A Review on Commercially Available Anthropomorphic Myoelectric Prosthetic Hands, Pattern-Recognition-Based Microcontrollers and sEMG Sensors used for Prosthetic Control

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***Abstract*—It has been reported that over 3 million individuals live with upper limb amputation worldwide. Losing a hand drastically reduces the individual's quality of life. Fortunately, there are several prosthetic solutions available in the market that try to restore some of the missing hand's functions and characteristics. This paper presents a review on three of the main components of a typical transradial myoelectric prosthesis that can be found in the market. The goal was to provide the reader with an overview of commercially available anthropomorphic myoelectric prosthetic hands with high degrees of freedom, pattern-recognition-based microcontrollers and sEMG sensors used for prosthetic control.**

Keywords—Myoelectric Prostheses, Pattern Recognition, Prosthetic Hands, sEMG Sensors

I. Introduction

Amputation can be described as the removal of a body extremity, which can occur due to several reasons, such as traumatism, neoplasia and vascular or infectious diseases [1]. The exact number of amputees worldwide is difficult to infer, as several countries do not keep track of numbers regarding amputations. However, in 2008, it was reported that approximately 10 million individuals live with some level of amputation worldwide, of which 30% are upper limb amputees [2]. Just in the United States, 541,000 upper limb amputations were reported in 2005, a number that is expected to double by 2050 [3]. Moreover, in the UK and Italy, 5200 and 3500 upper limb amputations occur each year [4], of which approximately 12% are transradial, which is a considerable percentage [4].

A transradial amputation takes place when both the radius and ulna must be sectioned, which implies the removal of the hand. Living without a hand substantially diminishes the autonomy for performing everyday tasks, along with the individual's quality of life. In order to match the needs of upper limb amputees and to restore some degree of quality of life, great effort has been made regarding the development of prosthetic solutions.

From the solutions available in the market, myoelectric prostheses are the most promising devices for restoring some of the missing limb's functions. Myoelectric prostheses exploit electromyography (EMG) signals voluntarily generated by the user to achieve control of the device [4]. The advances of the prosthetics industry and research in the last decades have allowed to develop various control strategies for this type of prostheses [5]. The most commonly used include On/Off, proportional and pattern-recognition control, which will be one of the focus of this paper.

Typical pattern-recognition-based control is illustrated in the diagram from Figure 1. Pattern-recognition is based on the fact that the residual muscles present in the stump can generate different EMG signal patterns for different, for example, hand gestures. First, the EMG signals, voluntarily generated by the amputee, are acquired using electrodes. Afterwards, the signals are processed for removing the unwanted noise, as the EMG is an extremely noisy signal by nature due to crosstalk, electromagnetic noise, electrocardiography (ECG) artefacts, inherent instability of the signal, among others [6]. Other techniques may be applied during the signal processing phase, such as signal enveloping or amplification.

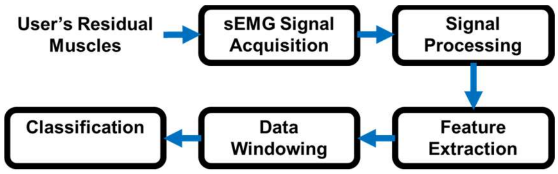

Figure 1: Typical pattern-recognition-based myoelectric control

The signal is then separated into windows, a process called data windowing. Features, which are relevant characteristics that can be acquired from the signal, are then extracted from each of these windows. Finally, a classifier (an algorithm based on machine learning) is used to decide to which class label the features from each window belong to. This output class label can be correspondent, for example, to a hand gesture. Finally, the prosthesis actuators behave accordingly to the output class label.

In Figure 2 is depicted the typical components of a transradial myoelectric prosthesis based on pattern-recognition control. Normally the used sensors are surface electromyography (sEMG) electrodes, which are non-invasive and are placed on the skin surface of the user's residual limb. The sEMG signal is very noisy, unstable and normally contains components from multiple muscle sources [7], besides, it is dependent on good skin contact and the surface electrodes can cause the user to sweat, which also affects the signal. Additionally, for pattern-recognition control, the electrode shift is an issue to take into account [8]. Implantable electrodes can be used to overcome these

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problems by providing a steadier, cleaner signal and recording of independent muscle sources [9], [10]. However, the invasiveness of this method is a disadvantage and an inconvenient for most amputees. For this reason and due to the fact of being more widely used, only sEMG sensors will be considered in this review.

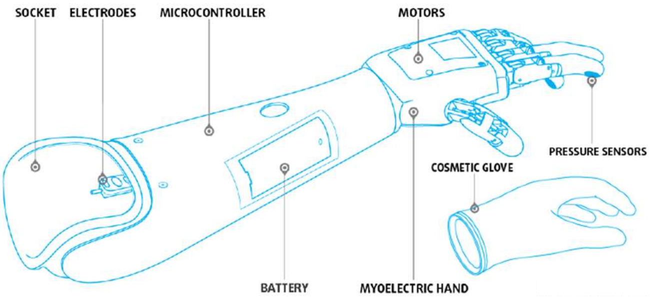

Figure 2: Typical components of a transradial myoelectric prosthesis

There is not a precise number of sEMG sensors to be used for a pattern-recognition-based control system. In fact, according to Li *et al*. [11], the number of sensors used in other works found in the literature vary between 4 and 16. However, this number can change according to the number of gestures to be recognized and sensor positioning, as it can also be observed in the work of Li *et al.* , where 6 to 8 sEMG sensors were sufficient to classify 10 different movements and only 4 sEMG sensors were sufficient for 6 basic movements. Young *et al*. [8] obtained similar results, recommending 4-6 sEMG sensors for classifying 7 movements. On the other hand, Naik *et al*. [12] achieved an accuracy higher than 90% for the classification of 11 finger movements with only 4 electrodes, after inferring the optimal positioning set-up.

Regarding signal processing, it can be performed analogically, on-board the sensor, or digitally on the microcontroller. After the sEMG signal is conveyed, data windowing, feature extraction and classification are all usually performed on the microcontroller, which can be considered the “brain” of a myoelectric control system. Additionally, it controls the motors present on the myoelectric hand, accordingly to the gesture or grasp correspondent to the classifier’s output.

Some more advanced transradial myoelectric prosthesis feature sensors for achieving grip force control feedback, such as the bebionic [13] and Michelangelo Hand [14]. These can be, for example, barometric pressure sensors, Force Sensitive Resistors (FSR) [15], or other type of tactile sensors [16], [17] that can be placed on the tips of the digits. Using the values these sensors provide, control strategies can be used to adjust grip force and avoid the slipping of objects [15], [18], [19] or to provide haptic feedback to the user [20], [21].

If the user wishes, a silicon cosmetic glove can also be used to cover the myoelectric hand and give it a more realistic look. The functionalities of the prosthesis usually remain the same, however it can make a difference for the user in terms of self-confidence and social acceptance. Advanced myoelectric protheses, such as the bebionic and the i-limb [22] have been designed taking this feature into account [23].

Overall, pattern-recognition control has more potential to control myoelectric prostheses with a high degrees-of-freedom (DOF) number than other standard control strategies [5]. Besides, it is a more intuitive control scheme if the correspondence between the EMG signals patterns and the prosthesis DOFs is appropriate.

The present review will focus on three of the main components of a transradial myoelectric prosthesis: the myoelectric prosthetic hand, the prosthetic microcontroller and the sEMG that can be used for the control of a myoelectric system. The main goal is to provide the reader with an overview of the solutions that are currently available in the market.

II. Myoelectric Prosthetic Hands

This section presents a selection of myoelectric prosthetic hands that can be found in the market. The focus was given to high-performance anthropomorphic prosthetic hands, with a high DOF number, which can allow more functionalities and a higher potential if controlled by a pattern-recognition-based system than prostheses with lower DOFs, such as Steeper’s Select Myoelectric Hand [24] or Ottobock’s SensorHand Speed [25]. The found high-end commercial myoelectric hands are the following: bebionic [13], Hero Arm [26], i-limb ultra revolution [22], LUKE Arm (radial configuration) [27], Michelangelo Hand [14], TASKA Hand [28] and VINCENT evolution 3 [29]. The devices are organized in Table I, along with the respective manufacturer, DOFs, number of actuators, available sizes, weight, maximum grasp and carry load, number of grip patterns, price and other relevant characteristics. These properties were chosen from a point of view of usability, which can be the most important factor for the end user.

A. Degrees-of-freedom and Number of Actuators

The work of Cordella *et al*. [4], which was based on a literature review on the need of upper limb prosthesis, inferred that myoelectric prosthesis users required the capacity of intuitively moving each finger separately. This is still a difficult feat to achieve but remains an active research topic. However, a prosthetic hand with high number of motorized DOFs can allow the user to perform a higher number of grip patterns, thus optimizing the device’s functionalities. Besides, it may have a higher potential for pattern-recognition-based control.

Most of the presented prostheses feature an actuator for each of the fingers, including for thumb rotation, such as the i-limb ultra revolution, the TASKA hand and VINCENT evolution 3, LUKE arm. However, some of them have passive thumb rotation, such as bebionic or passive flexion, such as the Hero Arm. The Michelangelo Hand is an exception among other high-end prostheses, as all its fingers are actuated by a single drive [30]. Curiously, it is also the only commercial hand prosthesis to have powered finger abduction/adduction.

A prosthetic wrist with at least one DOF is also part of the upper limb prosthesis users’ requirements [4]. Some of the hand prostheses presented in this paper have an integrated wrist, such as the Michelangelo Hand with Axon Rotation, the TASKA hand and the radial configuration of the LUKE Arm, which increases the number of DOFs and the device’s functionalities. However, only the LUKE arm has active wrist flexion and rotation, as the Michelangelo Hand with Axon Rotation has passive flexion and active/passive rotation and the TASKA hand only features passive flexion and rotation.

TABLE I: COMMERCIALLY AVAILABLE ANTHROPOMORPHIC PROSTHETIC HANDS

Product Name	**Manufacturer**	**DOF**	**Number of Actuators**	**Sizes (height in mm)**	**Weight (g)**	**Maximum Grasp Force (N)**	**Maximum Carry Load (Kg)**	**Number of Grips Patterns**	**Price (USD)**	**Other Characteristics**
Bebionic [13]	Ottobock	6	5	Small (165) Medium (190) Large (200)	390-460 (Small) 550-591 (Medium) 557-598 (Large)	140.1	45	14	11,000 [31]	Passive thumb rotation Adaptive grip
Hero Arm [26]	Open Bionics	5 (3 motor version) 6 (4 motor version)	3 or 4	Three sizes	280-346	*	8	4 (3 motor version) 6 (4 motor version)	6,600 [32]	First FDA approved 3D printed prosthesis Highly customizable Haptic feedback for notifications Adaptive grip
i-limb ultra revolution [22]	Össur	6	6	Small (182.5) Medium (185.1)	507 (Small) 515 (Medium)	136	90	24	Starting at 33,000 [33]	Mobile app for accessing programmable grip patterns Adaptive grip
LUKE Arm (Radial Configuration) [27]	Mobius Bionics	6	6	316 (Including wrist)	1400	*	*	6	100,000 [34]	Integrated active wrist Tactile vibratory feedback Adaptive grip
Michelangelo Hand with Axon Rotation [14]	Ottobock	4	3	*	~420	70	*	7	60,000 [35]	Integrated wrist with passive flexion and passive and active rotation
TASKA Hand [28]	TASKA Prosthetics	8	6	*	*	*	20	23	35,000 [36]	First waterproof prosthesis Integrated wrist with passive rotation and flexion Three colour options Adaptive grip
VINCENT Evolution 3 [29]	Vincent Systems	6	6	XS (145) S (150) M (160) L (170) XL (180)	386 (XS, if including wrist)	*	*	14	*	Vibrational force feedback The XS model is currently the smallest and lightest multiarticulating myoelectric hand with 6 motors Adaptive grip

*Not available

B. Size and Weight

Although the human hand has an average weight of 400g, prosthetic hands with this weight have been reported by users as being too heavy [23]. However, this can depend on variables, such as the age and gender of the user. Taking this into account, it is important that the manufacturer offers a selection of different sizes for the same prosthetic solution, so the user can choose the model that feels more comfortable and better matches her/his body characteristics.

From a general point-of-view, most of the manufacturers referenced in Table I have prosthetic hands available in different sizes. From all of the presented prosthetic hands, VINCENT evolution 3 is the one that offers the wider selection of sizes. Its XS size is the lightest myoelectric multiarticulating hand with 6 motors in the market, weighting only 386g, if including wrist. The hand from the Hero Arm however, is even lighter, as it is 3D-printed and it has less motors. However, it is not as robust as other prosthetic hands and offers less grip patterns.

C. Grasp Force and Carry Load

The capacity of performing tasks with higher strength is another of the user requirements identified by Cordella *et al.* [4]. A study showed the average amount of grasp force required for daily living to be about 68 N [23], which is a value close to the Michelangelo Hand's maximum grasp force. Considering the maximum grasp force values found for the selected prosthetic hands, all of them are superior to this value.

The maximum carry load is also a good indicator of the amount of force the prosthesis can exert, along with its robustness. Due to its titanium strengthen fingers, the i-limb ultra revolution can achieve maximum carry load of 90 kg. On the other hand, the Hero arm, being 3D-printed, can only lift objects with a maximum of 8 kg.

D. Grip Patterns

Having a wide selection of grasp types customized for daily living manipulation tasks (e.g. dressing, eating, writing) is also an important feature for a myoelectric hand according to users [4]. This can make the life of an upper limb amputee much easier. From a general perspective, the hand prostheses from Table I that have higher DOFs and number of actuators also feature a higher number of grip patterns, being the i-limb ultra revolution the one with the highest number.

Some works found in the literature also recommend the implementation of automated object grasping and slip prevention to reduce the attention of the user, allowing the performing of other parallel tasks [4], [37]. This feature can be observed on the bebionic. Furthermore, adaptive grip, i.e. the ability of the prosthetic hand to conform to different objects can also be observed in most of the presented prostheses.

Tactile feedback is also often referenced as a user requirement. This can make the amputee less dependent of visual feedback for prosthetic control, enhancing the device usability. The LUKE Arm features this property by using vibrational feedback. On the other hand, VICENT evolution 3 features force feedback, which allows the user to sense the amount of force applied by the prosthesis through different vibration levels.

E. Price

For the user, one of the most decisive factors when purchasing a prosthetic solution is the price. Prosthetic manufacturers usually do not display the price of their products in their website. Taking this into account, the prices presented in this review are taken from online articles and may not reflect the real product cost or may depend on the year of publication.

According to the values displayed on Table I, it may range from 6,600 up to 100,000 USD. Considering that, for most of the presented devices, this is only the price of the prosthetic hand, the price of a full system is substantially higher.

As seen in the case of the Hero Arm, 3D printing allows the final cost of the prosthesis to be drastically reduced. However, it has downsides, such as reduced robustness. Regardless, it remains an excellent alternative for less economically less favoured individuals.

III. Pattern-Recognition-Based Microcontrollers for Myoelectric Prostheses

Currently, there are still few pattern-recognition-based microcontrollers for prosthesis in the market. COAPT's Complete Control [38], the first of these control systems available in the market, was only commercialized in 2015 and became FDA approved in 2017 [39]. This system is composed by a microcontroller with high processing capabilities that processes sEMG signals and uses pattern-recognition algorithms for recognizing the user's intent, along with a co-amp that can collect up to eight sEMG signal channels and a button that can be interfaced with the prosthetic device for quick recalibration. It has been reported that the Complete Control system can cost around 15,000 USD [40].

More recently, in 2017, a second pattern-recognition control system for prosthetics has entered the market and became FDA approved in 2018 [39]. This system is called Sense and it was developed by Infinite Biomedical Technologies (IBT) [41]. The Sense system features a microcontroller with the pattern-recognition algorithm integrated on its firmware, along with eight IBT sEMG sensors.

IV. sEMG Sensors used for Controlling Myoelectric Prostheses

This section presents some of the sEMG sensors used for controlling myoelectric prostheses that can be currently found in the market. In Table II, eight of the found sensors are organized according to manufacturer. Configuration, dimensions, weight, gain adjustment, type of terminals and type of signal processing are presented for each of them.

As it can be observed, most of the sensors are manufactured by the same companies that develop prosthetic solutions, such as Ottobock, Touch Bionics and Steeper. From a general perspective, these sensors can be either cased of remote. While the remote ones allow the user to customize the position of the sensor terminals, it requires more cables to connect the latter to a separate module that analogically processes the signal. Cased sEMG sensors are easier to use in transradial prostheses, as they are compact and easier to place in a prosthetic socket.

TABLE II: COMMERCIALLY AVAILABLE sEMG SENSORS USED FOR CONTROLLING MYOELECTRIC PROSTHESES

Manufacturer	Product Name/Reference	Configuration	Dimensions (LxWxH)	Weight (g)	Gain Adjustment	Terminals	Signal Processing
Touch Bionics	PL069466/ PL069467 [42]	Remote	23 x 17.4 x 5.6 mm	*	Yes	Three 10 mm diameter gold-plated domes	Analog
	PL091050A/ PL091060A [42]	Cased	26.8 x 18.4 x 9.7 mm	*	Yes	Three stainless steel contacts	Analog
Steeper	ELEC60/ELEC50 [43]	Cased	27 x 18 x 10 mm	4.4	Yes	Three titanium contacts	Analog
Ottobock	13E200=50/ 13E200=60 [44]	Cased	27 x 18 x 9.5 mm	4.5	Yes	Three pure titanium contacts	Analog
	13E202=50/ 13E202=60 [44]	Cased (Suction socket)	*	*	Yes	Three pure titanium contacts	Analog
Liberating Technologies	DC200B=50/ DC200S=50 [45]	Remote	31 x 17.5 x 5 mm	*	Yes	Three metal domes (three sizes available)	Analog
IBT	Element [41]	Cased	28.8 x 16.8 x 6.7 mm	*	Yes (Digital)	Three titanium contacts	Digital
OYMotion	SKU:SEN0240 [46]	Two boards (Signal transmitter and dry electrode)	35 x 22 mm (LxW)	36	No	Three metal contacts	Analog

*Not available

Regarding the dimensions and weight, the available solutions are similar among each other, with the exception of OYMotion's SKU:SEN0240, which features a different configuration. This sensor is separated into two boards, one with three metal contacts and other that performs signal processing and transmits it.

As referenced in section I, the EMG signal is noisy, unstable and has components from several muscle sources. This requires the usage of signal processing in order to obtain an output ready for controlling a myoelectric system. From a general perspective, the solutions found in the market are double differential and feature onboard analogic signal processing, which is usually faster than digital. In order to obtain a steadier signal, onboard signal processing generally features amplification, filtering and enveloping. The IBT's Element, contrarily to the others presented in Table II, performs signal processing digitally, in a module outside the sensor, which allows it to be quite thin, comparing to other cased sEMG sensors.

Other characteristics, such as frequency bandwidth, temperature range and gain adjustment are also similar among the presented solutions. All of the sensors from Table II also require wiring. Additionally, output connectors do not vary much among these sEMG sensors, as it allows a high level of compatibility with prosthetics devices from other manufacturers.

Regarding the price, as referenced for the prosthetic hands' case, it is not displayed in the manufacturer's website. However, a high-end sensor, such as the 13E200 model by Ottobock can cost approximately 400 USD per sensor. On the other hand, a low-cost sensor, such as the OYMotion's SKU:SEN0240 costs around 30 USD, which is a substantial difference. However, this sensor does not feature adjustable gain, has bigger dimensions, is heavier and is not cased.

V. FINAL REMARKS

The goal of this work was to conduct a review on three of the main components of a transradial myoelectric prosthesis: anthropomorphic myoelectric prosthetic hands, pattern-recognition-based microcontrollers and sEMG sensors that can be used for the control of a myoelectric system. It is worth pointing out that the search was focused only on devices available in the market.

Regarding the myoelectric prosthetic hand, the characterization was performed in terms of DOFs, number of actuators, available sizes, weight, maximum grasp and carry load, number of grip patterns, price, among other. These characteristics were selected taking into account the satisfaction of the end user.

Although there are already prostheses in the market that allow tactile feedback, this should be a generalized practice, as it is a relevant feature for upper-limb prosthesis users. Moreover, a higher attention should be given to the user customization of the device and design. Most myoelectric hand prostheses only allow the user to choose between different sizes and a limited selection of colours. Printing in 3D can allow more freedom for user customization, as observed in the Hero Arm's case. This can be a crucial factor for the user who is concerned about the aesthetics of the prosthesis but does not want it to have a similar appearance to a real human arm.

Also, the price of anthropomorphic myoelectric hands should be decreased, as it is currently too high, and every amputee should have the opportunity of using high performance devices such as the ones presented.

Pattern-recognition-based microcontrollers for prostheses are still rare in the market. At least to the authors' knowledge there are only two commercially available devices. The usage of this type of devices should be generalized, as pattern-recognition-based control has a higher potential for controlling myoelectric hands with a high DOF number than other control schemes. However, advances in this area may encourage the commercialization of similar systems.

There is a wide variety of sEMG Sensors in the market, but the ones discussed in this paper focus on its use for prosthetic control. Much like prosthetics hands, the price of these sensors should be decreased, as the usage of a pattern-recognition-based microcontroller requires a higher number of sensors than other control schemes.

All of the presented sensors require wiring, which can constrain the design and placement of the prosthetic forearm casing. Besides, if the number of used sensors is high, positioning the wires inside the prosthesis structure can be cumbersome. Although there are wireless electrodes available in the market, such as DataLITE sEMG sensor by Biometrics [47], they are not optimized for myoelectric prosthetic control. In the future, wireless solutions should be developed. Regardless, some research work has been made on designing wireless sEMG systems for prosthetic control [48], [49].

Overall, efforts should be made for decreasing the price of the various components that compose a myoelectric prostheses and higher importance should be given to usability, design, and user customization.

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