing results and by his verbal responses.

3) Usage: Rigid hands produced a more precise control when performing pinch. Nonetheless, rigid hands present riskier grasps because of fewer contact points [24]. We observed that the objects grasped with the MyoBock hands could easily fall during transport phases. The scarce adaptability of rigid fingers, compared to human hands, sometimes forces an object to move rigidly around the contact points. For instance, the user had problems in the release phase because of the particular orientation of the object inside of the robotic hand. This issue could force a particular body posture of the user, which can compromise the contact of the sEMG sensors and, as a consequence, the commandment of the prosthesis.

4) In-Hand Manipulation: It is interesting to observe the effect on body configurations when grasping and releasing objects in a particular orientation (e.g. in Fig. 9). Fig.s 9(a), 9(b) and 9(e) exemplify the difficulties encountered with the MyoBock, where the release in a lot of the cases requires the help of both hands (without active use) to orient the object due to the impossibilities to perform some compensatory movements. Fig. 9(d) demonstrates that the preferred grasping orientation can differ from the optimal releasing orientation. However, the adaptation of the hand/fingers moving the object grasped with the SHP can reduce the use of compensatory movements and perform a more natural release with only one hand (e.g. in Fig.s 9(e) and 9(f)). In this training task, the SHP performed quicker, which is associated with a lower cognitive load.

To sum up, with MyoBock hands, the user is forced to perform excessive compensatory movements (as seen in Fig. 8), where large cognitive loads are involved to track the trajectory desired. Rigid prostheses often force bimanual manipulation in usual unilateral activities to compensate for an unsafe grasp or to locate the objects in a more feasible trajectory, as in Fig. 10(a)-10(c). These require time and restrict the subject’s performance, affecting the multitasking capability of the user, highlighted by his inability to maintain the conversation with the therapist. Large compensatory movements can compromise the contact between the sEMG sensors and the user’s skin. Moreover, the user’s fatigue can deteriorate EMG signals and favor the sweating of the residual arms. On the contrary, the SHP allows for the simultaneous operation of both prostheses due to the embedded intelligence in its mechanics and a more appropriate myoelectric control algorithm. A crucial aspect of prostheses acceptability is the level of embodiment that users feel towards the system, which is not only related to the physical appearance but also to the mechanics or functionalities, and the control intuitiveness. Although no particular testing was included in the experimental protocol, the therapist encouraged the integration of both systems to favor the learning and the sense of ownership of the prostheses. Fig. 11(a) presents an example of the user trying to imitate the hands of the
Fig. 11. Embodiment during training. (a) shows the patient executing mirror therapy. It consists of imitating the movement executed by the therapist for a quicker learning. (b) presents a natural position of the user while listening to the therapist with two SoftHand Pro.

therapist (known as mirror therapy) to enhance proportional and simultaneous control of both systems. In Fig. 11(b), the user was listening to the therapist and waiting for new tasks during the clinical training. This natural posture is an indicator of the possible embodiment felt by the user towards the SHP thanks to the softness of its fingers.

V. CONCLUSION

Individuals with bilateral amputation, apart from finding themselves with an incredible limitation to recover upper-limb functions, allow for more meticulous studies of proposed assistive devices and their effect on users’ life. In this article, we compare two prosthetic solutions with different principles (with adaptable and rigid fingers) in a subject with a bilateral amputation after 4h training with a therapist. The protocol includes the BBT and the ACMC outcomes for hand functionalities evaluation. Then, the client rates different aspects through the use of three surveys. While no improvement corresponding to the hand features is visible in BBT, the ACMC proved a higher hand functionality of the SoftHand Pro (SHP), probably related to its adaptive capability, and a consistent improvement (i.e., one clinical level) post-training in both artificial systems when the control method suits the patient’s muscle conditions. The latter highlights that the difficulties in exploring the use of 1 DoF can be identical to the use of a 19-DoFs system, which could provide a larger dexterity. Furthermore, the SHP obtained very good acceptability (SUS) and satisfaction (TAPES-R*) scores, and a larger perceived functionality (DASH). Even though this is only a case study, these results, together with some training observations, present proof of the needs of bilateral prostheses users, and highlight the potential of soft underactuated systems. Future investigations should address the different needs and experience of individuals with bilateral amputation more systematically, to extract more general and quantitative conclusions.

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