Engineering Applications of Artificial Intelligence 93 (2020) 103698

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

The PRISMA Hand I: A novel underactuated design and EMG/voice-based multimodal control ☆

Fanny Ficuciello *,[1], Giulio Pisani, Salvatore Marcellini, Bruno Siciliano[2]

PRISMA Lab, Department of Electrical Engineering and Information Technology, University of Naples Federico II, via Claudio 21, 80125, Naples, Italy

ABSTRACT

The novel underactuated design of the PRISMA HAND I and its multimodal control based on integrated electromyographic signals and voice commands is presented. Due to limitations of EMG sensors and residual physiological signals of amputees, a smart solution utilizing a voice recognition module has been integrated into the EMG control to realize advanced intuitive commands and easy connection with the arm. Inspired by neuroscience studies on the human hand, two motor synergies have been implemented. The thumb adduction/abduction independent motion allows in-hand manipulation. The transmission system is based on whiffletree and pulleys for motion differentiation and on antagonistic elastic tendons. Using EMG and voice commands, the motors are moved together in a certain number of combination suitably and easily programmed using Arduino electronic prototyping. The use of a current sensor allows controlling the strength of the grasp to handle also fragile objects. The contributions of this work are: the bio-inspired design of kinematics and motion couplings by means of two motor synergies, the simple and efficient control interface allowing easy connection to the arm and intuitive use, finally, the cost reduction using economic hardware and mechanical components while preserving performance.

1. Introduction

Robotic prostheses are a hot topic of research attracting the interest of many scientists from different disciplinary fields such as mechanics, electronics, robotics and neuroscience (Santello et al., 2016). The main issues related to the design of prostheses are: (i) a simple and intuitive user interface to reduce stress and extensive training (Biddiss and Chau, 2007), (ii) lightness and compactness of the design for easy fit and human-like aesthetics (Belter et al., 2013), (iii) high performances comparable to those of a real limb (Bennett et al., 2015), (iv) finally, low cost to make the device accessible to a large audience (Open Bionics, 0000a). About the first issue, besides cosmetic prostheses that have almost null level of function, there are two main categories of prosthetic devices which stand out for the communication and control method: body-powered and active controlled prostheses (Naidu et al., 2008). A literature review point out that body-powered prostheses require less training, they are more durable and provide better feedback to the user with respect to the externally powered alternatives (Carey et al., 2015). Active prostheses, instead, improve cosmetics and phantom-limb pain, further they can provide better functionality at the expense of more training. Moreover, the costs are higher also in terms of maintenance and fitting (Silcox et al., 1993). Prostheses commercially available at affordable costs are mostly simple passive grippers. Most advanced devices available on the market are described in Table 1 where weight, number of motors and number of joints are specified.

Yet different prototypes are available in literature that present complex actuation systems with high degrees of freedom (DoFs) and different number of motors up to 5, 6 independent controlled movements (Carrozza et al., 2002; Zollo et al., 2007; Wiste et al., 2011; Hong et al., 2007; Dalley et al., 2009; Ficuciello et al., 2012a). Those advanced devices present complex kinematics and actuation systems providing enhanced performances comparable with the human hand. On the other side, this leads to a complex user interface that is more difficult to control and requires more training time. The idea of using coordinated motions inspired by the human hand for robotic applications is the keystone towards smart hands simple to build and control while retaining much of the human hand functionality and skills (Santina et al., 2015; Cerulo et al., 2017). In general, the use of synergies creates a valid alternative that overcomes the limits of model-based methods for control and full-actuation trends for design (Ficuciello et al., 2010; Ficuciello, 2019a; Ficuciello et al., 2016b, 2019). In Lobo-Prat et al. (2014) a systematic classification method for active prosthesis is proposed based on three criterion: (i) the source of the physiological signal, namely

☆ This research has been partially funded by the Italian National programme POR FESR 2014-2020 within BARTOLO project CUPB41C17000090007 and by the Italian National programme PNR 2015-2020 within PROSCAN project CUP UNINA: E26C18000170005. The authors are solely responsible for the content of this paper, which does not represent the opinion of the European Community, and the Community is not responsible for any use that might be made of the information contained therein.

* Corresponding author.

E-mail addresses: fanny.ficuciello@unina.it (F. Ficuciello), giuliopisani1989@gmail.com (G. Pisani), s.marcellini@studenti.unina.it (S. Marcellini), bruno.siciliano@unina.it (B. Siciliano).

[1] Senior Member, IEEE.

[2] Fellow, IEEE.

https://doi.org/10.1016/j.engappai.2020.103698

Received 12 September 2018; Received in revised form 17 September 2019; Accepted 7 May 2020

Available online 29 May 2020

Table 1
Commercial prosthetic hands.

Name	Myohand MyoBock (0000b)	i-limb (i-limb, 0000c)	Bebionic (Bebionic, 0000d)	Michelangelo (Michelangelo, 0000e)
Weight	460	539	567	746
# Motors	1	6	5	2
# Joints	2	11	11	6

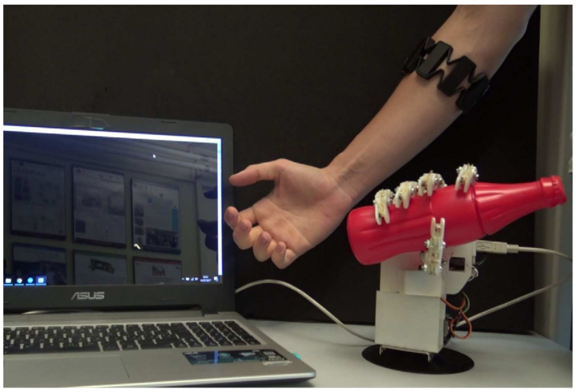


Fig. 1. PRISMA Hand I.

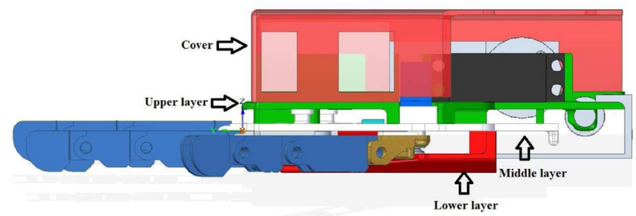


Fig. 2. PHI lateral view.

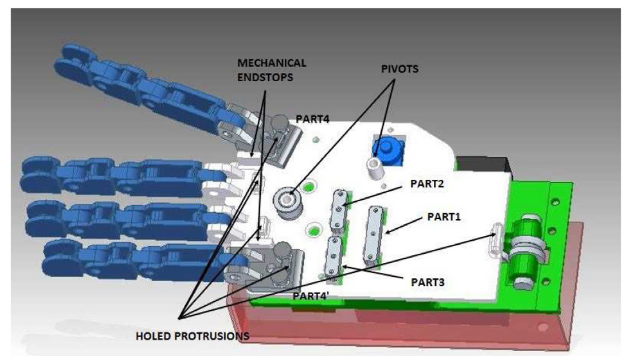


Fig. 3. PHI middle layer.

brain activity, muscle activation or contraction, (ii) the type of signal, namely, Electromyography (EMG), Electroencephalography (EEG), electric impedance, sonomyography (SMG); magnetoencephalography (MEG) and so on, (iii) the sensors used to measure the physiological signal, namely electrode, MEG machine, ultrasound scanner and so on. Other classification elements are in the kinematics, actuation system, control interface that detects the user's movement intention, and finally in the invasiveness of the sensors that detect the physiological signals. In Belter et al. (2013) the finger design and kinematics, the mechanical joint couplings, and the actuation methods are analyzed for a review on several commercially available myoelectric prosthetic hands. Despite such new technologies improving mechanics, control interface and actuation system (Bennett et al., 2016; Piazza et al., 2016), one big problem, besides the cost, remains the relationship between performance and acceptability from the patient side. To this purpose, the user interface has a crucial importance for the acceptability of the device. In this paper, we propose a low-cost innovative solution, the PRISMA Hand I (PHI, in Fig. 1) that brings together lightweight design, bio-inspired underactuation and easy user interface for intuitive and efficient control.

2. Motivation and ideas

In the construction of the PHI we tried to answer to the following requirements: (I) bio-inspired design with a number of DoFs comparable to the human counterpart to enhance performance and functionality, (II) human-like behavior and compliance during interaction with the environment while preserving simple and lightweight design, (III) easy and intuitive control interface to enhance the acceptability by the users, (IV) and finally low-cost design, materials and components. The main motivation of this work is to find a trade-off between the state-of-the-art device that delivers the ultimate in technology and performance but is still at prototype level, and a device easy to commercialize and comfortable to use while it provides optimal performance as well. PHI is a novel bio-inspired underactuated artificial hand. To answer to the requirement (I) we build the hand with size and kinematic structure very similar to the human hand, as described in Section 3.3. About (II) taking inspiration from the postural synergies concept and its application to robotic anthropomorphic hands, two motors have been adopted to obtain human like motions using tendon transmissions for joint couplings. The first motor reproduces the first postural synergy observed in the human hand. This is characterized by metacarpophalangeal, proximal interfalangeal and distal interphalangeal coordinated flexion motion and fingers' adduction motion. The fingers' extension and abduction motions are obtained by means of elastic antagonistic tendons, while the inter-finger coordination is obtained using a unique stiff tendon connected with the motor by means of servo pulleys and with the other finger tendons by means of whiffletree systems, pulleys and pivots, as described in details in Section 3. Both the transmission system and the compliance introduced by elastic tendons allow the hand adapting to different object shape and size. About the second motor, studies on fully actuated robotic hands demonstrate that thumb adduction/abduction motion depends especially from the third synergy that is responsible of successful precision grasps (Gabiccini and Bicchi, 2010; Ficuciello et al., 2014, 2012b, 2016a; Ficuciello, 2019b). Considering the important role of the thumb on grasp stability, in particular for the opposition role, we decided to use the second motor for adduction/abduction thumb motion. This motor can rotate the thumb during the grasp by creating synergies with the closure movement, thus providing internal manipulation capabilities. As far as the authors knowledge, this actuation system with the chosen motion couplings is different from previous solution (Santina et al., 2015; Piazza et al., 2016; Bennett et al., 2015) and allows different type of grasps (power, precise and lateral side) even of small objects, and internal manipulation, as described in Section 6.

About point (III), in the introduction we have highlighted that for robotic and prosthetic hands an important challenge is the control and the connection with the arm by means of electronics and physiological signals. EMG-based control has some limitations when the objective is to control a multi-DoF prosthesis to generate different motion patterns beyond the simple opening and closing movement. Long training is required so that the patient will be able to generate specific muscle

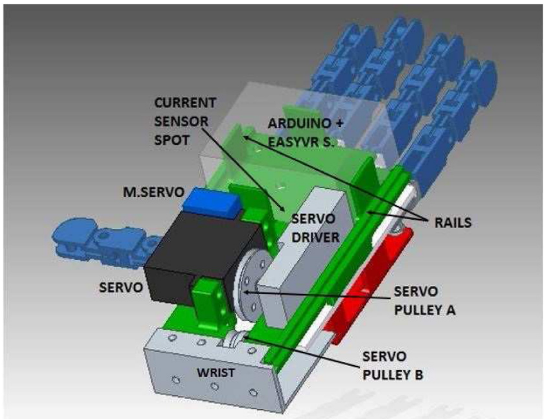


Fig. 4. The back of PHI.

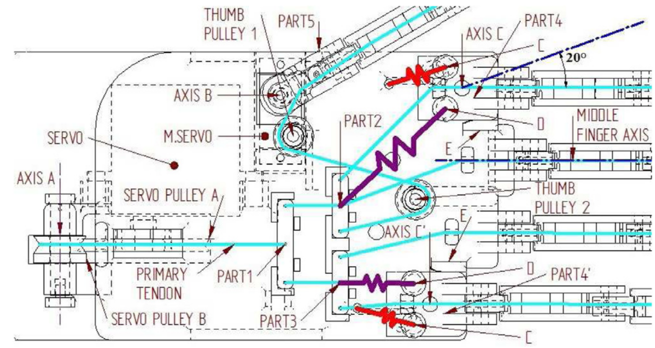


Fig. 5. Palm middle layer top view. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

signals to switch from a motion pattern to another. Other solutions use additional sensors that require the use of the other hand or of external devices like smart phones or sensorized objects. To avoid un-natural muscles movements or gestures and external accessories, in this work, a smart solution has been found using voice command to simplify the control interface while expanding the number of motion patterns which can be generated towards intuitive and fast control. The EMG signals are used to control the basic gestures like opening and closure of the hand and to activate the voice control. Using a voice command control strategy, the two motors can be moved together in a certain number of combination and at different velocities. Furthermore, the use of motor current sensors allows controlling with the voice also the intensity of the grasp to handle fragile objects. All those motion patterns can be suitably and easily programmed using Arduino electronic prototyping platform. In this way, the problem of connection and compatibility with a biological system is dramatically reduced, as well as conditioning and mapping of myoelectric control signals of an amputee and training phase. Finally, to address requirement (IV) 3D printing technology and Arduino programming are used. Thus, as an added value, the whole hand project is low cost and easy to be reproduced thanks to the use of commonly available components. The prototype hand build for the proof of concept has a total cost of 250 Euros.

3. Mechanical design and tendons routing

The PRISMA Hand I is realized by means of fast prototyping: the fingers, palm, whiffletree systems and back cover of the hand are constructed using 3D printing technology and Fused Deposition Modeling (FDM). The joints are obtained using steel bolts and the tendons are made of nylon and elastic synthetic fibers. The total weight of the device is less then one kilogram. The hand has two motors, a servo actuator that moves all the fingers for the closure and opening of the hand, and a small size actuator that provides the adduction/abduction motion of the thumb. This motion is independent and can generate internal manipulation when the hand is closed in a grasp configuration. The PHI palm design is bio-inspired and provides human-like allocation of fingers base frames in such a way to have different distances of the fingertips with respect to the base of the palm. From a technological point of view, this solution allows designing all the fingers equal to each other, enabling a simple and economic replacement in case of damage. The PHI palm is composed by 3 layers and a cover, as shown in Fig. 2. The middle layer, in Fig. 3, holds all the traction system and the joints connecting the fingers to the palm. The upper layer holds the electronic and control board and the servo actuator responsible for the whole hand closure. The lower layer works as a palm and has an ergonomic shape to improve the quality of the grasp by extending the possible contact area. It also holds the small sized servo actuator. Afterwords, an external cover is provided to protect the circuits from external contacts such that they are contained in a closed box, the back of the hand is shown in Fig. 4. In the following, the fingers tendon routing and the transmission system are described in detail.

3.1. The traction system

The hand closure is entrusted to the servo motor whose motion is transformed into a linear motion for tendon traction with the aid of the servo-pulleys A and B, see Fig. 4. The transmission, called whiffletree, is composed by 3 elements PART1, PART2, PART3 shown in Fig. 3. All the tendon paths are represented in Fig. 5. In absence of interaction, to close the hand completely until each joint reaches the end-stop, the primary tendon must move of 41 mm. During traction, the primary tendon pulls back the first transmission component called PART1 that presents 3 holes: the primary tendon is tied in the middle where is the differentiation pivot. The other two holes are on the end of the parts where are tied two tendons whose role is to pull back PART2 and PART3. This mechanism will create a differentiation between the closure of two finger groups: the first one is constituted by the index, thumb and middle finger, the second one is constituted by the ring and little finger. The motion transmission system, that includes the traction system based on the whiffletree differentiation mechanism and the antagonistic elastic tendons, is designed to allow the hand closing properly with and without the object. The first group presents a bigger antagonist force (described in Section 3.3) and thus it is the last one to be pulled back, causing the closure of ring and little fingers at first. Moreover, PART2 and PART3 holds two elastic bands that cause the abduction motion of the index and little finger respectively during hand closure, see Fig. 5. Finally, with a proper differentiation of the antagonistic elastic tendons the thumb can close with a little delay with respect to the other fingers. In Fig. 6 there is the representation of the whiffletree traction system. The variable p is the length of PART1 and p' is the length of PART2 and PART3. the tendons connecting PART1 to PART2 and PART3 have the same length. If l is the displacement of the primary tendon, namely the length of the tendon that the servo rolls around its pulley, and l_n with $n = \{t, i, m, r, l\}$ is the length of the tendon pulled back by the whiffletree for each finger, the relation between the primary tendon and finger tendon displacements are the following:

$$\begin{cases} l_m = l - a; & m = middle \\ l_i = l - a - b; & i = index \\ l_t = l - a + b; & t = thumb \\ l_i = l + a - b'; & r = ring \\ l_i = l + a + b'; & l = little \end{cases} \tag{1}$$

where

$$\begin{cases} a = \frac{p sin(\gamma)}{2} \\ b = \frac{p' sin(\alpha)}{2} \\ b' = \frac{p' sin(\beta)}{2} \end{cases} \tag{2}$$

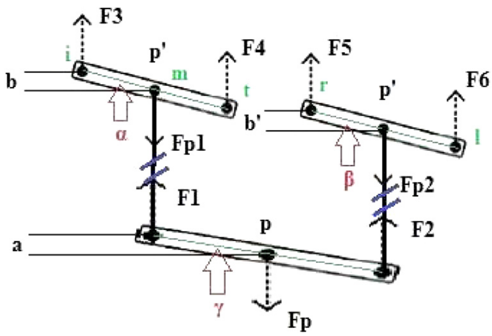


Fig. 6. Whiffletree transmission system.

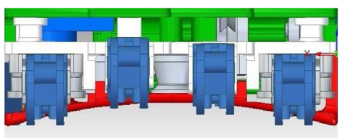


Fig. 7. Hand morphological arch structure.

3.2. Adduction and abduction

In order to reproduce the adduction and abduction movements for the index and little finger, PART4 and PART4' are designed to rotate around axes C and C' (Figs. 3 and 5). When the motors are in the home position (Fig. 10), the fingers hold the maximum adduction, when the hand is closed the fingers have the maximum abduction. The end-stops are made by means of mechanical blocks. The adduction/abduction motion is obtained by means of two elastic passive tendons (represented in red in Fig. 5) that hold the finger position in the maximum adduction and by two elastic tendons (represented in violet in Fig. 5) connected to the whiffletree traction system through PART2 and PART3 such that the adduction/abduction motion is connected to the closure and opening of the hand and synchronized with the other fingers.

3.3. The fingers

Each finger is composed of proximal, middle and distal phalanxes. The phalanxes' length ratio are coherent with the human anatomy. The shape and size of each phalanx is designed to allow introducing tactile sensors and soft plastic fingertips. Inspired by human anatomy, each finger base frames are placed at different distances from the palm frame such that the longitudinal arch of the hand will provide a convex shape of the palm. The distal transverse arch of the hand is represented in Fig. 7. The peak of the arch is at the middle finger while at the lower level there are the little and index finger. To realize the finger tendons a common flexible fiber that withstand a 10.9 kg tension has been used, while for the primary tendon the fiber has been chosen to withstand a 21.8 kg tension. The tendon path is well explained in Figs. 8 and 9. The hand traction system provides a single tendon per finger which passes entirely inside the finger. The internal route is designed to have low friction and a proper behavior during the closing and opening phase. Thanks to protrusions properly positioned a lever system is created such that during the closure phase it leads the phalanxes to get in contact in correspondence of the parts circled with a continuous line in Fig. 9. Furthermore, protrusions to prevent the finger hyperextension are properly designed and highlighted in the figure thanks to dashed circles.

On the backside of the finger three elastic fibers are used as antagonistic tendons to ensure fingers extension. Those tendons anchorage each phalanx to the previous element of the kinematic chain by means of protrusions (marked in black in Fig. 9). Due to the presence of a single actuated tendon for the finger closure, to ensure a good grasping ability the antagonist forces agent on the phalanxes are differentiated. The elastic tendons that move the proximal phalanxes of the fingers exhibit lower rigidity in order to anticipate the closing movement with respect to the movement of the other phalanges. This antagonistic tendon differentiation allows the hand enveloping objects by adapting to its shape: the proximal phalanx rotates around the middle layer joint until it reaches the end-stop (collision between proximal phalanx and the palm), then the middle phalanx begins his rotation until reaches its end-stop (collision between proximal phalanx and middle phalanx), finally the distal phalanx moves until it reaches its endstop (collision between middle and distal phalanx). In the presence of the object, when one of the phalanxes get in contact with the object it stops moving, and the next one in the kinematic chain proceeds the motion until the object is wrapped. The hand kinematics is calculated using the Denavit–Hartenberg (D–H) convention. The D–H parameters are shown in Table 2. The joints end-stops are shown in Table 3.

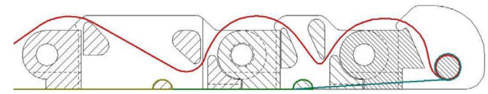


Fig. 8. Tendon routing of the PHI's finger.

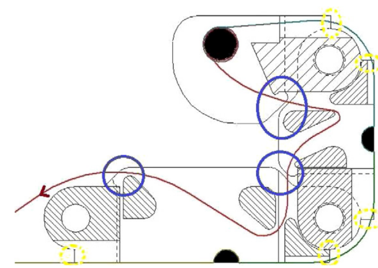


Fig. 9. Finger tendon routing during hand closure.

Table 2
PHI Denavit–Hartenberg parameters.

Link (Thumb)	d [mm]	θ	a [mm]	α [deg]
1	6	θ_1	20	90
2	0	θ_2	40	0
3	0	θ_3	25	0
4	0	θ_4	25	0
Link (Index)	d [mm]	θ	a [mm]	α [deg]
1	4	θ_1	15,8	90
2	0	θ_2	40	0
3	0	θ_3	25	0
4	0	θ_4	25	0
Link (middle)	d [mm]	θ	a [mm]	α [deg]
2	0	θ_2	40	0
3	0	θ_3	25	0
4	0	θ_4	25	0
Link (Ring)	d [mm]	θ	a [mm]	α [deg]
2	1,5	θ_2	40	0
3	0	θ_3	25	0
4	0	θ_4	25	0
Link (Little)	d[mm]	θ	a [mm]	α [deg]
1	4	θ_1	15,8	90
2	0	θ_2	40	0
3	0	θ_3	25	0
4	0	θ_4	25	0

4. Electronic board and components

Remote actuation is adopted in the design of the PHI as in biological structures, and a tendon transmission system is designed to distribute

Table 3
PHI angles excursion.

(Thumb)	*thetamin* [deg]	*thetamax* [deg]
1	0	90
2	0	130
3	0	93
4	0	92,5
(Index)	*thetamin* [deg]	*thetamax* [deg]
1	20	0
2	0	115
3	0	93
4	0	92,5
(middle)	*thetamin* [deg]	*thetamax* [deg]
2	0	115
3	0	93
4	0	92,5
(Ring)	*thetamin* [deg]	*thetamax* [deg]
2	0	115
3	0	93
4	0	92,5
(Little)	*thetamin* [deg]	*thetamax* [deg]
1	−20	0
2	0	115
3	0	93
4	0	92,5

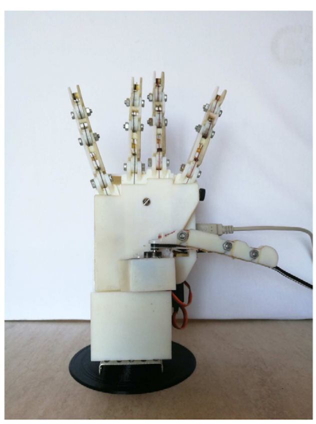


Fig. 10. PHI home position.

the motion to the whole structure using only two motors. The middle sized servo, TowerPro MG996R, is placed on the backhand and is mated with a pulley (SERVO PULLEY A) whose dimension allows to envelope the tendon for the hand complete closure when the actuator rotates of 180°. This actuator is connected with the primary tendon thus it is responsible of the whole hand closure. The motor runs 180° and weight 55g, the dimensions are of $(40.7 \times 19.7 \times 42.9)$ mm, stall torque of 10 kg/cm, operating speed of 0.20 s/60 degree and voltage of 4.8 V (Towerpro, 0000f). The small sized servo, SG90 9G, is placed into the palm layer, this motor allows the thumb adduction/abduction joint motion gaining in hand dexterity. The motor runs 360° and weight 9 g, the dimensions are of $(23 \times 12.2 \times 29)$ mm, stall torque of 1.8 kg/cm, operating speed of 0.10 s/60 degree and voltage of 4.8 V (Towerpro, 0000f). The PHI has one current sensor, the Allegro ACS712 (Allegro, 0000g) which provides economical and accurate solutions for AC or DC current sensing in industrial, commercial, and communications systems. The sensor is allocated in the PHI Hand to measure the current of the servo actuator, that moves all the fingers, as an economical solution to regulate the interaction with objects/environment. Indeed, it allows defining the desired strength during the grasp. The control is implemented using the microcontroller ArduinoUNO based on the ATmega328P. We choose this device due to the versatility for the

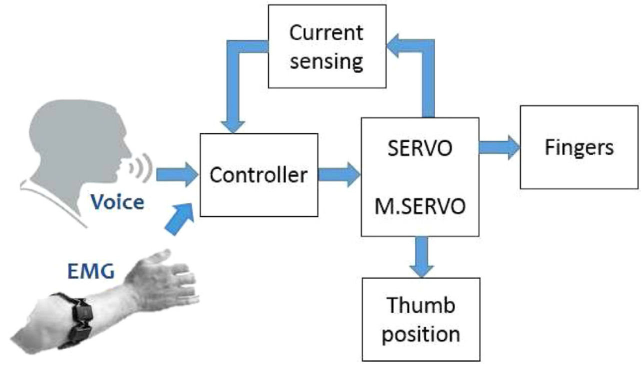


Fig. 11. PHI Control scheme.

Fig. 12. Myo gesture recognition.

prototyping and the low cost. For the voice recognition, a multi-purpose speech recognition module, the EasyVR shield 3.0, has been used. This device allows the creation of a command menu where the user can teach each command with voice training cycles using the program VRCommander.exe. As motor driver, we used the 16 ADAFRUIT 16-Channel 12-Bit PWM servo driver with 12-bit resolution at 60 Hz update rate. For the EMG measurement a wearable gesture and motion control device, the Myo Armband Myo Armband (0000h), has been used. The Armband contains eight non-invasive EMG sensors and an IMU sensor. The Myo armband allows pre-configured gestures recognition like: fist, fingers spread, wave in, wave out and double tap, Fig. 12. These gestures can be used simultaneously with the accelerometer and the gyroscope of the IMU to expand the set of the commands. In this application, we exploited only the EMG sensor because our goal is to proof the efficiency of the voice command integration with any EMG sensor. The Prisma Hand I can be controlled by voice command and by the Myo contemporaneously. The Myo communication program allows to exchange data at 20 Hz with Arduino.

5. Control with EMG and voice commands

The PHI after power on goes to the home position, represented in Fig. 10, with the flexion joints of all the fingers at 0°, the index and little finger in adduction position at 20°, the thumb at 0° from the palm plane. Once the hand has reached the home position, the microcontroller is ready to receive voice and EMG command from the user. According to the scheme in Fig. 11 the control program is conceived to receive up to three sequence of commands to define the desired grasp. The first command is a voice command to set the desired abduction angle of the thumb, the second command set the desired strength or velocity of the grasp and finally the third command is an EMG signal for the closure/opening and internal manipulation. The thumb adduction/abduction motion for internal manipulation can be executed also with voice command, as explained in Section 6. The three hierarchical command layers are represented in Table 4. If the second layer is not settled the control takes a default value for the strength and the velocity of the grasp.

The Myo armband program is able to recognize five different gestures which are mapped into as many different motion patterns on the PHI, see Fig. 12:

Table 4
Commands table.

VOICE	HOME	RIGHT	MIDDLE	LEFT	
VOICE	WEAK	MEDIUM	STRONG	SLOW	FASTER
EMG	OPEN	CLOSE	MANIPULATION		

(a) Voice command not acknowledged. (b) The voice control mode is activated.

Fig. 13. A led light allows the user to understand when the voice control mode is correctly activated (green) and when the voice command has not been acknowledged (red).

- *Fist action*: activates the motor that moves the primary tendon, the Prisma Hand will close with the thumb in the abduction position chosen by the voice command. If no command is given, a thumb abduction of 30° will be achieved as a default value, see Fig. 14
- *Fingers Spread*: activates the motor that moves the primary tendon, the Prisma Hand will open and the thumb comes back to the home position, Fig. 10
- *Fingers Double Tap*: the action consists in a double tap executed with the thumb and the middle finger. When this action is detected the voice control mode is activated and a led light on the wrist attests that the hand is ready to receive the voice command, Fig. 13. If the light is green it means that the module is activated. A red light means that the voice command has not been acknowledged and the use has to repeat it.
- *Wrist Bending*: it is composed by two wrist bends, inside and outside. When they are detected, the small actuator moves the adduction/abduction thumb to manipulate the grasped object, see Fig. 15.

The voice commands are used to change the characteristics of the opening and closing movements. With voice control the user can change thumb abduction, strength and speed. The voice commands are described below.

- *HOME*: The small servo configures the desired position of the thumb at 0°
- *LEFT*: The small servo configures the desired position of the thumb at 30°
- *MIDDLE*: The small servo configures the desired position of the thumb at 60°
- *RIGHT*: The small servo configures the desired position of the thumb at 90°
- *SLOW*: It sets the servo lower speed for the hand closure, this is the default option when this setting is not commanded
- *FASTER*: It increases the speed for the hand closure, it is possible to pronounce this command for a maximum of four time. If T is the time lapse of the slower closure, then the new closure time will be T/n where n is the number of times the user repeats this command
- *WEAK*: It sets the hand clutch at the lower strength
- *MEDIUM*: It sets the hand clutch at the medium level, this is the default option when this setting is not commanded.
- *STRONG*: It sets the hand clutch at the maximum level

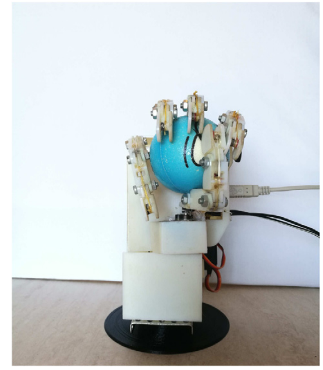


Fig. 14. PHI grasping a ball.

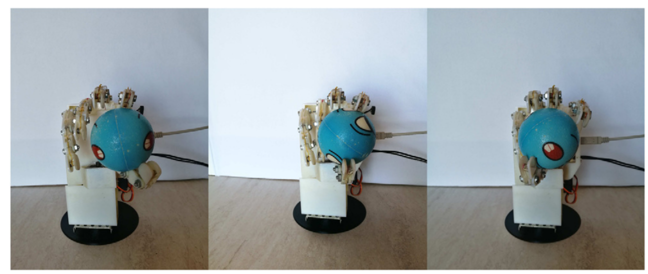


Fig. 15. PHI manipulating a ball.

A brief consideration should be provided regarding the Myo armband gesture recognition. Some gestures can be difficult to be recognized on an amputee arm, such as the double tap to activate the voice command control or the wrist wave for the internal manipulation. In this regard, voice control module could be activated using a sequence of muscle contraction, and internal manipulation could be provided by a sequence of voice commands.

6. Experimental tests

To test the robotic hand we have chosen a set of daily used objects to be grasped. The video footage to this paper shows the motion of the hand under the operator voice and EMG commands. The hand is capable to handle a wide set of grasps like power and precise grasp also of small objects, as depicted in Fig. 16. The test for the strength control is made on a plastic cup grasped in weak and strong mode, Fig. 18. The hand closure with different thumb abduction settled by means of voice commands are depicted in Figs. 17(a)–17(c). The whiffletree motion differentiation allows the hand grasping different kind of objects by softly adapting to their shape. To settle the desired final thumb opposition, voice command is used to coordinate the abduction thumb motion with the hand closure. The aid of voice command increases hand performance and versatility, allowing an independent opposition thumb motion. Conversely, it is not possible to extract this "detailed information" from EMG signals during the hand closure. In Fig. 15 the thumb changes position during grasping to allow internal manipulation. In this case, we tested the EMG command using the wrist bending gesture. Indeed, the hand is already closed and the user is free to provide an additional EMG command for thumb motion. It goes without saying that voice commands can be used for internal manipulation as well.

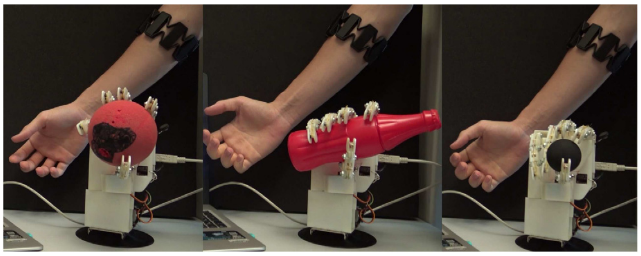
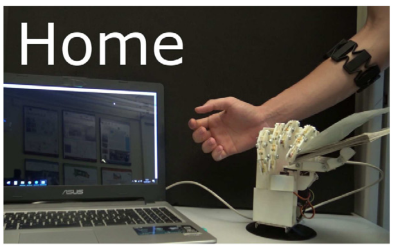
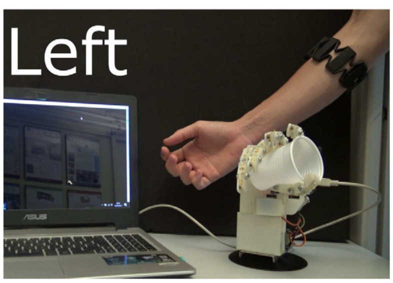


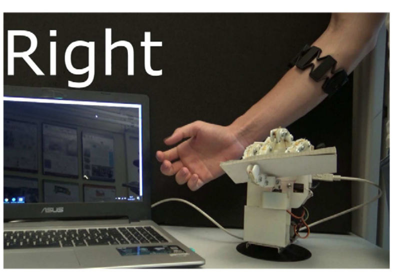
Fig. 16. PHI grasps of daily used objects.



(a) Thumb home position (0°)



(b) Thumb left position (30°).



(c) Thumb right position (90°).

Fig. 17. The hand can close with different thumb opposition settled by means of voice commands.

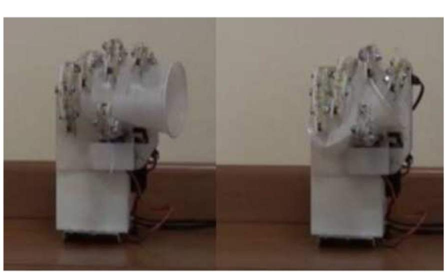


Fig. 18. PHI strength control, weak mode on the left and strong mode on the right.

7. Conclusions

The design and control of the PHI undeactuated prosthetic hand with voice and EMG commands have been presented. The PHI thumb adduction/abduction independent motion allows to handle any kind of objects, to perform internal manipulation and precise grasps of small objects. Moreover, the control module based on voice command added to an EMG-based control provides great performance improvement allowing extra motion capabilities while preserving simplicity of the control interface and ease use for the patient. Finally, the motor current sensing grants the capability to handle even fragile objects. The hand can be easily integrated with widespread commercialized and low cost technologies such as Myo armband and voice recognition module, with very good functioning results. Despite advanced hands with more than two motors and complex user interfaces with invasive sensors, PHI represents a reliable high performance and low cost hand that has the potential to be easy commercialized thanks to the low price and the easy usability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.engappai.2020.103698.

References

Allegro, 0000g. Allegro ACS712 Current Sensor. http://www.allegromicro.com.

Bebionic, 0000d. Bebionic. https://www.youtube.com/watch?v=8Cn-SZzXrv0.

Belter, J., Segil, J., Dollar, A., Weir, R., 2013. Mechanical design and performance specifications of anthropomorphic prosthetic hands: a review. J. Rehabil. Res. Dev. 50 (5), 599–618.

Bennett, D., Dalley, S., Truex, D., Goldfarb, M., 2015. A multigrasp hand prosthesis for providing precision and conformal grasps. Front. Neurorobotics 20 (4), 1697–1704.

Bennett, D., Mitchell, J., Truex, D., Goldfarb, M., 2016. Design of a myoelectric transhumeral prosthesis. IEEE/ASME Trans. Mechatron. 21 (4), 1868–1879.

Biddiss, E., Chau, T., 2007. Upper limb prosthesis use and abandonment: a survey of the last 25 years. Prosthet. Orthot. Int. 31 (3), 236–257.

Carey, S., Lura, D., Highsmith, M., 2015. Differences in myoelectric and body-powered upper-limb prostheses: systematic literature review. J. Rehabil. Res. Dev. 52 (3), 247–262.

Carrozza, M., Massa, B., Micera, S., Lazzarini, R., Zecca, M., Dario, P., 2002. The development of a novel prosthetic hand-ongoing research and preliminary results. IEEE/ASME Trans. Mechatron. 7 (2), 108–114.

Cerulo, I., Ficuciello, F., Lippiello, V., Siciliano, B., 2017. Teleoperation of the SCHUNK S5FH under-actuated anthropomorphic hand using human hand motion tracking. Robot. Auton. Syst. 89, 75–84.

Dalley, S., Wiste, T., Withrow, T., Goldfarb, M., 2009. Design of a multifunctional anthropomorphic prosthetic hand with extrinsic actuation. IEEE/ASME Trans. Mechatron. 14 (6), 699–706.

Ficuciello, F., 2019a. Hand-arm autonomous grasping: synergistic motions to enhance the learning process. Intell. Serv. Robot. 12 (17), 17–25.

Ficuciello, F., 2019b. Synergy-based control of underactuated anthropomorphic hands. IEEE Trans. Ind. Inf. 15 (2), 1144–1152.

Ficuciello, F., Carloni, R., Visser, L., Stramigioli, S., 2010. Port-Hamiltonian modeling for soft-finger manipulation. In: Proc IEEE/RSJ Int Conf on Intelligent Robots and Systems, Taipei, Taiwan, pp. 4281–4286.

Ficuciello, F., Federico, A., Lippiello, V., Siciliano, B., 2016a. Synergies evaluation of the SCHUNK s5fh for grasping control. In: 15th International Symposium on Advances in Robot Kinematics.

Ficuciello, F., Migliozzi, A., Laudante, G., Falco, P., Siciliano, B., 2019. Vision-based grasp learning of an anthropomorphic hand-arm system in a synergy-based control framework. Sci. Robot. 4.

Ficuciello, F., Palli, G., Melchiorri, C., Siciliano, B., 2012a. Planning and control during reach to grasp using the three predominant UB hand IV postural synergies. In: Proc IEEE Int Conf on Robotics and Automation, Saint Paul, pp. 2255–2260.

Ficuciello, F., Palli, G., Melchiorri, C., Siciliano, B., 2012b. Postural synergies and neural network for autonomous grasping: a tool for dextrous prosthetic and robotic hands. In: Pons, J., et al. (Eds.), Springer Berlin Heidelberg, pp. 467–480.

Ficuciello, F., Palli, G., Melchiorri, C., Siciliano, B., 2014. Postural synergies of the UB hand IV for human-like grasping. Robot. Auton. Syst. 62, 357–362.

Ficuciello, F., Zaccara, D., Siciliano, B., 2016b. Synergy-based policy improvement with path integrals for anthropomorphic hands. In: Proc IEEE Int Conf on Intelligent Robots and Systems, Daejeon, Korea, pp. 1940–1945.

Gabiccini, M., Bicchi, A., 2010. On the role of hand synergies in the optimal choice of grasping forces. In: Proc. of Robotics: Science and Systems, Zaragoza.

Hong, L., Meusel, P., Hirzinger, G., Minghe, J., Yiwei, L., Zongwu, X., 2007. The modular multisensory DLR-HIT-hand: Hardware and software architecture. IEEE/ASME Trans. Mechatron. 13 (4), 461–469.

i-limb, 0000c. i-limb. https://www.youtube.com/watch?v=m1TEX7lvMn8.

Lobo-Prat, J., Kooren, P., Stienen, A., Herder, J., Koopman, B., Veltink, P., 2014. Non-invasive control interfaces for intention detection in active movement-assistive devices. J. Neuroeng. Rehabil. 11 (168), 1–22.

Michelangelo, 0000e. Michelangelo. https://www.youtube.com/watch?v=1SdGvn0QH3k.

Myo Armband, 0000h. Myo Armband. https://www.myo.com/.

MyoBock, 0000b. MyoBock. https://www.youtube.com/watch?v=REJsa4sbr-g.

Naidu, S., Chen, C., Perez, A., Schoen, M., 2008. Control strategies for smart prosthetic hand technology: An overview. In: 30th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. EMBC, Vancouver, BC, Canada, pp. 4314–4317.

Open Bionics, 0000a. Open Bionics Startup. https://www.openbionics.com.

Piazza, C., Santina, C.D., Catalano, M., Grioli, G., Garabini, M., Bicchi, A., 2016. SoftHand Pro-D: Matching dynamic content of natural user commands with hand embodiment for enhanced prosthesis control. In: Proc. IEEE Int. Conf. on Robotics and Automation, Stockholm, Sweden, pp. 3516–3523.

Santello, M., Bianchi, M., Gabiccini, M., Ricciardi, E., Salvietti, G., Prattichizzo, D., Ernst, M., Moscatelli, A., Jorntell, H., Kappers, A., Kyriakopulos, K., Albu-Schaeffer, A., Castellini, C., Bicchi, A., 2016. Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands. Phys. Life Rev. 17, 1–23.

Santina, C.D., Grioli, G., Catalano, M., Brando, A., Bicchi1, A., 2015. Dexterity augmentation on a synergistic hand: The Pisa/IIT SoftHand+. In: Proc IEEE-RAS 15th Int Conf on Humanoid Robots, Seoul, Corea, pp. 497–503.

Silcox, D., Rooks, M., Vogel, R., Fleming, L., 1993. Myoelectric prostheses. A long-term follow-up and a study of the use of alternate prostheses.. J. Rehabil. Res. Dev. 75 (12), 1781–1789.

Towerpro, 0000f. Towerpro Servos. http://http://www.towerpro.com/.

Wiste, T., Dalley, S., Varol, H., Goldfarb, M., 2011. Design of a multigrasp transradial prosthesis. ASME J. Med. Devices 5 (3), 1–7.

Zollo, L., Roccella, S., Guglielmelli, E., Carrozza, M., Dario, P., 2007. Biomechatronic design and control of an anthropomorphic artificial hand for prosthetic and robotic applications. IEEE/ASME Trans. Mechatron. 12 (4), 418–429.