exeley INTERNATIONAL JOURNAL ON SMART SENSING AND INTELLIGENT SYSTEMS

Article | DOI:10.21307/ijssis-2018-005 Issue 0 | Vol. 0

Technical Features and Functionalities of Myo Armband: An Overview on Related Literature and Advanced Applications of Myoelectric Armbands Mainly Focused on Arm Prostheses

P. Visconti,[1] F. Gaetani[1], G. A. Zappatore[2] and P. Primiceri[1]

[1]Department of Innovation Engineering, University of Salento, 73100, Lecce, Italy.

[2]BionIT Labs Company, 73100, Lecce, Italy.

*E-mails: paolo.visconti@unisalento.it, f.gaetani@adamshand.it, g.zappatore@adamshand.it, patrizio.primiceri@unisalento.it.

This article was edited by Rosario Morello.

Received for publication February 5, 2018.

Abstract

Technological advances in manufacturing smart high-performances electronic devices, increasingly available at lower costs, nowadays allow one to improve users' quality of life in many application fields. In this work, the human–machine interaction obtained by using a next generation device (Myo armband) is analyzed and discussed, with a particular focus to healthcare applications such as upper-limb prostheses. An overview on application fields of the Myo armband and on the latest research works related to its use in prosthetic applications is presented; subsequently, the technical features and functionalities of this device are examined. Myo armband is a wearable device provided with eight electromyographic electrodes, a 9-axes inertial measurement unit and a transmission module. It sends the data related to the detected signals, via Bluetooth Low Energy technology, to other electronic devices which process them and act accordingly, depending on how they are programmed (in order to drive actuators or perform other specific functions). Applied to the prosthetic field, Myo armband allows one to overcome many issues related to the existing prostheses, representing a complete electronic platform that detects in real-time the main signals related to forearm activity (muscles activation and forearm movements in the three-dimensional space) and sends these data to the connected devices. Nowadays, several typologies of prostheses are available on the market; they can be mainly distinguished into low-cost prostheses, which are light and compact but allow for a limited number of movements, and high-end prostheses, which are much more complex and featured by high dexterity, but also heavy, bulky, difficult to control and very expensive. Finally, the Myo armband is an optimum candidate for prosthetic application (and many others) and offers an excellent low-cost solution for obtaining a reliable, easy to use system.

Keywords

Electronic modules, IoT applications, myoelectric signals, prosthesis, wireless connectivity.

Nowadays the electronics field, increasingly open source, offers growing possibility to users and designers to create smart systems featured by high performances and advanced functionalities while maintaining low costs. Thanks to the technological progresses in the manufacturing of smart electronic devices, it is possible to exploit their features in many application fields, from entertainment, to industry, to healthcare, etc. In this paper, the technical features and functionalities of a smart electronic device named *Myo armband* are presented; it can be used in numerous applications, as explained and illustrated in the paper, due to its excellent technical features and ease of use. It is a wearable device by Thalmic Labs Inc. provided with eight electromyographic (EMG) electrodes, a 9-axes inertial measurement unit (IMU) (3-axes gyroscope, 3-axes accelerometer and 3-axes magnetometer) and a transmission module (Myo Armband web site; Thalmic Labs Inc., 2013–2018). The EMG electrodes detect the signals related to muscles activity of the user's forearm and the IMU detects the forearm movements in the three-dimensional space. The acquired data are sent, via the Bluetooth Low Energy (BLE) module embedded into the armband, to other electronic devices (actuators, microcontrollers, and so on), which perform specific functions depending on the received data and on their installed software. An important application field of Myo armband, addressed in this paper, is that of the prostheses; in fact, the myoelectric sensors embedded into the Myo armband can be exploited to detect the muscular activity of upper-limb amputees and thus to control the prosthesis movements. Nowadays two main categories of commercial prostheses can be found on the market: the low-cost ones, which are simple to use, light and compact, but with limited dexterity, and the high-end ones, with individually movable fingers and thus highly dexterous, but really expensive and often difficult to control for the patients. The impossibility to find a right compromise between these two categories can lead the patient to become discouraged and to decide not to wear/buy any prosthesis. Myo armband results an optimum candidate to use in these cases, since it represents an easy-to-use device which can greatly simplify the prosthesis control. Many research studies, reported and discussed in this paper, focus on the possible applications of Myo armband and on its huge potentialities for improving the quality of life of its users. Hence, in this paper, an overview on the application fields of the Myo armband is reported highlighting the features of such device and the application typologies in which this device can be used; also its features are presented and analyzed in the last paragraph of the paper. In addition, in this paper, a prototypal prosthesis which makes use of the Myo armband is presented; a detailed analysis of the realized prosthesis will be presented in the future, anyway, the prosthesis, named Adam's Hand and properly developed and realized by BionIT Labs Company in collaboration with some research groups of the University of Salento, demonstrates the huge potential that Myo armband offers for such kind of applications.

Myo armband and myoelectric prostheses: A literature review

The following section is reported an overview of research studies focused on possible advanced applications of the MYO armband and on related algorithms for improving the user interaction with the connected devices.

Research studies on possible advanced applications of MYO armband and related issues

Several research studies have been conducted on the suitability of the Myo armband for prosthetics and virtual reality applications. For example, an experimental study was carried out in order to compare the narrow bandwidth of the Myo armband (which records the EMG signals with a limited bandwidth of about 200 Hz) with a conventional EMG acquisition system that captures the full EMG spectrum (Mendez et al., 2017). The authors showed that a mean classification error of 5.82 ± 3.63% for conventional EMG acquisition system and 9.86 ± 8.05% for Myo armband was obtained in an experimental test of pattern recognition with eight able-bodied participants, each performing nine different hand gestures.

A further research study focused on the development and implementation of a platform called Myo-HMI, an improved Human–Machine Interface (HMI) for Myo Armband users (Donovan et al., 2016). In particular, the authors developed a friendly graphic user interface in order to give the users the possibility to visualize in real time, on their PC desktop, the myoelectric signals provided from the Myo armband depending on the user forearm movements; in addition, a 3D-printed prosthetic hand and a virtual reality system were also developed, the latter with the aim of showing a virtual human hand on the interface, in order to verify the functionality of the developed Myo-HMI software and thus to control in real-time the myoelectric signals (Donovan et al., 2016).

A new model for hand gesture recognition in real time by using the Myo armband has been proposed in Benalcázar et al. (2017). The authors used as input of the implemented model the electromyography signals acquired from the Myo armband placed on the forearm and set as output the label of the gesture executed by the user at any time. This way, by using *k*-nearest neighbor and dynamic time warping algorithms, a real-time hand gesture recognition was obtained; in particular, the authors analyzed five classes of gestures that the Myo armband system recognizes by default: double tap, fist, spread fingers, wave in, and wave out. As a result of this comparison, they determined that their model presents better recognition accuracy (86%) than the Myo system (83%) (Benalcázar et al., 2017). Anyway, the Myo armband is featured by the advantage that the working gesture recognition system does not rely on any external sensors (i.e., motion capture system), but the sensors are embedded in the armband itself, recognizing the gesture commands and acting accordingly. These important features are exploited and studied to obtain a better user–machine interaction, for example to control robot movements by means of hand gestures, as demonstrated by the authors in Sathiyanarayanan et al. (2015). In this research work, the authors demonstrated that, through the Myo armband, velocity and braking of the realized robot can be controlled effectively. The potentialities of Myo armband were studied also by authors in Ganiev et al. (2016), where they demonstrated that the best way to detect electrical activities in muscles is to use EMG sensors; in fact, thanks to these sensors, the researchers obtained from the user forearm muscles very clear and relevant data, then used to control a proper designed virtual robotic arm (Shin et al., 2015; Ganiev et al., 2016). An application of Myo armband in the development of a controlling interface for PeopleBot robot was developed in Morais et al. (2016); the aim of the researchers was to use the robot to reach bio-infected or radioactive environments without requiring the human presence (tele-operations), but also to help elderly or disabled people on tasks involving motion or drag and drop objects. To integrate the Myo armband and PeopleBot robot, the authors used the robot operating system for processing the signals provided by Myo armband and hence to send the corresponding control signals to the robot controller; this way, the researchers found that Myo armband allows one to obtain a very fast controlling response. In addition, the mean classification rate in correctly distinguishing the different movements was of 93.6%; this percentage value was obtained by analyzing movements performed by volunteers who repeated 20 times each gesture in a random sequence.

Myoelectric prostheses and related algorithms for improving the user–prosthesis interaction

The control of smart external devices, such as prosthetic hands, based on surface EMG signals and pattern recognition algorithms, are issues addressed by different researchers. The EMG-based pattern recognition is inherently influenced by disturbances such as signal variation resulting mainly from electrode-skin impedance changes and sensor errors due to sweating, electrode donning-doffing, short circuits or loss of electrode contact to the skin (Vidovic et al., 2016). Several bio-sensing technologies focus on hand motion capture and its application to hand prostheses interfacing: these sensing techniques include electromyography, sonomyography, mechanomyography (MMG), intra-cortical neural interfaces, electroneurography, electroencephalograhy, near infrared spectroscopy (NIRS), magnetoencephalography and functional magnetic resonance imaging (Fang et al., 2015). The combination of two or more of these techniques can improve the human–machine interfacing (Fang et al., 2015; Guo et al., 2017). In this context, the authors in Guo et al. (2017) presented a hybrid approach to overcome the limitation of EMG through MMG-assisted myoelectric sensing; in particular, they developed an integrated hybrid sensor system for simultaneous EMG and MMG measurements. Two types of non-contact MMG sensors using either accelerometer or microphone were investigated; the obtained results demonstrated that the complementary information provided by EMG and MMG sensors allowed to attenuate the effect of EMG sensor faults.

Also the NIRS technique was studied in conjunction with the surface electromyography for overcoming the limitations of myoelectric control; three types of sensors (EMG-only, NIRS-only and hybrid EMG-NIRS) were investigated and the experimental results showed that real-time performance for controlling a virtual prosthetic hand were significantly (with level of statistical significance: $p<0.05$) improved by combining EMG and NIRS (Guo et al., 2017).

Furthermore, different algorithms were studied and developed with the aim to reduce the recalibration time for the myoelectric prosthesis; in fact, due to inherent non-stationarity in surface EMG signals, prosthesis systems need to be recalibrated day after day in daily use applications in order to improve the prosthesis–patient interaction. A domain adaptation (DA) framework, which automatically reuses the models trained in earlier days as input for two baseline classifiers, was proposed in Liu et al. (2016). The authors demonstrated that the implemented method is able to improve the robustness of myoelectric control algorithms against day-to-day surface EMG variability. The developed adaptive model can be trained much faster than the baseline model, using only a fraction of the retraining data required by the non-adaptive methods (Liu et al., 2016). The myoelectric signal variations were also studied in Yang et al. (2017); these variations are due to the different muscle contractions, dynamic arm movements and outer interfering forces. The authors examined four different training paradigms (data-collection protocols) quantifying their effectiveness for obtaining a robust classification. Hence, they showed that training with dynamic arm postures and different scales of muscle contraction helps to improve the robustness of the classification (even when an outer force on the hand of 250 g was applied). Finally, inspecting individual finger motions, the researchers found an uneven spatial distribution of the misclassification rate, which may introduce a series of incorrect actions. The palm's orientation and forces applied to the prosthetic hand, which generates extra EMG activities, are two significant factors that should be considered, rather than different arm positions, when developing dexterous finger control for advanced prosthetic hands (Yang et al., 2017). A further study focused on an enhanced representation of muscular activities obtained by increasing the amount of information that can be extracted from individual and combined EMG channels (Khushaba et al., 2017). The authors, by using time-domain descriptors, estimated the EMG signal power spectrum characteristics; they demonstrated that their procedure was able to obtain, on a large number of hand and finger movements, significant reductions in the achieved error rates in comparison to other methods, with an average improvement of 8% (Khushaba et al., 2017). Authors in Menon et al. (2017) studied the classification accuracy of different EMG signal patterns, one of the main determinants of real-time controllability of a prosthetic limb. An extensive investigation was conducted to study the effects on the classification accuracy of the analysis window's length (in ms), of the window's overlap and the number of electrode channels, as well as their interactions. The researchers established that the effect on classification accuracy of analysis window's length and overlap is independent of the electrodes number for all participant groups (partial-hand and trans-radial amputee volunteers and able-bodied volunteers); whereas, the reduction in classification error depends on the number of electrode channels and on the type of limb deficiency (Menon et al., 2017).

The authors in Cipriani et al. (2011) have presented the design and the performance evaluation of a 16 degrees of freedom self-contained robotic hand, to be used as a research tool for neuro-controlled upper limb prosthetics. Motion is generated by four brushed DC motors and transmitted to five under-actuated fingers by means of non-back-drivable mechanism (which drives the simultaneous flexion/extension of middle, ring, and little fingers, as well as their adaptation to the object, allowing a stable, multiple contact grasp as in the natural hand) and differential mechanisms. Its actuation distribution allows the hand to stably perform fundamental grips useful in activities of daily living. The fingers contain a total of 32 force, position and tactile sensors and the hand hosts an internal control architecture able to plan grasps and to exchange with the external world proprioceptive and exteroceptive sensory signals.

A comparative evaluation in order to analyze the value of two gesture input modalities (Myo Gesture Control Armband and Leap Motion Controller) versus two clinically established methods (task delegation and joystick control) was performed in Hettig et al. (2017). The results showed the relevance of task characteristics to the performance of specific input modalities. In general, gesture control failed to exceed the clinical input approach, but the Myo gesture control armband showed a potential for simple image selection task (Hettig et al., 2017).

Authors in Lenzi et al. (2016) presented the mechatronic design of an anthropomorphic trans-humeral prosthetic arm, the Rehabilitation Institute of Chicago (RIC) arm; in particular they described the design of the RIC arm, including the integration of custom external rotor motors, cycloid transmissions, non-back-drivable clutches, and custom pattern recognition control. Compared with commercially available arms the RIC arm provides an added wrist flexion degree of freedom within the same mass envelope and it allows higher joint speeds and torques.

Anyway, as previously reported, many research studies are focusing on the possible applications of Myo armband and on its huge potentialities for improving the quality of life of its users in several application fields. The algorithms used to better exploit the signals provided from the EMG electrodes are becoming more and more accurate and are still under investigation in order to improve the human–machine interaction; many researchers work to obtain a devices and algorithms that, in the case of a the hand prostheses, allow to the user to have the feeling of owning your own real hand. In fact, concerning the medical field and in particular that of prosthetic applications, several research works are investigating on algorithms and methods of pattern recognition to improve the prosthesis–patient interaction, also by using, besides information provided by the EMG electrodes, data obtained through other sensing techniques. Therefore, as demonstrated by different research works, Myo armband is an optimum candidate to detect the muscles electrical activity and to control, based on the detected EMG signals, external devices as a function of the specific application.

Application fields of myo armband

The increased integration between technology and humans, besides the studies of flexible and bendable electronic equipment such as roll up displays and wearable devices, has attracted the attention of many researchers and companies in developing even more sophisticated and complex devices with high performances, but simple to use for the users.

In particular, the employment of MYO armband, as demonstrated by numerous research studies (Sathiyanarayanan et al., 2015; Shin et al., 2015 ; Ganiev et al., 2016; Morais et al., 2016), is not limited to application in the prosthetic field; indeed, MYO armband can be used also in many other applications such as, for example, the development of a robotic arm piloted through natural hand movements or for controlling a mechanical device by means of hand gesture, thus avoiding the use of joysticks or other radio control devices.

Therefore, by exploiting the electrical signals generated by the contractions of the forearm/arm muscles (detected by the eight EMG electrodes) in order to control the movements of wrist, hand, and fingers (as shown in Fig. 1), MYO armband is able to drive the connected devices through the Bluetooth technology.

An application field where MYO armband is widely used is that of games; "Fruit Ninja" is a good example of how the armband can be used to slice the fruits passing on the screen using the user gestures; another example is "Race the Sun", a game in which the user has to control the path toward the sun of a volatile in order to avoid its death (as depicted in Fig. 2).

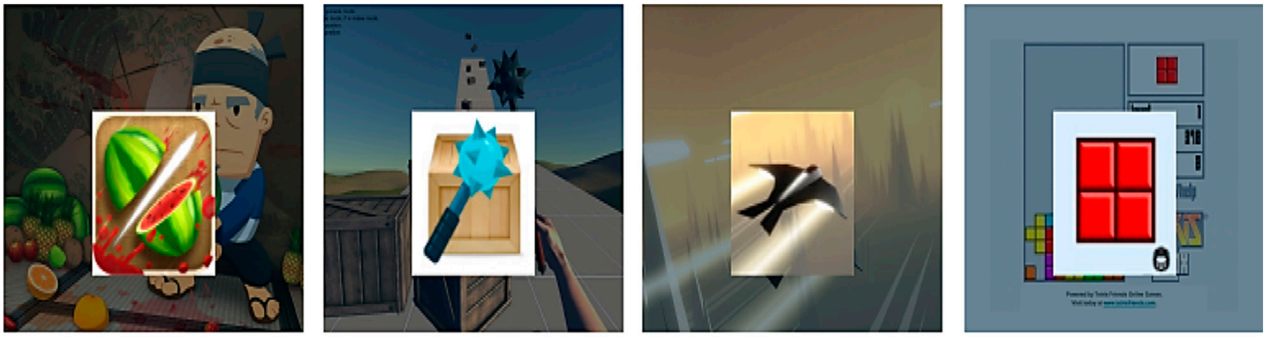
In Figure 3, two users wearing the Myo armband have to paint the whiteboard with two different colors; the player who is able to fill the board faster (in the figure the blue one) is the winner. In Figure 4A the player, by using the Myo armband, is controlling a weapon, while in Figure 4B he is driving a kart.

Myo armband can be used to play with many other games, as reported on the Myo device website (Myo Armband web site; Myo Market, 2013–2016). Another application field of the Myo armband is related to entertainment: as an example, the famous DJ Armin Van Buuren (electronic/dance music), made Myo Armband an important part of his shows, by relating plays of lights to his movements during on-stage performances (Fig. 5).

Anyway, apart from the applications previously reported, as shown in Figure 6, Myo armband can be also used for controlling flying drones, robot movements (particularly relevant during military maneuvers, where the trained military personnel can remotely drive a robot simply by wearing and using the armband) and so on.

Furthermore, as shown in Figure 7, it is also possible to use the armband to navigate on PC desktop between the different windows, selecting and exploring several applications and performing many different tasks; a good example is its use as presentations

Figure 1: By analyzing electrical activities of forearm muscles, the MYO armband detects hand movements in each direction (Myo Armband web site). Copyright © Thalmic Labs Inc. 2013–2016.



Fruit Ninja Connector Crate Whacker Race The Sun Connector Myo + Tetris

Figure 2: Myo armband allows to play several games by detecting the gestures performed by the user wearing it and sending the related signals to a PC/TV provided of Bluetooth connection. Copyright © Thalmic Labs Inc. 2013–2016.

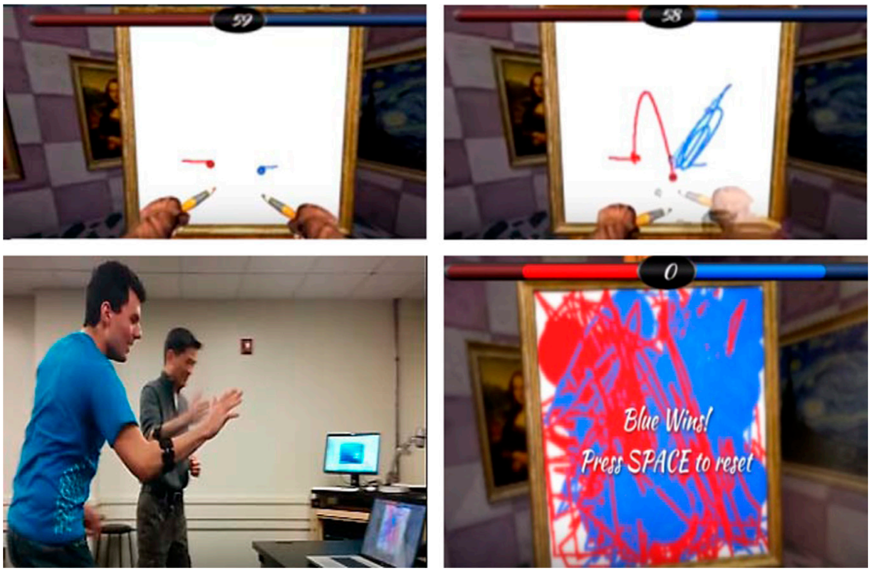


Figure 3: In this game, two players wearing Myo armband must paint as fast as possible a whiteboard; the player who in a given time fills a larger area of the board wins.

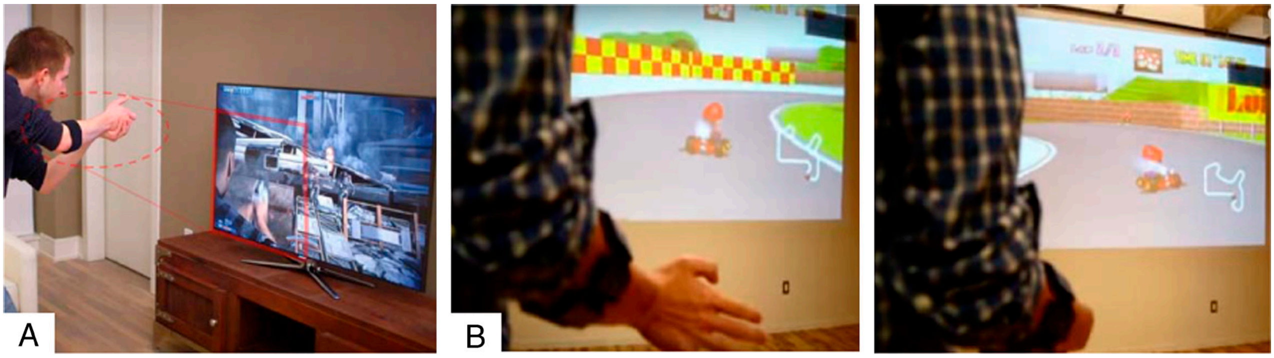


Figure 4: Through Myo armband the player interfaces with two different console games.

Figure 5: Myo armband is used by the artist, who wears it during his shows, to create plays of lights depending on his movements.

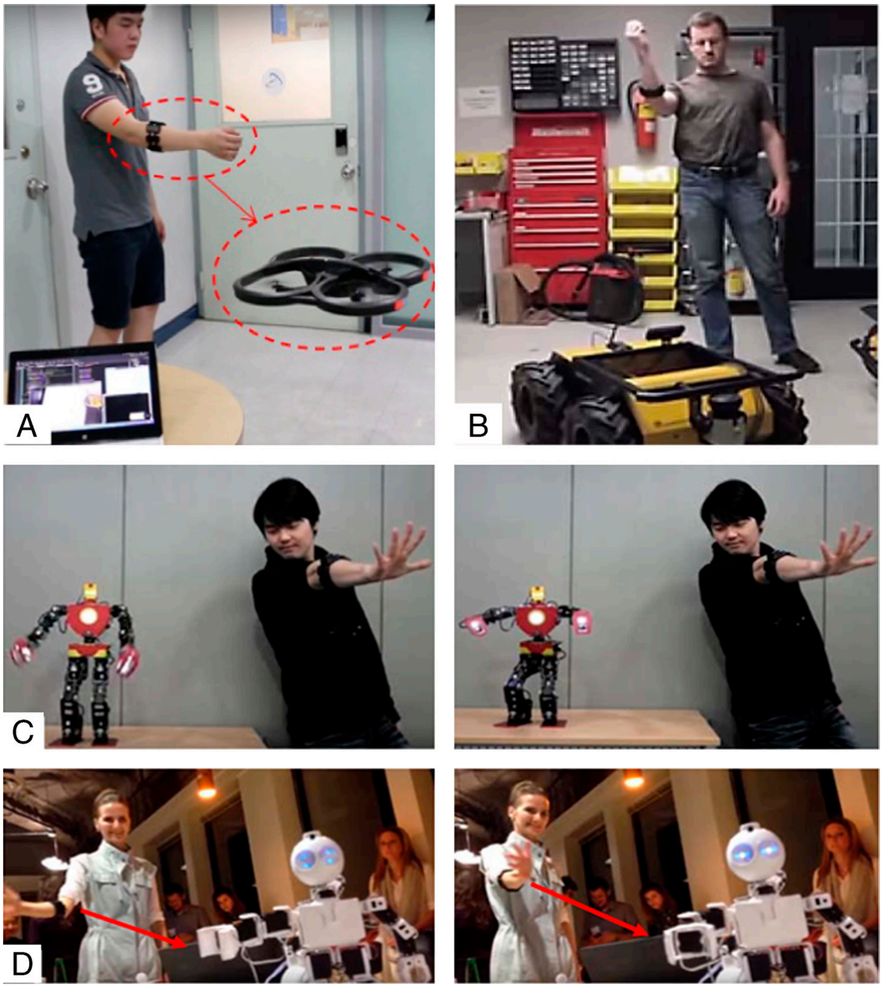


Figure 6: Myo armband allows to control (A) flying drones, (B), (C), and (D) robot movements and many other mechanical devices simply by moving the arm which wears the armband.

remote controller: the user, by wearing the Myo armband, can control the presentation software with proper gestures and motion (respectively through EMG and IMU readings).

The application fields of Myo armband, as cited above, are numerous: apart from games, robotic and computer applications, it also finds application in the healthcare field. In particular the company TedCas,

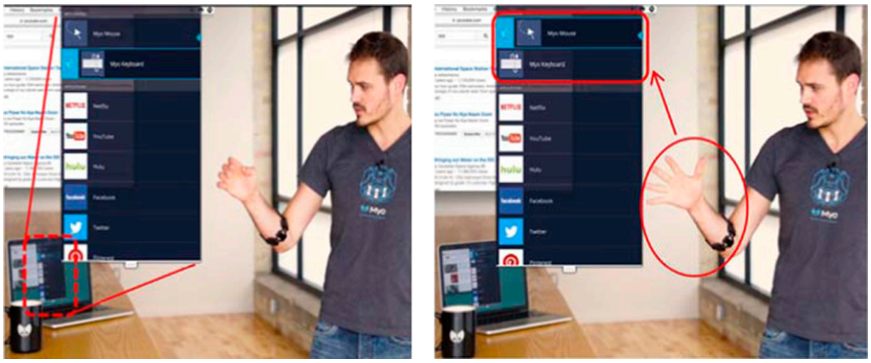


Figure 7: By using Myo armband, it is possible to navigate on the PC desktop and to use several software and applications.

Figure 8: Myo armband used in a surgery room for controlling a camera to visualize the examined body part, without having to physically touch a controller or medical instrument and thus improving user safety and reducing infections risk.

a leader in medical imaging, by using the Myo armband, various cameras and voice recognition software has realized a technology addressed to surgeons that during surgeries can control in real-time several medical instruments, as shown in Figure 8.

This way, the surgeons can perform by themselves many actions that should be otherwise performed by other people, keeping their hands clean and free during surgeries and thus reducing surgeries time and improving the patients' safety by reducing the risk of infection. For example, through the armband, the surgeons can rotate a 3D image of the examined body part by simply moving the hand, or pilot a camera to visualize in detail the tissues under analysis during a surgery without any physical contact (ADORA-MED d.o.o.).

In order to illustrate the huge potential offered by the Myo armband in prosthetic applications, in the following the last progresses in this field, are reported. The Myo armband, in fact, can also be used to control the movements of a prosthesis that replaces an amputated limb. Figure 9 shows a patient with a prosthetic arm directly connected to his skeleton (osseo-integration) during an experimental test at the Johns Hopkins University (Thalmic Labs Inc., 2013–2017); the used prosthesis employs two Myo armbands on the upper arm to detect the electrical activity of the biceps and triceps muscles.

So, the patient is able to correctly grab, lift, move and release the grasped object thanks to the Myo armbands which allow precise and correct prosthesis's movements.

Figure 10 shows the amputee patient wearing the Myo armband and a bland is used to better tighten the armband around the arm.

By moving the arm, the amputee is able to move the robotic prosthesis, attached to a support, placed at a certain distance from her. In Figure 11 the patient is raising her arm and the robotic prosthesis follows her movements.

In Figure 12, it is shown the arm wearing the Myo armband, covered by the bland; in Figure 12A the muscles contraction can be noted, while in Figure 12B, the arm muscles are relaxed. In addition, by performing proper muscles' contractions or movements, it is possible to move even a single finger of

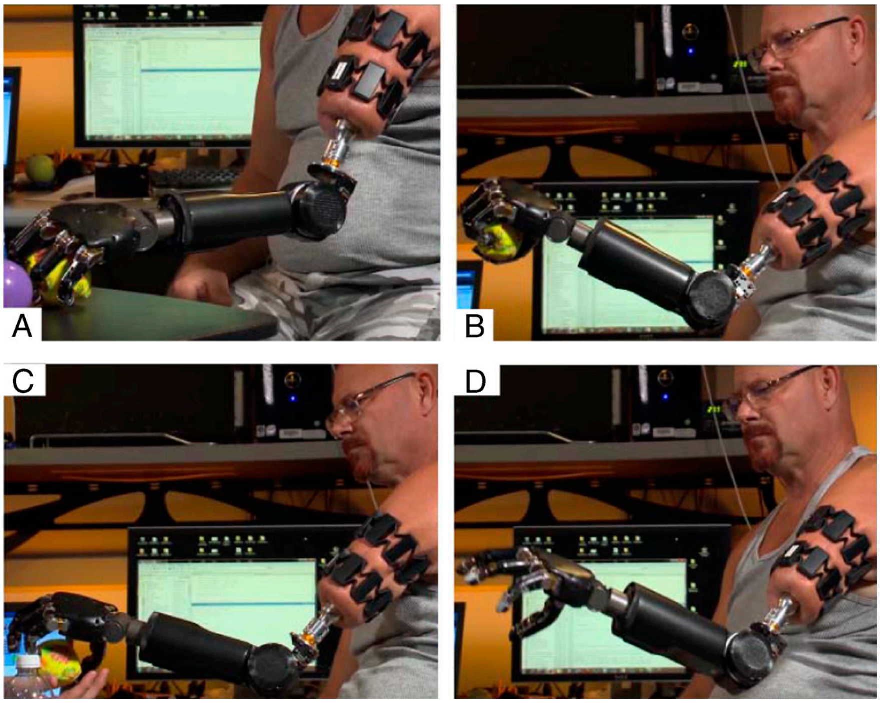


Figure 9: Two Myo armbands used to control the movements of a trans-humeral prosthesis; in this specific experimental test, the patient first grabs and then releases a tennis ball. Copyright© Thalmic Labs Inc. 2013–2016.

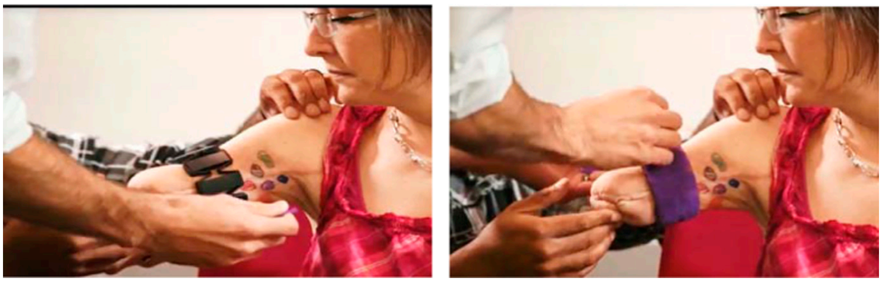


Figure 10: Myo armband worn by the patient; the purple band serves to better tighten the armband around the arm. Copyright © Vice Media Inc. 2016.

Figure 11: The patient controls the robotic prosthesis placed at distance from her. Copyright © Vice Media Inc. 2016.

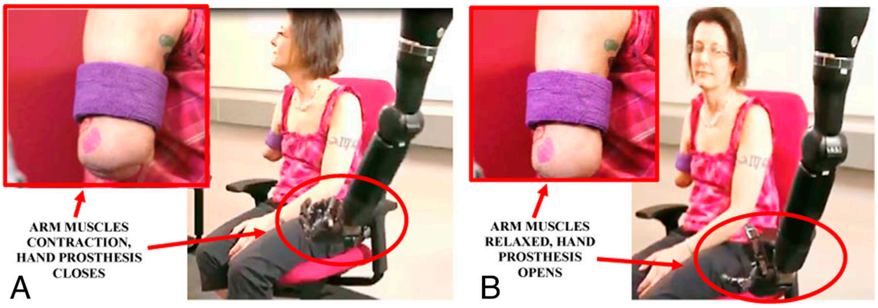


Figure 12: By activating the arm muscles, the prosthetic hand closes (A), whereas by relaxing the arm muscles the prosthetic hand opens (B).

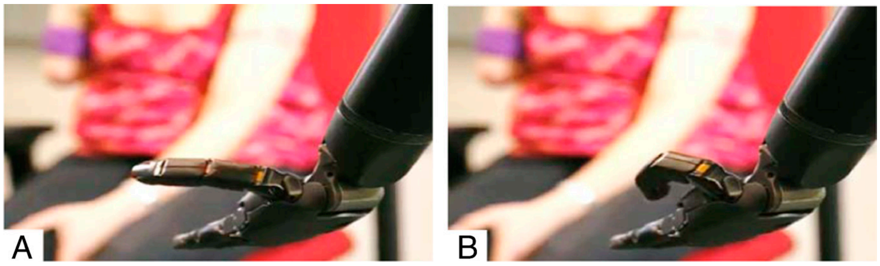


Figure 13: The patient wearing the Myo armband is able to move even a single finger of the robotic prosthesis placed at distance of about 1 meter from her.

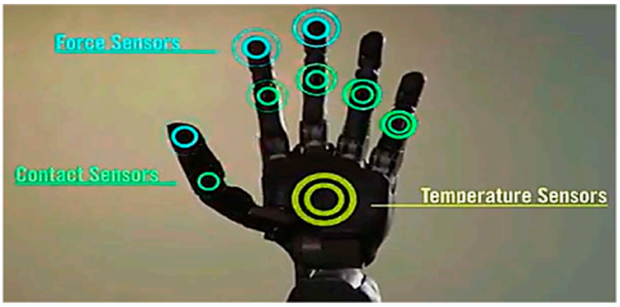


Figure 14: Prosthetic hand with indicated the installed sensors: Force Sensors are highlighted in blue, Contact Sensors in green and Temperature Sensors in yellow. Copyright © Vice Media Inc. 2016.

the prosthesis, as shown in Figures 13A and B where, as an example, the prosthesis thumb is, respectively, opened and then closed.

By providing the prosthetic hand with sensors such as force sensors, temperature sensors, and contact sensors, as shown in Figure 14, the patient obtains information related to the grasped objects.

In particular, the contact sensors allow the patient to feel the consistency of the grasped objects; through some sensors/electrodes positioned on the skin as shown in Figure 15, this information is received by the arm and exploited to communicate when the prosthetic hand touches an object. In the experimental test of Figure 15, the doctor touches the prosthetic fingers and the patient receives a feedback of the touch, “feeling” the contact.

Overview on prostheses typologies available on the market and latest technological progresses

Nowadays several typologies of active upper-limb prostheses are available on the market: the main distinction can be made between passive prostheses, body-powered prostheses and myoelectric prostheses.

Passive upper-limb prostheses are used for cosmetic restoration and have limited if any functional capabilities. They do not generally have active prehension, so do not restore the hand functionality, but some fingers may be designed to be placed manually to improve the prosthesis function (as an example, thumb opposition). Passive prostheses are compact, light, and need little maintenance, above all regarding the cosmetic silicone glove, which is much less stressed compared to active prostheses’ one.

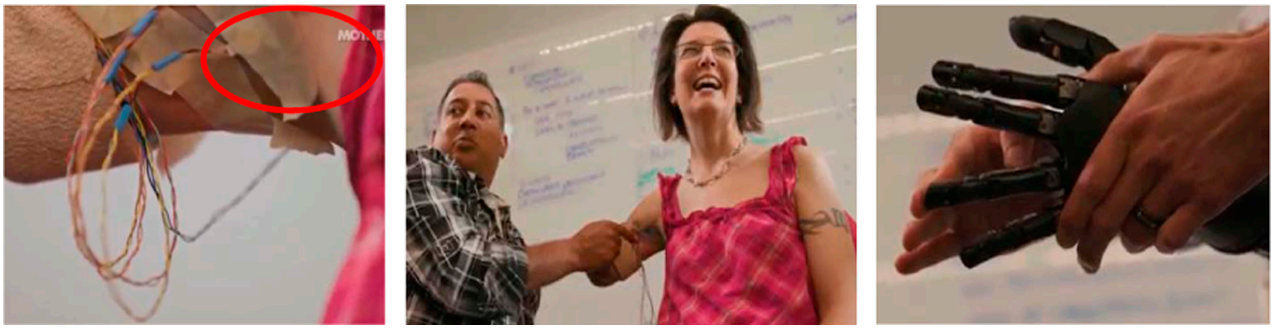


Figure 15: The contact sensors provide feedback signals to the patient that "feels" the touched objects. Copyright © Vice Media Inc. 2016.

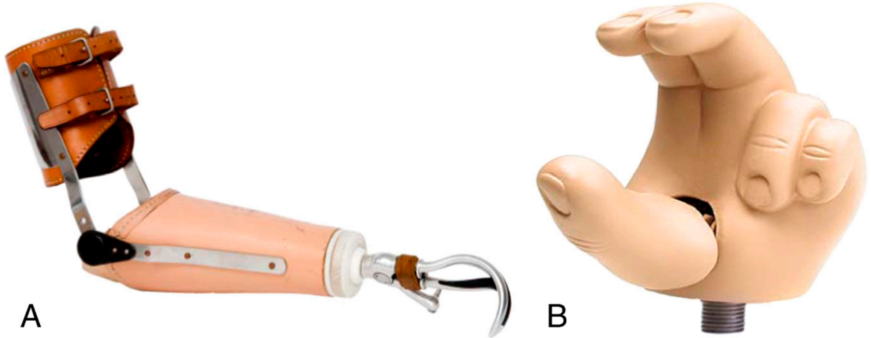


Figure 16: Two typologies of body-powered prostheses. They are compact, low cost and lightweight, but are characterized by limited dexterity.

Body-powered prostheses are maneuvered and powered by excursion and force from gross body movements with the use of a harness system; in particular, depending on the level of amputation, the prosthetic hand is controlled either by abduction of the shoulder or flexion of the wrist. Two main typologies of body-powered hands are available: voluntary opening (VO), which are normally closed and are opened when a movement is performed, or voluntary closing (VC), which in contrast are normally opened and are closed following a shoulder/wrist movement. These hands are not expensive, robust, and light, but the functional range of motion can limit hand function. A body-powered hook is shown in Figure 16A, while in Figure 16B is shown the Child CAPP Hand prosthesis sold by the Fillauer LLC company (Fillauer LLC, 2018); the latter prosthesis, used by children, is particularly small and lightweight (just 161 g) and it is provided with an inner spring whose tension can be manually adjusted.

Myoelectric prostheses are powered by an external battery system and as explained above are operated through EMG signals derived from muscle contractions. Among myoelectric prostheses, two main device categories can be distinguished (Fig. 17): the 1 DOF (degree of freedom) prostheses are actuated by a single motor and allow one to perform the contemporary opening/closing of three fingers (thumb, forefinger and middle finger); these prostheses are light, compact, low cost and easy-to-use, but are also highly limited in the movements that the user can perform; poli-articulated prostheses, instead, employ five/six motors which allow independent movements of each finger, and thus are heavier, bulkier, and more difficult to control, but at the same time they are highly dexterous.

The main issue of poli-articulated prostheses is related to the difficulty encountered by user to control them; in fact, these devices need a greater amount of data related to the user muscular activity, compared to the 1-DOF prostheses, due to the greater number of movements that they can perform. Therefore, a more accurate processing of the EMG signals is needed besides of a larger number of muscular groups to be monitored in order to obtain an effective control of the device. These factors inevitably involve a more complex electronic system for the prosthesis management, which consequently

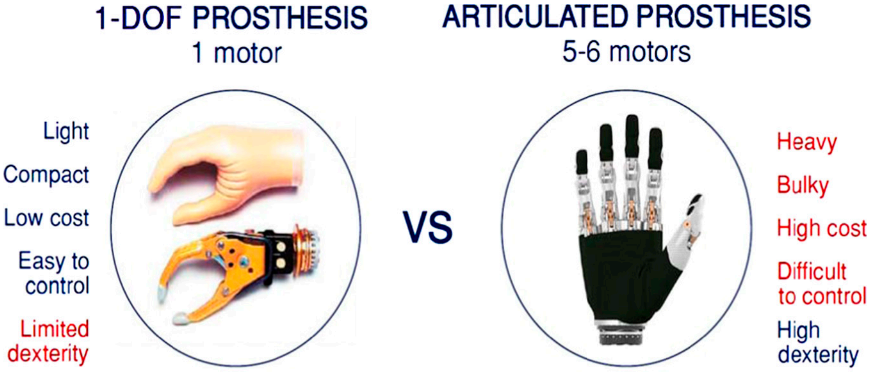


Figure 17: Main commercial myoelectric prostheses typologies available on the market nowadays with their respective advantages (in blue) and disadvantages (in red): 1-DOF prostheses are simple but characterized by limited dexterity, while poli-articulated prostheses are highly dexterous but heavier, bulkier and very expensive.

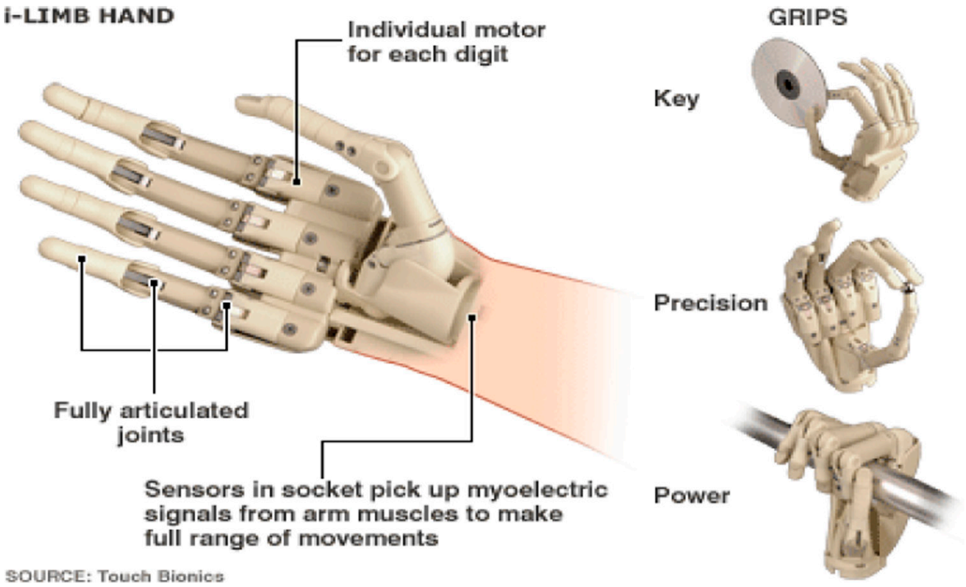


Figure 18: I-limb poli-articulated prosthesis produced by Touch Bionics: the user can perform power, precision and many other grips thanks to the five motors embedded into the device (Touch Bionics Inc, 2018). Copyright © Touch Bionics Inc. and Touch Bionics Limited. 2018.

causes an increase of the prosthesis cost, besides the higher costs associated with more complex mechanical components. The high costs of these prostheses can lead the patient to become discouraged and to decide to not wear/buy this kind of prostheses.

Figure 18 shows a poli-articulated prosthesis, i-limb hand, produced by Touch bionics (Touch Bionics Inc, 2018), with the indication of its principal components.

The *bebionic* hand, an advanced poli-articulated prosthesis provided by Ottobock company, provides 14 different grip patterns. The prosthesis, shown in Figure 19, is provided with five motors, one for each finger, microprocessors that continuously monitor the position of each finger, a proportional speed control to give precision control over delicate tasks, four wrist options, selectable thumb positions and auto-grip, i.e., the prosthesis automatically senses when a gripped item is slipping and adjusts the grip to secure it (Ottobock HealthCare GmbH (a)).

The hand prosthesis employs myoelectric sensors to detect the muscle's activities and allows one to perform fingers movements in a very precise way, as shown in Figure 20.

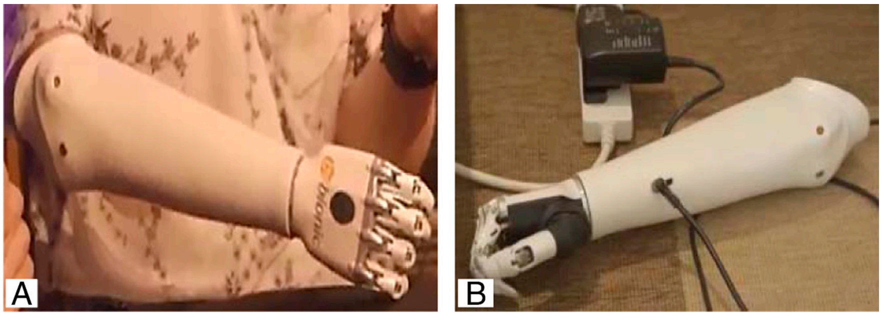


Figure 19: Bebionic hand prosthesis worn by a patient (A) and connected to the power supply in order to recharge the battery (B). Copyright © Vice Media, Inc. 2016.

Figure 21 shows the bebionic hand socket and the used myo-electrodes, models 13E200=50/13E200=60 or 13E202=50/13E202=60, installed within it; as shown in the schematic view of Figure 22, two myo-electrodes are used; they send, in wired mode, the detected signals to the microprocessors integrated into the prosthesis (Ottobock HealthCare GmbH (b)).

With reference to new 3D-printed devices, both the *Brunel Hand* by *Open Bionics* (shown in Figs. 23A and 23B) and the *Victoria Hand* prostheses (Fig. 23C) are relevant. However, these products, although available at low cost since realized by means of 3D printing technology, present limitations concerning the movements actuation. In fact, the fingers of Open Bionics hand are actuated by means of nylon tendons, which are characterized by high frictions, and by five different servo-motors, creating a bulky and heavy structure (Open bionics web site; Victoria Hand project). Another model of open source robotic hand is the InMoov Hand, shown in Figure 24, in which the fingers' movements are actuated by employing five different servomotors positioned in the forearm (InMoov open source 3D printed life-size robot).

The Alfred Mann Foundation has created Implantable Myoelectric Sensors (IMES); these are multiple single-channel implanted EMG sensors which allow an amputee to control his/her artificial limb by means of the arm's muscular activity. Figure 25 shows the IME sensors implanted into the arm of a patient. EMG signals, generated by the residual muscles at each implant site, are amplified and digitized by the IMES; an extra-corporeal Telemetry Controller (TC) within the limb prosthesis controls a time division multiplexing (TDM) sequence to provide power and manage RF transmissions from each implant over a common inductive link. Each IMES is wirelessly powered and telemeters an EMG signal (Troyk et al., 2007; Baker et al., 2010; Laboratory of Neural Prosthetic Research © 2018, 2018). The TC decodes the received EMG signals from all of the IMES devices, and passes the multi-channel EMG data to a Prosthesis Controller. By locating the IMES in separately innervated muscles, each IMES can be treated as an independent control site with minimal cross-talk or interference (Merrill et al., 2011; Tan et al., 2014; Laboratory of Neural Prosthetic Research © 2018, 2018;). The user, by thinking to open/close or rotate the prosthetic hand, or to

Figure 20: The advanced bebionic prosthesis produced by Ottobock allows to independently move each finger in a very precise way. Copyright by Ottobock © 2018.

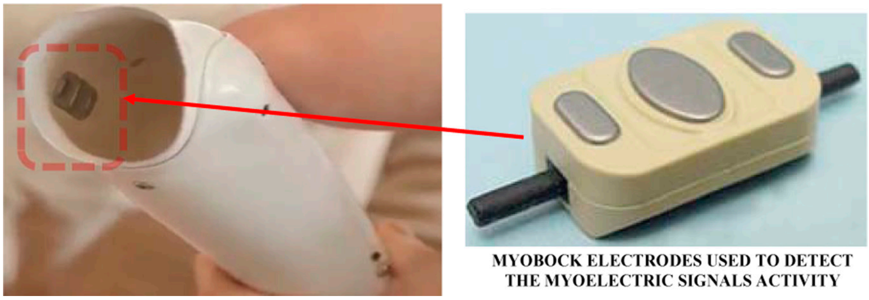


Figure 21: Myo-electrodes (MyoBock) provided by *Ottobock* installed into the prosthesis socket.

move specific fingers, is able to perform many common movements, as shown in Figure 26.

However, although advancements in prosthetic limbs have been beneficial and nowadays allow amputees to carry out daily activities with reasonable ease, they do not provide the user with sensory feedback. In this context, the recent technology progresses in the prosthetic field have allowed to obtain the first upper-limb amputee in the world who is able to “feel“ the grasped object in real-time with a sensory-enhanced artificial hand. The prosthetic system has been created by *Silvestro Micera* and colleagues from the *École polytechnique fédérale de Lausanne (EPFL)* in Switzerland and the *Sant'Anna School of Advanced Studies (SSSA)* in Italy. The prosthetic hand, containing sensors and electrodes, is wired to the user forearm and is controlled through the surface myographic electrodes integrated into the prosthesis.

When the patient touches an object, refined electrical impulses are sent to the central nervous system through other electrodes, surgically implanted into the nerves of the upper arm, allowing the patient to instantly feel it. A prototype of this system, worn by its user, is shown in Figure 27.

In order to create sensors that could detect information from touch, the scientists measured tension in artificial tendons that control finger movements. This measurement is then turned into an electrical current; however, since the central nervous system is unable to understand this kind of signals, proper developed computer algorithms are used to transform these signals into a refined impulse that can be understood by sensory nerves, as shown in Figure 28.

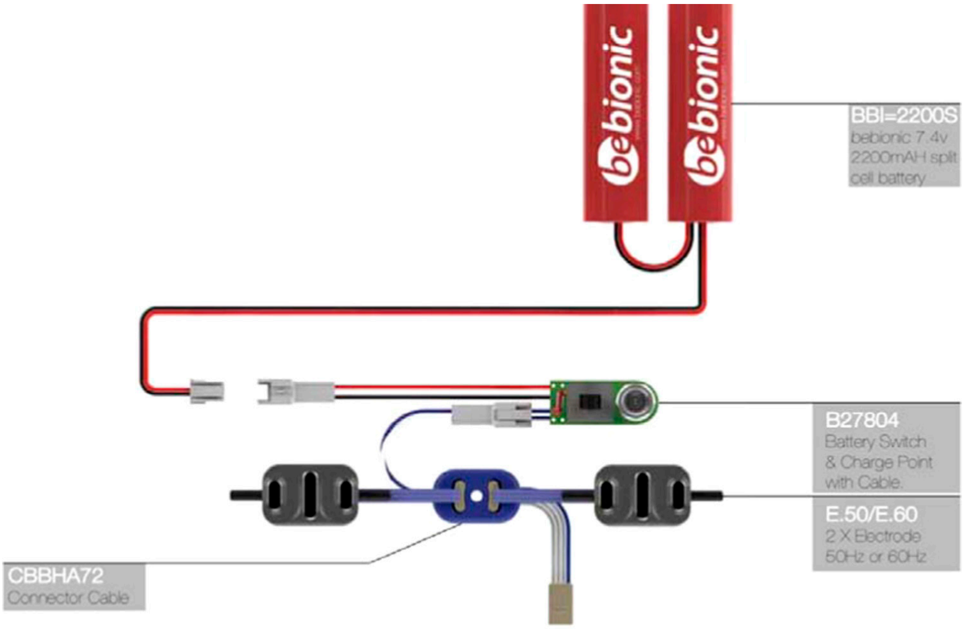


Figure 22: Connection scheme of the two Myo-electrodes installed into the prosthesis with the battery switch/charging module (B27804) and the rechargeable battery, model BBI=2200S, used to feed the prosthesis (Ottobock HealthCare GmbH (b)). Copyright by Ottobock © 2018.

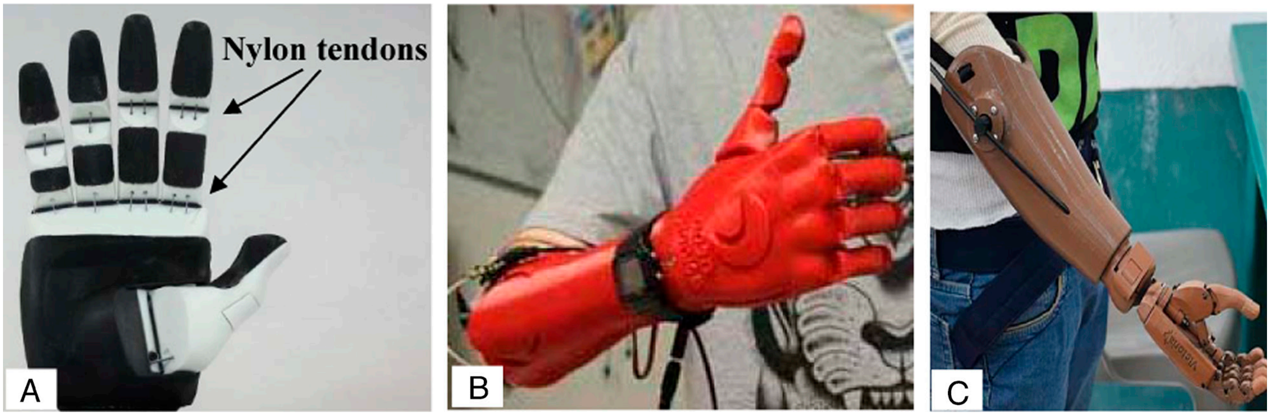


Figure 23: Myoelectric prostheses produced by Open Bionics, (A) and (B), with the used nylon tendons highlighted, and Victoria Hand Project body-powered prosthesis (C).

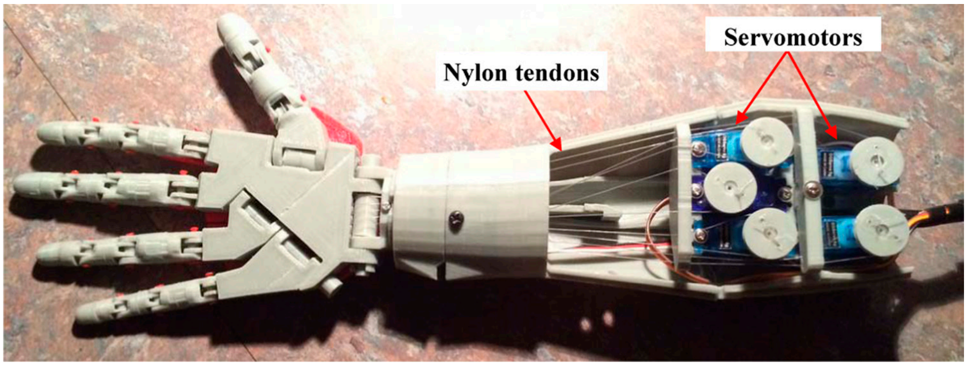


Figure 24: InMoov robotic hand with highlighted the nylon tendons and the servomotors positioned in the forearm which actuate the fingers movements.

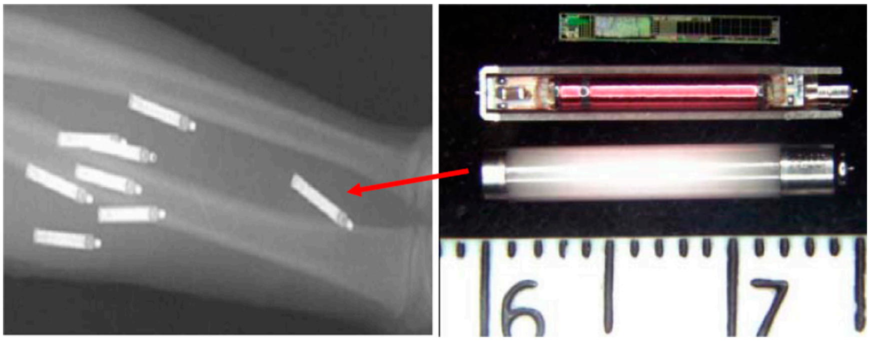


Figure 25: Several IMES sensors implanted into the arm of an upper-limb amputee. The sensors are 1.5 cm long and are powered wirelessly by a common transmitter coil within the Telemetry Controller (Troyk et al., 2007; Baker et al., 2010; Merrill et al., 2011; Laboratory of Neural Prosthetic Research © 2018, 2018). Copyright © Laboratory of Neural Prosthetic Research, 2018.

These new impulses are then sent through wires into four electrodes that have been surgically implanted into the nerves of the upper arm, therefore producing the sense of touch (Tan et al., 2014; Raspopovic et al., 2015).

This way, the patient is able to detect her grip strength on the objects she grasps, as well as their shape and consistency. Furthermore, recent technological progresses in prosthesis manufacturing allow one to replicate nearly perfect size and weight of the natural hand.

Figure 26: The patient with the IMES system implanted is able to perform numerous movements and tasks with his prosthetic hand (Laboratory of Neural Prosthetic Research © 2018, 2018). Copyright © Laboratory of Neural Prosthetic Research, 2018.

The main disadvantages of this prosthetic system are its high cost, related to the high level of technology implemented, and its intrusiveness (i.e., surgical operations are needed to implant the myoelectric sensors).

Two other innovative techniques for prostheses control can be mentioned: the *myokinetic* control interface, which aims to track the muscles contractions by means of magnetic field sensors, implanting permanent magnets into the user forearm (Tarantino et al., 2017), and the *ultrasonic* technology, according to which ultrasound signals can detect continuous and simultaneous movements of the arm muscles, which thanks to the use of machine learning can be associated in real time to each single finger, together with the force level the user intends to use (Georgia Institute of Technology, 2017).

With reference to commercial hand prostheses, algorithms related to the correct acquisition of the EMG signals and consequently to the correct actuation of the mechanical parts are not available on the product web-page. Anyway, for a simple prosthesis such as a hook prosthesis, the algorithms, if implemented, are very simple; in contrast, algorithms relat-

Figure 27: The prosthetic hand containing sensors and electrodes which allow to “feel“ in real-time the shape, roughness and consistency of the grasped objects.

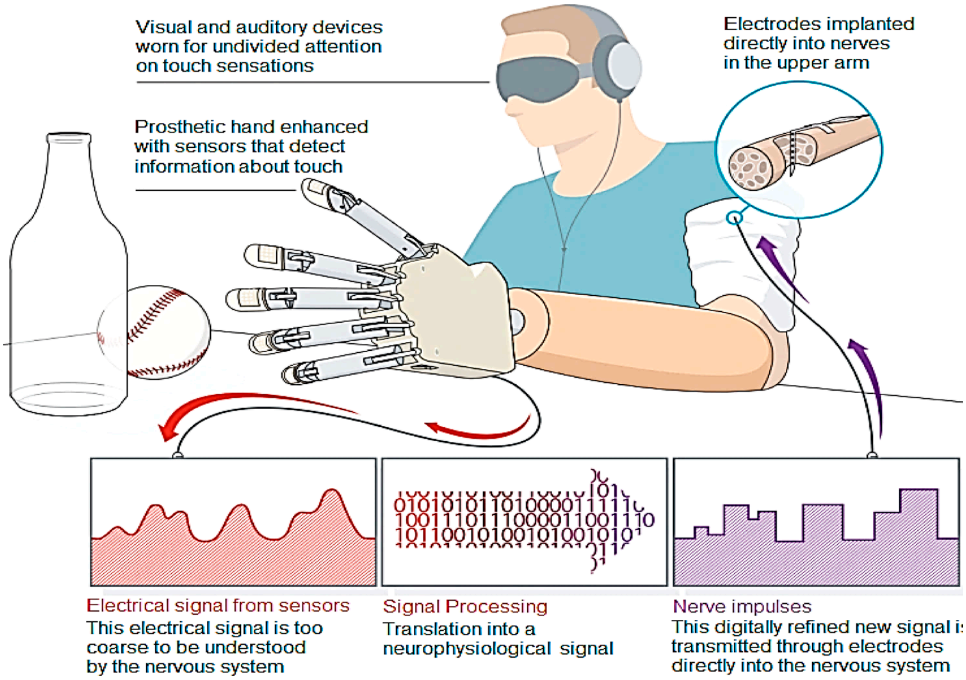


Figure 28: Prosthetic hand provided with sensors which allow the user to feel the grasped objects; the information is sent directly into the nervous system (Tan et al., 2014). Copyright © American Association for the Advancement of Science, 2018.

ed to articulated prostheses (those featured by high dexterity) are much more complexes.

The prosthesis realized by BionIT Labs Company in collaboration with the department of Innovation Engineering of University of Salento, allows one to overcome the issue previously discussed and highlighted in red in Figure 17; the innovative underactuated mechanism on which the prosthesis named *Adam’s Hand* is based can actuate 15 degrees of freedom with just one motor, instead of the five–six motors conventionally used in other prosthetic devices. The torque is automatically distributed among the fingers that adapt to the specific form of the grasped object, always developing the most stable grip. The transmission is based on geared differential modules, stiff and compact, that exert constant forces independent of the fingers kinematic state. The fingers can also move independently through the use of dedicated clutches or brakes (Zappatore et al., 2016; Zappatore et al., 2017). This allows one to simplify the control logic and to save on prosthe-

Figure 29: The realized prosthesis offers several advantages compared with other available prosthesis: it is easy-to-use, light, silent, it has low power consumption and low cost.

sis cost, weight, and dimensions, together with a lower power consumption and a less noisy actuation linked to the use of a single motor (as indicated in Fig. 29).

The realized prosthesis is also designed in a modular way, in order to adapt to different amputation levels: the main unit is provided with artificial intelligence and can also be used for post-traumatic rehabilitation procedures and muscular training for non-amputee patients, while the hand module can be also mounted on robotic arms in order to assist, eventually through EEG, completely paralyzed users.

Thanks to Myo armband, user gestures can be recognized and an algorithm, that uses rectified and filtered EMG and 9-axes IMU signals, evaluates the strength required to actuate each movement. These data are time-averaged and given as input to a single layer neural network that is initialized through a training phase performed at the system start.

The myoelectric prosthesis is also provided with sensors and actuators: the *LM35* temperature and *FSR-400* pressure sensors, installed into each fingertip, communicate the acquired data to the Arduino Micro board on which the developed custom board is based and, by means of the *Raspberry Pi* board housed in the prosthesis socket, these data are visualized on the touchscreen display in order to provide a feedback to the user (Primiceri et al., 2016; Visconti et al., 2016; Visconti et al., 2017a, 2017b;).

The Arduino micro board receives the Myo armband EMG and IMU data through a *HM-11* BLE module, while the recognized poses are reported on the touchscreen display in real-time. The realized electronic control board, the switching regulator used for the Raspberry Pi board power supply and the touchscreen mounted on the Raspberry Pi board, together with the related housing into the prosthesis socket, are shown in Figure 30A; the employed Lithium battery and the Myo armband are also indicated (Patrono et al., 2017; Visconti et al., 2017c, 2017d).

The employed mechanism is based on the use of a single DC motor for fingers movement and two servomotors for wrist movement, unlike traditional poli-articulated prostheses, which employ from five to six motors to drive and control each finger motion, as discussed above.

The use of a single motor to actuate the whole hand allows one to simplify the prosthesis control, as well as to save on its cost and weight, also improving the device autonomy. Moreover, data concerning EMG and IMU signals are processed by a properly developed *Wolfram Mathematica* software and can be monitored remotely by the orthopedic staff that follows the patient during the rehabilitation period (Fig. 30B), thanks to the Wi-Fi connectivity provided by the Raspberry PI board.

Myo armband: functionalities and technical features

The Myo armband, shown in Figure 31, is produced by the Thalmic Labs Canadian company and, as discussed above, it is mainly used to acquire the myoelectric signals produced by the user forearm muscles (Myo Armband web site; Thalmic Labs Inc., 2013–2018).

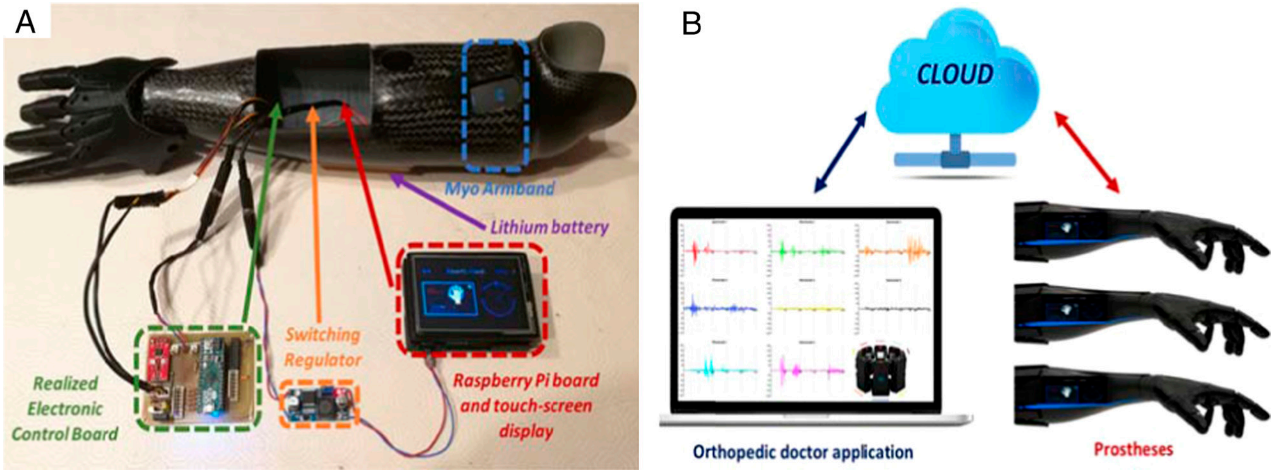


Figure 30: The different electronic modules used in the realized prosthesis (A) and data exchange between prosthesis and the orthopedic doctor application (B).

Figure 31: View of the Myo armband used in the realized prosthesis - Copyright ©Thalmic Labs Inc. 2013–2016.

The device is provided with eight EMG electrodes, a 9-axes IMU composed of a 3-axes accelerometer, a 3-axes gyroscope and a 3-axes magnetometer and a vibration motor used to alert the user when a particular event occurs. Its technical specifications are reported below:

- Freescale Kinetis ARM Cortex M4 120Mhz MK22FN1M MCU;
- BLE NRF51822 chip;
- vibration motor;
- Inven-sense MPU-9150 at 9 axes IMU;
- 8 x ST 78589 operational amplifier (one for each electrode);
- 2 x lithium battery 3.7 V - 260mAh.

The armband operation is managed by *ARM Cortex M4* processor, while data transmission are performed through the BLE NRF51822 chip, which exchanges data with HM-11 BLE module mounted on bottom side of the prosthesis driving/control unit. In Figure 32A, MYO armband is shown disassembled while Figure 32B shows the electronic control board embedded into the main central element with the previously described sections highlighted in different colors.

In particular, the *BLE NRF51822* chip for the wireless transmission is highlighted in blue, the *ARM Cortex M4* microcontroller in red, the antenna which transmits the data in grey, the vibration motor for the user feedback in brown and the micro-USB connector in purple. The latter is used to recharge the battery and to update the device firmware.

Two rechargeable lithium batteries, shown in Figure 33, are used to supply the armband; these are located into two elements of the armband and can be recharged providing a voltage value of 5 V by means of the micro-USB connector.

EMG Electrodes employed for muscles activity detection

The correct detection of the EMG signals, by means of the employed EMG electrodes, is a key factor to consider in order to properly control the prosthesis.

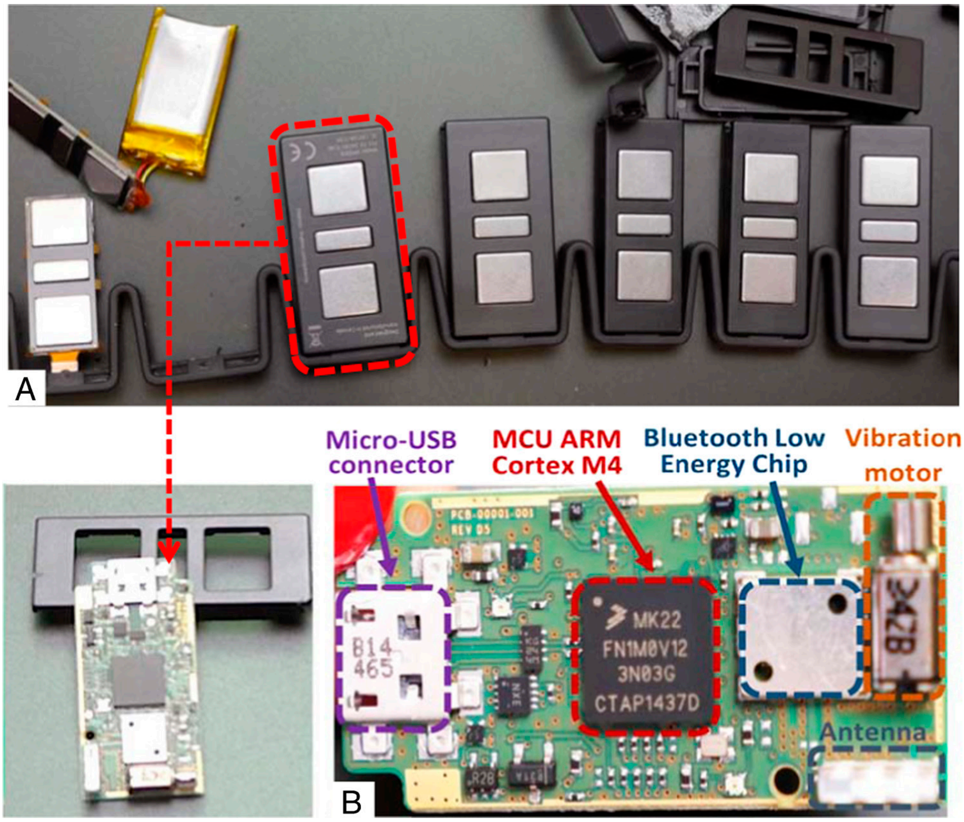


Figure 32: View of Myo armband elements (A) and of the electronic control board embedded into the main element (B); the micro-USB connector is highlighted in purple color, MCU ARM Cortex M4 in red, BLE chip in blue, the vibration motor in brown and the antenna in grey.

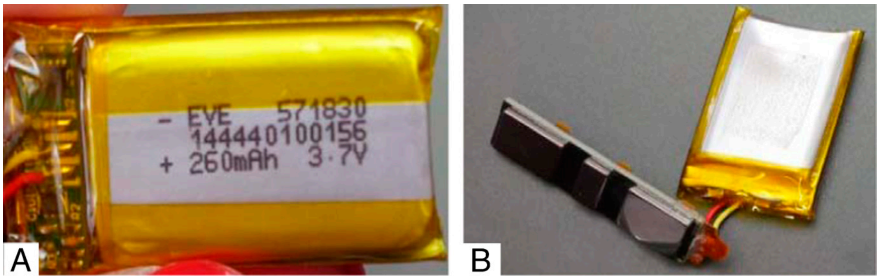


Figure 33: Lithium battery embedded into two elements of the Myo armband (A) and view of the battery housed behind of one of the eight electrodes (B).

In order to acquire the EMG signals, the voltage value/electric field associated with the muscles activity has to be detected; this potential is produced through the electrical depolarization of the muscular fibers in response to an electric pulse provided from the nervous system. Bipolar electrodes are used for the measurement of the muscular signals, which will be then amplified by using proper amplification circuits (Carlo, 1997), (Criswell, 1998). Two typologies of EMG sensors can be used in this kind of application: the insertion sensors and the surface sensors.

The EMG insertion sensors (shown in Fig. 34A) allow obtaining very accurate and localized measurements of the muscles activity; the disadvantage of this type of sensors is that they are very invasive since they have to be inserted into the user's muscle through the use of a needle. The use of this typology of EMG sensors in the context of the realized prosthesis was

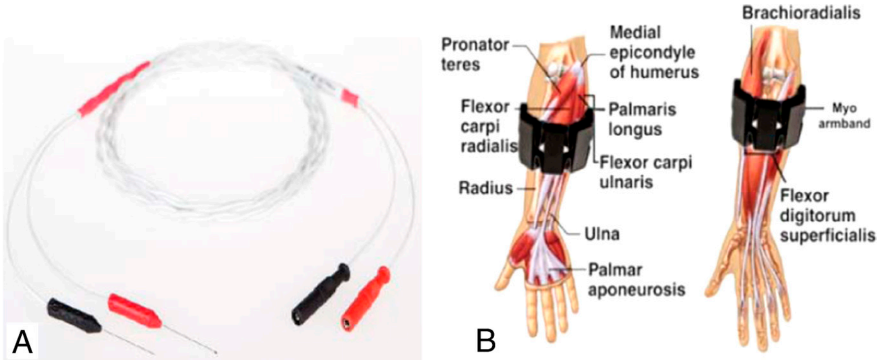


Figure 34: EMG insertion sensors result invasive for the patient (A), while MYO armband, worn on the forearm, is able to easily detect the muscular activity of the indicated muscles without resulting invasive (B).

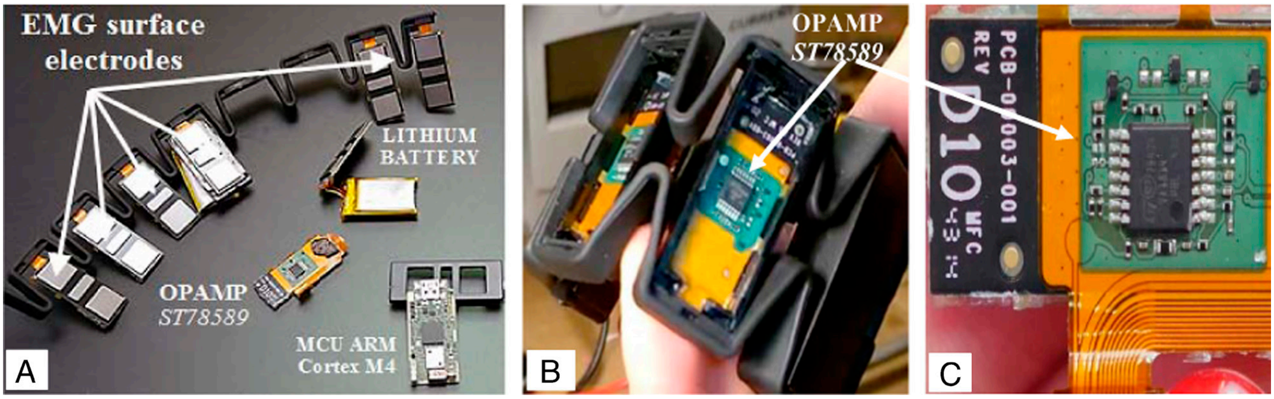


Figure. 35: View of the eight EMG surface electrodes employed in the Myo armband, together with the other components integrated into its cover (A), and of the ST78589 operational amplifier (B), (C).

excluded; in fact, Adam's Hand does not require so detailed information on a specific muscle area and, in addition, the use of needles could be impractical for the patient and even cause infections. This is the reason they are not used on commercial prostheses.

On the other hand, the EMG surface electrodes employed by Myo armband can provide information about activity of the forearm muscles shown in Figure 34B; this information, even if not detailed, is still sufficient to control the realized prosthesis, due to its ease of control; moreover, they are not invasive and are easy to integrate into the prosthesis socket.

The EMG surface electrodes are divided into two main categories: the passive and the active (differential) ones. The formers are composed of a single conductor and needs a conductive material which guarantee an optimal coupling with the skin. The active electrodes, instead, are composed of three conductors; the central one is located close to the analyzed muscle and detects the muscular activity, while the other two, placed before and after the central one along the same muscle, act as filters and provide noise immunity, allowing for a better signal reading. In particular, as shown in Figure 35A, Myo armband employs eight active EMG electrodes located in eight different areas of the forearm; the ST78589 operational amplifier, shown in Figures 35B and 35C, is used for the amplification of the signal provided from the EMG electrodes and it is integrated into each element of the armband.

InvenSense MPU-9150 gyroscope/ accelerometer: technical features

The information related to the forearm spatial position is detected through the IMU, a 9-axes inertial base (model InvenSense MPU-9150, shown in Fig. 36A), integrated into the Myo armband. It combines a 3-axes MEMS gyroscope, a 3-axes MEMS accelerometer, a 3-axes MEMS magnetometer and a Digital Motion Processor hardware accelerator engine, as shown in its inner block diagram (Fig. 36B).

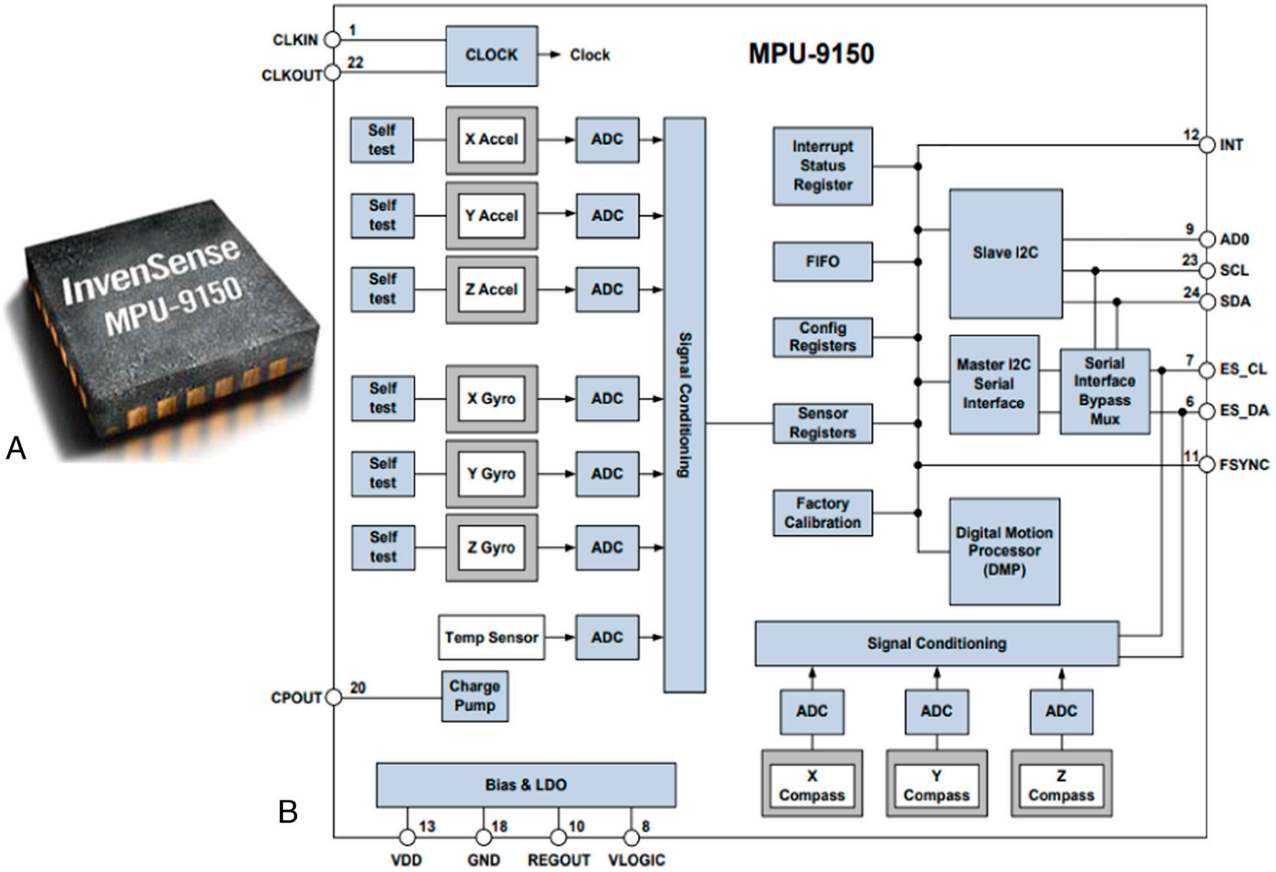


Figure 36: InvenseSense MPU-9150 in its *LGA* Package (A), and its inner block diagram (B).

As shown in Figure 36B, the MPU-9150 is featured with three 16-bit analog-to-digital converters (ADCs) used to digitize the gyroscope outputs, three 16-bit ADCs used to digitize the accelerometer outputs and three 13-bit ADCs used to digitize the magnetometer outputs (MPU-9150 Product Specification Revision 4.3, 2013). The MPU-9150 IMU is soldered on the bottom side of the Myo armband control board, as highlighted in Figure 37.

Myo armband control board presents also a vibration motor that can provide the user with a vibratory feedback; in particular, it is possible to give many information simply by changing the vibration duration. The events that can be notified include warning of low battery, feedback on the grip force, sensors/actuators fault, high temperature on the fingertips and correct synchronization of the armband.

Summarizing, the Myo armband presents many advantages compared to other devices/sensors used to acquire the muscles activity (the EMG signals); it integrates besides the EMG electrodes also the IMU unit useful to detect the position of the forearm in the three-dimensional space; it provides an easy solution for the user that needs only to wear the armband and not to place EMG sensors on the skin with consequently introduction of electrical noise that can deteriorate the signals detection. Therefore, Myo armband is a compact device with integrated sensors, processing and transmitting unit, that allows the correct detection of the needed signals simply by wearing it on the forearm, without using cables because the transmission is performed through BLE technology. The disadvantage can be due to the number of EMG electrodes that it integrates, but, for the prosthesis control the eight electrodes are more than enough to detect the electrical activity of the main muscular groups of the arm/forearm.

Conclusions

In this research work, the human–machine interaction performed by using the last generation device *Myo* armband is analyzed and discussed, with particular focus to healthcare applications such as upper-limb prostheses. The Myo armband can be used in numerous applications due to its excellent technical features

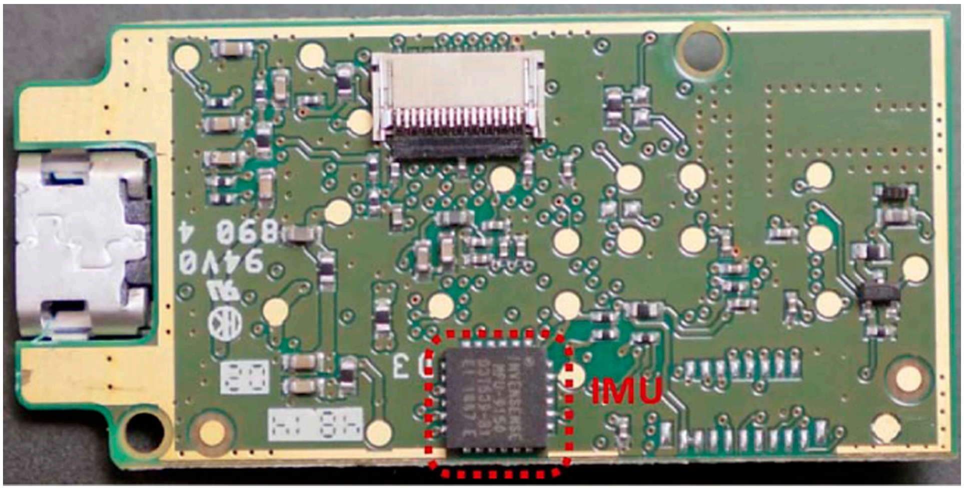


Figure 37: Bottom side of the Myo armband control board: the MPU-9150 IMU is highlighted in red.

and ease of use; it is provided with eight electromyography electrodes, a 9-axes IMU, and a transmission module; all the acquired data are sent wirelessly (through BLE technology) to the control electronics to use actuators or perform other specific tasks. After an overview on Myo armband application fields and on the latest research works related to its use in prosthetic applications, we analyzed and discussed in detail its technical features and functionalities.

A trans-radial myoelectric prosthesis prototype, named Adam's Hand and realized by BionIT Labs company in collaboration with our research department is also presented; it is equipped with sensors and actuators that move the hand and the wrist and which are controlled by the user myoelectric signals detected through Myo armband: the related EMG data, together with IMU data, are in fact sent wirelessly to the control electronics in order to activate a DC motor that handles the five fingers and two servomotors that actuate the wrist. The realized driving/control electronic unit manages the different prosthesis modules: it acquires data from five force sensitive resistors (FSR) and five *LM35* temperature sensors, one for each finger, it drives two *Futaba S3305* servo-motors used for wrist movement and a *Maxon DCX 19S* DC motor used for fingers movement. The Arduino-based control unit receives data from Myo armband by using the *HM11* module that integrates *SoC Texas Instruments CC2541* chip and it exchanges data with a Raspberry Pi board (placed into a properly realized case which also houses a LCD display). The Raspberry Pi board collects these data and, through Wi-Fi connection, sends them on cloud to a dedicated web server to be monitored remotely by the orthopedic staff. Further Adam's Hand details will be described in the future; anyway, the realized prosthesis confirms that Myo armband is an optimum candidate to be used in these kind of applications, allowing to get reliable, robust and low cost electromyographic data.

Literature Cited

ADORA-MED d.o.o. For Surgeons – ADORA Assistant. Website: https://adora-med.com/#section_video.

Baker, J., Scheme, E., Englehart, K., Hutchinson, D., and Greger, B. Aug. 2010. Continuous detection and decoding of dexterous finger flexions with implantable myoelectric sensors. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 18(4): 424–32.

Benalcázar, M.E., Jaramillo, A.G., Zea, J.A., Páez, A., and Andaluz, V.H. 2017. Hand gesture recognition using machine learning and the Myo Armband. 25th European Signal Processing Conf. (EUSIPCO), Kos, Greece, 28 Aug–2 Sept, 2017: 1040–4, DOI: 10.23919/EUSIPCO.2017.8081366.

Carlo, J.D.L. 1997. The use of surface electromyography in biomechanics. *Journal of applied biomechanics* 13: 135–63.

Cipriani, C., Controzzi, M., and Carrozza, M.C. May 2011. The SmartHand transradial prosthesis. *Journal of NeuroEngineering and Rehabilitation* 8(29): 2–13.

Criswell, E. 1998AQ5.

Donovan, I., Valenzuela, K., Ortiz, A., Dusheyko, S., Jiang, H., Okada, K., and Zhang, X. 2016. MyoHMI: a low-cost and flexible platform for developing real-time human machine interface for myoelectric controlled applications. IEEE Int. Conference on Systems, Man and Cybernetics SMC 2016, Budapest, Hungary, Oct. 9–12, 2016: 4495–500, DOI: 10.1109/SMC.2016.7844940.

Fang, Y., Hettiarachchi, N., Zhou, D., and Liu, H. 2015. Multi-modal sensing techniques for interfacing hand prostheses: a review. *IEEE Sensors Journal* 15 (11): 6065–76.

Fillauer LLC. 2018), http://fillauer.com/Upper-Extremity-Prosthetics/body-powered-systems/hands-and-gloves/child-hands/child-CAPP-hand.html

Ganiev, A., Shin, H.S., and Lee, K.H. 2016. Study on virtual control of a robotic arm via a Myo Armband for the self- manipulation of a hand amputee. *International Journal of Applied Engineering Research* 11(2): 775–82.

Georgia Institute of Technology. (2017), www.news.gatech.edu/2017/12/11/force-strong-amputee-controls-individual-prosthetic-fingers.

Guo, W., Sheng, X., Liu, H., and Zhu, X. 2017. Toward an enhanced human–machine interface for upper-limb prosthesis control with combined EMG and NIRS signals. *IEEE Transactions on Human–Machine Systems* 47(4): 564–75.

Guo, W., Sheng, X., Liu, H., and Zhu, X. 2017. Mechanomyography assisted myoeletric sensing for upper-extremity prostheses: a hybrid approach. *IEEE Sensors Journal* 17(10): 3100–8.

Hettig, J., Saalfeld, P., Luz, M., Becker, M., Skalej, M., and Hansen, C. 2017. Comparison of gesture and conventional interaction techniques for interventional neuroradiology. *International Journal of Computer Assisted Radiology and Surgery* 12(9): 1643–53.

InMoov open source 3D printed life-size robot. available at: http://inmoov.fr.

Khushaba, R.N., Al-Timemy, A.H., Al-Ani, A., and Al-Jumaily, A. 2017. A framework of temporal-spatial descriptors- based feature extraction for improved myoelectric pattern recognition. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25(10): 1821–31.

Laboratory of Neural Prosthetic Research © 2018. (2018), Illinois Institute of Technology. Website: http://neural.iit.edu/research/imes/.

Lenzi, T., Lipsey, J., and Sensinger, J.W. 2016. The RIC arm—a small, anthropomorphic transhumeral prosthesis. *IEEE/ASME Transactions on Mechatronics* 21(6): 2660–71.

Liu, J., Sheng, X., Zhang, D., He, J., and Zhu, X. 2016. Reduced daily recalibration of myoelectric prosthesis classifiers based on domain adaptation. *IEEE Journal of Biomedical and Health Informatics* 20(1): 166–75.

Mendez, I., Hansen, B.W., Grabow, C.M., Smedegaard, E.J.L., Skogberg, N.B., Uth, X.J., Bruhn, A., Geng, B., and Kamavuako, E.N. 2017. Evaluation of the Myo Armband for the classification of hand motions. International Conference on Rehabilitation Robotics (ICORR), QEII Centre, London, UK, July 17–20, 2017: 1211–4, DOI: 10.1109/ICORR.2017.8009414.

Menon, R., Di Caterina, G., Lakany, H., Petropoulakis, L., Conway, B.A., and Soraghan, J.J. 2017. Study on interaction between temporal and spatial information in classification of EMG signals for myoelectric prostheses. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 25(10): 1832–42.

Merrill, D.R., Lockhart, J., Troyk, P.R., Weir, R.F., and Hankin, D.L. 2011. Development of an implantable myoelectric sensor for advanced prosthesis control. *Artificial Organs* 35(3): 249–52.

Morais, G.D., Neves, L.C., Masiero, A., and Castro, M.C.F. 2016. Application of Myo armband system to control a robot Interface. Proc. of 9th Int. Conf. on Biomedical Engineering Systems and Technologies, (BIOSTEC 2016), Vol. 4: 227–31, DOI:10.5220/0005706302270231.

MPU-9150 Product Specification Revision 4.3. 2013, InvenSense Inc., Document Number: PS-MPU-9150A-00. Technical Document: www.invensense.com/wpcontent/ploads/2015/02/MPU-9150-Datasheet.pdf.

Myo Armband web site. Thalmic Labs. Website: www.myo.com/.

Myo Market. 2013–2016, Wthalmic Labs Inc. Website: https://market.myo.com/.

Open bionics web site. available at: www.openbionics.com.

Ottobock HealthCare GmbH (a). available at: http://bebionic.com/the_hand/features/.

Ottobock HealthCare GmbH (b). Technical document: http://bebionic.com/distributor/documents/RSL-LIT373-_bebionic_Tech_Manual_Small_web1.pdf.

Patrono, L., Primiceri, P., Rametta, P., Sergi, I., and Visconti, P. 2017. An innovative approach for monitoring elderly behavior by detecting home appliance's usage. IEEE Proc. of 25th Int. Conference on Software, Telecommunications and Computer Networks SoftCOM, Split – Croatia, Sept. 21–23, 2017: 1–7, DOI: 10.23919/SOFTCOM.2017.8115547.

Primiceri, P., Visconti, P., Melpignano, A., Vilei, A., and Colleoni, G.M. 2016. Hardware and software solution developed in ARM mbed environment for driving and controlling DC brushless motors based on ST X–NUCLEO development boards. *International Journal on Smart Sensing and Intelligent Systems* 9(3): 1534–62.

Raspopovic, S., Capogross, M., Petrini, F.M., Bonizzato, M., Rigosa, J., Di Pino, G., Carpaneto, J., Controzzi, M., Boretius, T., Fernandez, E., Granata, G., Oddo, C.M., Citi, L., Ciancio, A.L., Cipriani, C., Carrozza, M.C., Jensen, W., Guglielmelli, E., Stieglitz, T., Rossini, P.M., and Micera, S. 2015. Restoring natural sensory feedback in real-time bidirectional hand prostheses. *Science Translational Medicine* 6(222): 222ra19, doi: 10.1126/scitranslmed.3006820.

Sathiyanarayanan, M., Mulling, T., and Nazir, B. 2015. Controlling a robot using a wearable device (MYO). *International Journal of Engineering Development and Research IJEDR1503035* 3(3): 1–6.

Shin, H.S., Ganiev, A., and Lee, K.H. 2015. Design of a virtual robotic arm based on the EMG variation.

Advanced Science and Technology Letters 113: 38–43, http://dx.doi.org/10.14257/astl.2015.113.09.

Tan, D.W., Schiefer, M.A., Keith, M.W., Anderson, J.R., Tyler, J., and Tyler, D.J. 2014. A neural interface provides long-term stable natural touch perception. *Science Translational Medicine* 6(257): 1–25, DOI: 10.1126/scitranslmed.3008669.

Tarantino, S., Clemente, F., Barone, D., Controzzi, M., and Cipriani, C. 2017. The myokinetic control interface: tracking implanted magnets as a means for prosthetic control. *Scientific Reports* 7(17149): 1–11, doi: 10.1038/s41598-017-17464-1.

Thalmic Labs Inc. (2013–2017), www.youtube.com/watch?v=LSuzMxQDmzg.

Thalmic Labs Inc. (2013–2018), www.thalmic.com/.

Touch Bionics Inc. (2018), www.touchbionics.com/.

Troyk, P., Michele, G., Kerns, D., and Weir, R. 2007. IMES: an implantable myoelectric sensor. 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2007 (EMBS 2007), Lyon, France, Aug. 22–26, 2007: 1730–03.

Victoria Hand project. available at: www.victoriahandproject.com.

Vidovic, M., Hwang, H.J., Amsuss, S., Hahne, J., Farina, D., and Müller, K.-R. 2016. Improving the robustness of myoelectric pattern recognition for upper limb prostheses by covariate shift adaptation. *IEEE Transactions Neural Systems and Rehabilitation Engineering* 24(9): 961–70, doi: 10.1109/TNSRE.2015.2492619.

Visconti, P., -Ekuakille, A.L., Primiceri, P., Ciccarese, G., and de Fazio, R. 2017b. Hardware design and software development for a white led-based experimental spectrophotometer managed by a PIC-based control system. *IEEE Sensors Journal* 17(8): 2507–15, doi: 10.1109/JSEN.2017.2669529.

Visconti, P., Sbarro, B., and Primiceri, P. 2017a. A ST X-Nucleo-Based telemetry unit for detection and wifi transmission of competition car sensors data: firmware development, sensors testing and real-time data analysis. *International Journal on Smart Sensing and Intelligent Systems* 10(4): 793–828.

Visconti, P., Orlando, C., and Primiceri, P. 2016. Solar Powered WSN for monitoring environment and soil parameters by specific app for mobile devices usable for early flood prediction or water savings. *IEEE 16th Int. Conference on Environment and Electrical Engineering*, Florence, Italy: 1–6, DOI:10.1109/EEEIC.2016.7555638.

Visconti, P., Giannotta, G., Primiceri, P., de Fazio, R., Brama, R., and Malvasi, A. 2017d. Operation principle, advanced procedures and validation of a new Flex-SPI communication Protocol for smart IoT devices. *International Journal on Smart Sensing and Intelligent Systems* 10(3): 506–50.

Visconti, P., Giannotta, G., Primiceri, P., de Fazio, R., Brama, R., and Malvasi, A. 2017c. Framework implementation, firmware development and characterization of FlexSPI communication protocol: energy consumption analysis and comparison with I2C standard. *International Journal on Smart Sensing and Intelligent Systems* 10(4): 754–92.

Yang, D., Yang, W., Huang, Q., and Liu, H. 2017. Classification of multiple finger motions during dynamic upper limb movements. *IEEE Journal of Biomedical and Health Informatics* 21(1): 134–41.

Zappatore, G.A., Reina, G., and Messina, A. 2017. Analysis of a highly underactuated robotic hand. *International Journal of Mechanics and Control* 18(4): 17–23.

Zappatore, G.A., Reina, G., and Messina, A. 2016. Adam's hand: an underactuated robotic end-effector", in Boschetti, G., and Gasparetto, A. (eds), *Advances in Italian Mechanism Science. Mechanisms and Machine Science* 47, Springer, Cham: 239–46.