Role of Electrolyte Gels in Signal Transmission Across the Interface Between Skin and Surface Electrodes in Hand Exoprosthesis

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A key component of a successful external myoprosthesis is not a part of the prosthesis, but an area: the interface between the prosthesis and the amputation stump. This is because in this area takes place a critical exchange of information, in the form of a myoelectrical signal being transferred from the muscles, through the fascia, fat and skin, to the surface EMG sensors, that in turn transfer this information to a part of the prosthesis that is responsible with the analysis, augmentation and use of this signal in order to control the movements of the electromechanical parts of the prosthesis. Any condition that leads to an impaired transmission of information from the skin to the EMG sensors inevitably leads to an underperformance of what may otherwise be a highly developed model of exoprosthesis, thus potentially rendering it no more useful than a basic mechanical model. We aim to review the possible difficulties that may arise in this area, and that may lead to a faulty transfer of signal, with a loss in quantity or quality. For this purpose, we will review the current literature for this subject, including reference books and articles, and complete this information with our personal experience. In doing this, we hope to provide a guide to practitioners, bioengineers and patients alike, in order to be able to anticipate and correct any potential problem as they may arise.

Keywords: EMG sensors, myoelectric prosthesis, bioelectric interface

One of the key components of a successful external myoprosthesis is not so much a part of the prosthesis, but an area: the interface between the external prosthesis, represented by the socket, and the amputation stump.

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Objectives

Any condition that leads to an impaired transmission of information from the skin to the EMG sensors inevitably leads to an underperformance of what may otherwise be a highly developed model of exoprosthesis, thus potentially rendering it no more useful than a basic mechanical model.

Our objective is to review the chemical, metallic and biologic components of the interface and evaluate the possible difficulties that may arise in this area, and that may lead to a faulty transfer of signal, with a loss in quantity or quality. In the literature, such difficulties, especially in the dermatologic spectrum, are described with a prevalence of up to 70% [1, 2].

In doing this, we hope to provide a simple guide for practitioners, bioengineers and patients alike, in order to be able to anticipate and correct any potential problem as they may arise.

Experimental part

Materials and methods

In order for a myoelectric prosthesis to function, there must be an adequate transmission of EMG signals from the muscles in the patient's amputation stump to the prosthesis itself. This transmission is influenced by three factors: the tissues that compose the skin, the electrode (the receiver) and the electrolyte used to facilitate signal transmission [3].

The myoelectrods used in bionic limb command fall into two categories:

- Surface electrodes – noninvasive and easy to change if deteriorated. The can be passive (they just receive and transmit signal) or active (they receive, amplify and transmit signal).

- Intramuscular - This can measure potentials with higher precision and fall into two sub-categories: needle type and wire type (bipolar).

Surface EMG sensors are usually used in the myoelectric control of prosthesis (fig. 1).

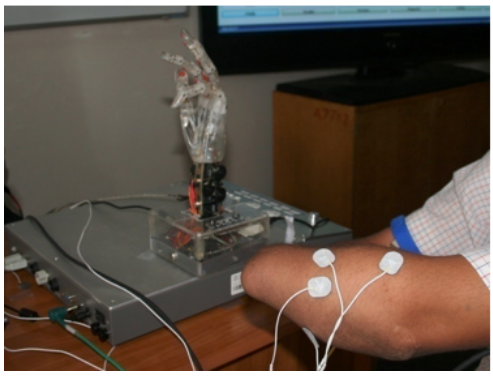

Fig.1. Surface EMG sensors on an amputated forearm during signal processing and experimental myoelectric prosthesis module tests. This image is from the author's personal database.

These sensors are essentially electrodes that detect small amplitude biopotentials, from less than 30 mV when measured directly at the muscle to less than 1 mV when measured on the skin [4], and are made of conductive materials, from gold Au and silver Ag to stainless steel, and also various alloys with a layer of silver chloride AgCl or silver/silver chloride Ag/AgCl covering their surface (or any

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other hipoallergenic conductive alloy), while the electrolyte gel contains sodium chloride NaCl or potassium chloride KCl, forming a very stable electrochemical combination [3]. Electrode gel and sometimes paste have the role of reducing the electrode-skin impedance and forming a conductive path between skin and electrode [4, 5].

The electrolyte gel has the role of a chemical interface between the patient's skin and the metallic component of the electrode. The chemical reactions that take place at this interface (between gel and metal) are both oxidative and reductive; the metal is most often the alloy of silver and silver chloride - Ag/AgCl - over 80% of all surface electrodes [5, 6]. This layer of alloy permits current to pass freely from the muscle across the junction between electrolyte and electrode, introducing less noise into the measurement in comparison to simple silver Ag electrodes [5].

Ag/AgCl electrodes seem to have a low electrode-skin impedance and thus a high signal to noise ration, which means a better quality signal, but in real life dry electrodes seem to pe preferred, as wet electrodes are disposable difficult to use constantly on the long term [4].

There are modern alternatives to the use of electrolyte gel that have been developed and released in recent years. According to Myers et al, in their 2015 article [7], silver nanowires were used to construct a wearable dry sensor that can be used for electromyography, with efficiency comparable to Ag/AgCl wet electrodes when a patient is stationary but with fewer motion artifacts when the patient is moving, and also eliminating the need for an electrolytic gel. The team claims no signs of skin irritation were seen and the sensor is robust, with highly conductible flexible silver nanowires embedded in a flexible polymer, which would allow for a long term use.

Jiang et al, in their 2017 article [4], describe the construction and testing of a sEMG sensor that consists of a polypyrrole-coated nonwoven fabric sheet (PPy electrodes), sewn on to an elastic band, that fits over the amputation stump. While testing, the authors have found a high correlation coefficient between PPy electrodes and Ag/AgCl electrodes when reading measurements taken with both types of electrodes from the same muscle fibers, suggesting that PPy electrodes may be an efficient alternative to Ag/AgCl electrodes.

The use of electrolyte gels in both electromyography (EMG) as well as electrocardiography (EKG) is somewhat problematic in long term use, as the gels may lead to skin irritation and are cumbersome, as they dry up and need to be re-applied in order to maintain the efficacy of the sensor.

In their 2011 article, Laferriere et al compared signals from two different types of dry electrodes, IBMT flexible dry electrodes and Orbital Research electrodes, to signals from standard Ag/AgCl electrodes, and found comparable sensitivity when detecting small unloaded muscle contractions and large loaded contractions. [8]. Searle and Kirkup, in their 2000 article [9], compare wet, dry and insulating bioelectrodes, testing electrode impedance, static interference and motion artefact; they find that in many of the situations recreated in the laboratory dry and insulating electrodes compare favourable to wet electrodes. For example, there was 40 dB and 34 dB less interference with dry and insulated electrodes than there was with wet bioelectrodes, while artifact levels were reported to be an average of 8.2 dB and 6.8 dB lower for dry and insulated electrodes compared to wet electrodes.

Dry electrodes are generally reusable, while wet electrodes are most often disposable; in his 2002 report [5], Day finds that they both have similar performances, and points out that disposable electrodes have a decreased risk of improper and inconstant measurement characteristics. Also, he finds that disposable gel electrodes seem to minimize the risk of electrode displacement during rapid movements.

In order for a surface sEMG sensor to function properly, the skin of the amputation stump needs to be cleaned, and an electrolyte gel is either applied on the skin, or is pre-applied on the sEMG sensor, if a wet sensor is used. Excessive sweating, excessive pilosity, local hypothermia or hyperthermia may negatively affect electrolyte gel behavior [3].

New generation myoelectric prosthesis often incorporate haptic feedback effectors and artificial tactile sensors (fig. 2) in order to complete and improve the feed-back loop, thus providing the patients with a means of integrating the prosthesis and the interface, and of interacting with the environment around them in a way that is one step closer to recreating the natural experience [10, 11].

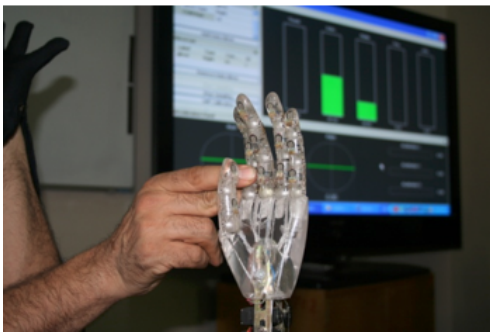

Fig. 2. Tactile pressure sensors on an experimental myoelectric hand exoprosthesis, reacting to human touch, as it can be seen on the display in the background. This image is from the author's personal database

Recently, there has been great progress in the area of myoelectric sensors. For example, in his 2015 paper, Pasquina describes integrated intramuscular sensors named IMES - Implantable Myoelectric Sensors, that work by picking up small electric charges within a muscle, after being implanted, and sending that information wirelessly to an electromechanical prosthetic hand through an electro-magnetic coil built into the prosthetic socket [12]. Even though this technology offers great promise, to the vast majority of amputees it is unavailable in the immediate future, and standard surface electrodes are still the go-to solution for EMG signal acquisition and transmision.

With this in mind, we proceed to review some of the most often encountered medical problems affecting the skin of the amputation stump, and implicitly the interface between stump and prosthesis.

Basic hygene is very important to having and maintaining a working interface between the external prosthesis and the amputation stump. Each prosthesis user should be advised to wash their amputation stump daily with soap, especially before donning the prosthesis. This is both to prevent irritation and skin infection, and to eliminate the layer of dead skin cells and natural sebum that forms on a regular basis, as these create a barrier between the EMG sensors and the skin. Regularly, the prosthesis socket should be cleaned, and the sensors gently wiped. Also, in the case of patients with excess pilosity on their forearms (fig. 3), these should be shaved regularly, for a better contact between sensor and skin [13, 14].

Regarding scars on the amputation stump, we have had a patient with a voluminous scar, following his run-in with an electric animal food processor (fig. 4), and following

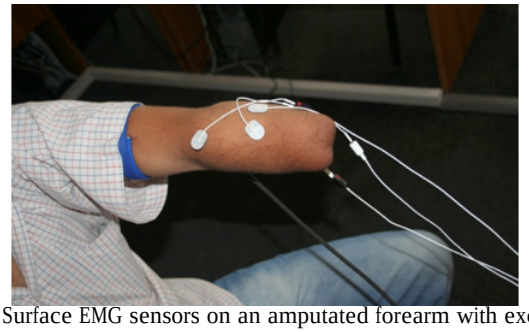

Fig. 3. Surface EMG sensors on an amputated forearm with excess pilosity. This image is from the author's personal database

that we decided to adress an unusual problem: what are the potential difficulties in the constant interaction between the prosthesis and the stump? Scars make electrical signal reception by the sEMG sensors very difficult, as they often are surface manifestations of a deeper layer of irregular fibrosis, wich is essentially just another layer for the electrical signal to go through from the muscle to the sEMG sensor. Subcutaneous fat and fascia are the normal tissues to be taken into account when discussing the passage of electrical current from the emiting muscle to the receiving EMG surface electrode, and the thickness of these layers may have a significant effect on EMG signal intensity [15].

Contact dermatitis is a common condition, easily mistaken for skin infection [16-18]. It is directly associated with wearing the socket and it consists of: itching (sometimes very intense), a sensation of burning and erithema [19].Campbell et al. list many causes: detergents in the stump sock, nickel, and chromates used in leathers, skin creams, and antioxidants in rubber, topical antibiotics, and topical anesthetics [14]. The treatment consists of: removal of the irritant, meticulous cleaning, a topical cream containing steroids, and compression locally.

Bacterial folliculitis is a problem in stumps that do not undergo through thorough hygene, or have an excessively hairy skin, or the skin secretes sebum in excess[20,21]. It can lead to cellulitis of the stump, and even to abcesses. The treatment is simple, and consists of hygene, and adressing the dermatological infections with topic antibiotics. Prevention is easy and important, and consists of regular if not daily washing of the amputation stump with a mild or neutral soap and also trimming of excess hair, or even IPL epilation [22].

Epidermoid cysts occur at the edge of the socket, more frequently in an lower-limb amputation. They can be excised, or the socket can be modified [23, 24].

Verrucous hyperplasia is a wart - like growth on the skin at the end of the stump, caused by proximal constriction. It manifests as fissuring, thickening, ulceration and infection of the distal stump. Treatment consists of: antibiotics for the infection, salicylic acid applied locally to soften the keratin, hygene and socket modification[25, 26, 13].

Tumors that appear on the amputation stump, wether benign or malignant, such as intraepithelial carcinoma or squamous cell carcinoma, will be treated accordingly, in close collaboration with an dermatological oncologist, through biopsy, surgical excision and chemotherapy or radiotherapy [27, 28].

Stump oedema syndrome is an increase in the total volume of liquids in the distal stump. Redness or mild oedema often appears when a new prosthesis is worn for the first time. The treatment consists of wearing shrinker socks or elastic bandages until the oedema recedes. If

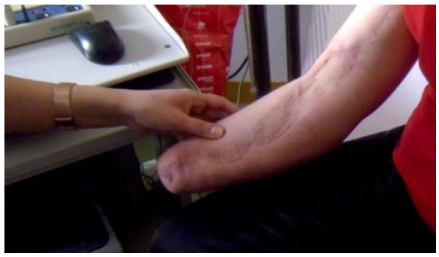

Fig. 4. Extensive scarring on a forearm amputation stump. This image is from the author's personal database

the condition persists, a re-fitting of the prosthesis is necessary [20,29].

There are many other pathologies affecting the amputation stump, less frequently, including nonspecific eczematization, chronic ulcers, callus formation, psoriasis, blisters from prosthetic rub, pressure induced purpura, diabetic vasculopathy or fungal infection, the treatment of wich does not constitute the scope of this paper [1, 2, 13, 20, 21, 27, 30].

Results and discussions

We conducted an interdisciplinary literature overview, taking into account significant pathologies that may have an impact on the interface between the myoelectric prosthesis and the amputation stump, with a special interest in the dermatological issues that may affect the skin of the stump. We also looked at the different types of sensors, and we may argue that dry sensors, including the modern PPy and silver nanowire models, fare equally or better than traditional, wet electrodes, and have an excellent potential for further use in the myoelectric control of exoprosthesis in the future.

The interface is fluid concept, ammending itself to tansformation and evolution in time. A new direction for this concept is the full integration of the prosthesis within the amputation stump, creating a merged human-prosthesis interface.

The basic groundwork for the creation of a merged human-prosthesis interface is being done through the surgical procedure known as osseointegration, through which a titanium implant is affixed to the distal part of the medullary canal of the transected bone in an amputation stump, with a certain portion of the implant remaining outside the patient's body. The portion fo the implant that sits in the medullary canal may be covered in hydroxyapatite in order to stimulate osseointegration. After the implant is integrated and the wound around it is stabilised, an external prsothesis is affixed to it through varius connection pieces, thus allowing the patient a better control of the prosthesis, and also greater strength during utilisation [31].

In the forearm, osseointegration has been used as a means of affixing external prosthesis through the use of threaded titanium implants in both the radius as well as the ulna, both in the proximal portion, with favorable results [32].

An ongoing project named DeTOP (Dexterous Transradial Osseointegrated Prosthesis with neural control and sensory feedback) spearheaded by the BioRobotics Institute of Sant'Anna School of Advanced Studies, Pisa - Italy plans to take the concept even further, by combining osseointegrated implants in the ulna and radius that would connect to the prosthesis via mechatronic couplers with implanted electrodes in the musculature of the arm, that would transmit the myoelectric signal through the osseointegrated implants directly to a robotic hand, capable of aferent feedback and efferent control [33].

A combination of myoelectric control and osseointegration takes things one step further with APL's Modular Prosthetic Limb, developed by the Johns Hopkins University Applied Physics Laboratory (APL). In a 2016 press release, it is claimed that the combination removes the need for a prosthetic socket, wich improves vastly the mobility and reach of the bionic arm [34].

The interface between the prosthesis and the stump is still an interface between a human organ and a medical device. The prosthesis, referring to the socket, as the part that comes into contact with the stump, needs to be, in a very real sense, biocompatible. It needs to be constructed from biocompatible materials because it interacts with an organ of the human body: the skin, in a medical setting, and so the principles of biocompatibility apply to this case too, be it unusual in both the orthopaedic and the engineering sense.

Conclusions

We, both the surgeons and the engineers, all concentrate on the bionic hand, the effectors, the way in wich the prosthesis relates to the exterior world, but little work in comparison has been done in the area of the interface: a virtual space that directly dictates how much control the patient has over his prosthesis.

In effect, the interaction between the exoprosthesis and the amputation stump represents a common are of interest for both the medical personnel that is involved in the process of amputation and fitting the stump with a prosthesis, as well as the engineers that create the matherials of with the exoprosthesis are made of.

On would argue that the aforementioned matherials may be classifies as biomatherials and treated as such, in respect to the fact that they represent a point of interaction between inorganic and organic matter, with a need for the former to be tolerated and, sometimes, integrated with the latter.

Holding this in mind, we must recognise the importance of the interface between the bionic limb (the exoprosthesis) and the amputation stump, and take all measures to ensure that it may function within the optimal parameters.

As for the future, we hope that a greater effort would be directed at adressing the difficulties of creating and maintaining a working interface, with the aim to fully integrate the external prosthesis and it's wearer.

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