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Development of a prosthetic arm: experimental validation with the user and an adapted software

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***Abstract*—In the world of upper limb prostheses, few companies propose different kinds of hand, wrist and elbow prostheses but their control is often difficult to understand by the patients.**

We have decided to develop new myoelectric prosthetic arm (elbow, wrist and hand) by axing our development on the use of new technologies and user centered design methodology.

In this paper, we are explaining the different kinds of prostheses currently manufactured their advantages and their drawbacks. Then, we explain our designing choices of the prosthesis and the movements it can realize. We detail the control chosen to simplify the use and the instrument of the product by the patient. In the last part, an adapted software is developed and used to validate experimentally the practice by the patient.

I. INTRODUCTION

IN the domain of handicapped people, the amputees are one of the most important group in the world. The aim of developing prostheses is mainly to improve their conditions of life and to help them recover independence and dignity. In this paper, we are concerned with prostheses designed for upper limb amputees – elbow, wrist and hand.

Current high tech prostheses exist but they are very expensive and often of complex use, and it is thus difficult for a patient to get the kind prosthesis it would like to have. Our aim is to benefit from the affordances of new technologies for proposing products less costly and offering a better comfort of use to the amputees.

A first study has shown [1] that to be used and appreciated by the patient, a prosthesis must be functional, aesthetics, quiet, light and easy to use and instrument [2]. This last characteristic is the most important one quoted by patients and prothesists. A prosthesis whose instrumentation is complex will not be used. That is why we have developed a methodology that allows the patients to be involved in the design of personalized and easy to instrument prothesis, and technological tools that make it possible to have the prothesis adapted to the patient.

In this article, firstly we describe the current situation where three categories of prosthesis are proposed by companies. Then, we explain our design methodology and the technological tools mentioned above. These especially include control diagrams that help the patient understand the feedback of the prothesis, and also allow the prothesist to adapt the parameters of the prothesis to the physical capacities of the patient.

The first validation tests of the control diagrams showed the interest of having a specific software for supporting the patient understanding. In the fourth part, we explain the main functionalities of this software and the potential it offers for prosthesis control modifications. In the final part, we graphically show some results of an experimental use of this software for validating the control choices of the prosthesis jointly with the user.

II. THE PROSTESES IN THE WORLD

Before introducing our innovative product, we describe the different prostheses developed by the main prosthetic societies: UTAH, OTTA BOCK and PROTEOR. These three companies concentrate 90% of the market.

Currently, three kinds of prostheses are proposed:

- aesthetics prostheses,
- mechanical prostheses,
- myoelectric prostheses.

A. *Aesthetics Prostheses*

Their aim is only aesthetics, and this type of prosthesis is generally used by patients. In the majority of the cases, the prosthetic arm is created from a standard mould. It means that the resemblance to the healthy member is not optimal. This type of prosthesis does not carry out any movement; it only serves to restore the patient body appearance. This kind of prosthesis is for instance manufactured by the OTTO BOCK society [3] and a complete aesthetics prosthesis is shown in figure 1.

B. *Mechanical Prostheses*

Mechanical prostheses try to approach the functionality of the lost member. They can be manual (use with the assistance of the healthy member) or with cable requiring the use of a harness.

Three kinds of mechanical elbow products are currently offered to the patients.

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Fig. 1. Picture of complete aesthetics prosthesis

The first is the elbow with toothed rack, which is released thanks to a pushbutton actuated by the valid hand or by a cable. Many drawbacks are attached to this mechanical elbow: noise of the toothed rack, the limited number of positions of the front arm and the bad aesthetic of the pushbutton.

The second elbow is the elbow with friction, which moves thanks to the friction of a spiral spring on the axis of the elbow [4]. A cable ordered by the other shoulder actuates blocking: one traction locks it, another unbolts it. It is more functional than the previous one, but maintains the position less firmly. In addition, it needs a double order from the amputee, which is not always easy to carry out.

Lastly, there is an automatic elbow from OTTO BOCK (figure 2). The front arm is manufactured out of plastic and is not very solid. Its distal part (near to the wrist) is cylindrical and is simply cut to the length of the healthy member. Unfortunately, prosthetic arm will not resemble to the healthy member.

Fig. 2. Mechanical elbow from OTTO BOCK

Being informed of all the drawbacks of these mechanical prostheses and having the technologies to improve them, our objectives are to propose to the patients a more functional mechanical prosthesis and solutions compared to the criteria of aesthetics, quiet, light and easy to instrument (intuitive use by the patient.

C. *Myoelectic Prostheses*

Myoelectric signals (Electromyogram or EMG) are electrical signals registered from the muscles activities. Thanks to these signals, a great number of applications are possible. With surface electrodes placed directly on the skin, it is for instance possible to measure functional motor activities such as washing teeth or writing [5]. Applications for controlling a robot hand with EMG signals have also been developed [6]. Now, it becomes possible to control computers without joysticks or keyboards. An experiment to demonstrate bioelectric flight control of 757 class simulation aircraft landing at San Francisco International Airport has been tested [7]. A pilot closes a fist in empty air and performs control movements which are captured by a dry electrode array on the arm, analyzed and routed through a flight director permitting full pilot outer loop control of the simulation.

The EMG are nevertheless complex signals with noise and they are easily influenced by many factors. Then, from the interpretation to the use, the EMG need several specific treatments [8].

The consequences of the Viet Nam war were at the origin of the development of the UTAH products. This society was the first to propose the EMG technology to control the prosthesis. The picture below (figure 3) shows EMG prosthesis of elbow from the UTAH Company.

Fig. 3. EMG arm prosthesis proposed by UTAH

The OTTO BOCK society also proposes prosthesis of hand coupled with a myoelectric elbow [9]. Unfortunately, the whole system proposed by this society is too expensive for patient (about 45 K€). The hand is a tree legs grip with an aesthetic glove.

D. *Conclusion*

This state of the art shows that there are technical problems for prostheses and their application. The most important is the average cost of the myoelectric prosthesis: 23 k€ for the elbow, 7.5 k€ for the hand and its wrist. The high prices of these prostheses explain the weak diffusion and use.

A great number of myoelectric prostheses are criticized by amputees because of the lack of aestheticism and the difficulty of control: co-contraction needed to control the prostheses is too difficult. Some of them are noisy (mechanical prosthesis) and sometimes the prosthesis doesn't answer as the patient wants.

For all these reasons, we want to improve the functionality of the myoelectric prostheses as their aesthetic aspect, by using new technologies as manufacturing tools and electronics and mechanics innovations.

The project of developing a myoelectric upper limb prosthesis was born in 1998. Accordingly, Tech.Innovation society was created in 2000. Its aim is to be the first to propose functional and aesthetic myoelectric prostheses at a reasonable cost, completely refunded by health insurances.

III. PROPOSAL OF A NEW DESIGN AND AN INNOVATIVE CONTROL FOR THE PROSTHESIS

A. The design proposal

The main advantage point of our design concern the economical design choices of the prosthesis to improve the quality, the aestheticism, the functionality and the weight. The new central geometrical structure integrates much of the elements: the motors, the batteries, the bevel gearbox, the weight compensator, the control card and the hand. The optimal placement and the functions of these elements are detailed by the authors in [1].

A maximum of the parts of this prosthesis are designing in CAD and build thanks to stereolithiography process, which an economical process. The result of the final arm which integrates all the functional elements is shown in figure 4. The advantages of this process are the lightness and the solidity but also the possibility to build the shape wanted. It is then possible to propose a prosthesis shape nearest to the healthy member shape of the patient.

Fig. 4. Picture of the body part of the prosthesis with the elbow: use of Stereolythography process by Tech.Innovation society.

As an example of simple but concrete innovation, we have decided to choose a Lithium battery (the same that commercial ones). This choice enabled us to divide by two the weight of the batteries and to reduce the production costs.

Finally, figure 5 shows the current prosthesis proposed by Tech.Innovation Society. In this figure, we can easily locate the fit, the elbow, the wrist, the hand and the body part (operating part). The fit allows the adaptation between the patient and the prosthesis; it integrates the two EMG electrodes.

Fig. 5. Myoelectric Prosthesis from the Tech.Innovatin Society

It is very important not to neglect the position of the EMG electrodes in the fit. As explained in [10], the identification of the innervation zone is widely used to optimize the accuracy and precision of noninvasive surface electromyography (EMG) signals because the EMG signal is strongly influenced by innervation zones.

B. Control of the prosthesis adapted to the user requirement

Concerning the design of specific product (in medical and surgical domains for example), it is important to integrate the user in the design process not only to design for him but to design with him. Thus, notions of User Centred Design (UCD), Participatory Design (PD) and Scenario Based Design (SBD) are integrated in our design work.

Using this methodology, a great number of projects are currently working around Software, Web and Human-Machine Interface development [11-13]. These projects focused on users’ behaviours are multi-disciplinary and need many experts from different domains in addition to data processing specialists. This research methodology naturally proposes collaboration between engineers, researchers, technicians, users, etc. Some concrete application examples show the advantages of the implication of these various partners [14-16].

In our context of improving the prosthesis control, we typically need feedback information from the user. Its integration in the design process allows common new proposals with engineers and researchers.

The main evolution we propose with the patient is to use the six degrees of freedom of the prosthesis without co-contraction of the muscles: a strong contraction allows the motor selection and the movement is carried out by weak contractions.

To produce signals, the patient contracts the biceps or the triceps, which are the two healthy muscles he can use. With only two electrodes placed in the fit of the prosthesis, he can control the opening and the closing of the hand, the two rotations of the wrist and the extension / inflection of the elbow. There is one motor for each movement. Thanks to the decision-making process proposed in figure 6, the order has been simplified; indeed no co-contraction is required to carry out a movement.

The figure 6 represents the diagram of the prosthesis motor activations according to the patient contractions of only two muscles (without co-contraction).

When the hand motor is selected, a weak contraction of the biceps opens the hand and a weak contraction of the triceps closes it. The operations are the same for the others motors selected.

The identification of a strong or a weak contraction is explained in [1]. This study explains the treatment of the signal emitted by the muscles to be adapted to the decision-making process proposed. It deals with the main problems of signal recognition. For an easier instrumentation, we propose a protocol for which the top priority is to differentiate more quickly the strong signals from the weak signals and the dubious signals. This led us to work on the tangent at the origin of the sensors output signal (after treatment). Thus, by determining a slope of contraction for a given patient, we can work on straight lines forms.

Moreover, a simple adjustment of the control card makes possible to adapt the prosthesis to the sensitivity of the user and to regulate the delay with the emitted signals. Thanks to the adapted software developed, this adjustment can be carried out simultaneously with the use of the prosthesis.

IV. ADAPTED SOFTWARE TO MEASURE MUSCULAR ACTIVITIES AND TECHNICAL PERFORMANCES

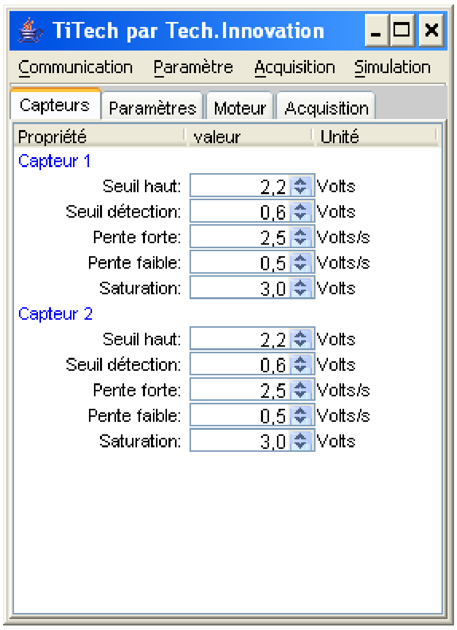
The first version of the prosthesis allowed us to observe the patient in situation and evaluate the adequacy of the product to his requirements. Technical choices, mechanical design, and control have been tested during specific experiments. To assist these experiments, the Titech Software has been developed with the aim to:

- adjust the microprocessor parameters that allow the real time adjustments of the slopes and detection thresholds for the strong and week signals generation (figure 7 in French),
- collect and visualize in real time the muscular activities of the patient.

The user observations and analyses are mainly focused on the increasing of the prosthesis control with the aim to better understand his interaction with the product.

From the first observations in situation of use, the patient pointed out to us some incomprehension of the prosthesis movements following its muscular contractions.

Thanks to the Titech software functions developed, it was possible to visualize properly what the patient was explaining. We observed with her the muscles she exactly



Propriété	valeur	Unité
Capteur 1		
Seuil haut:	2,2	Volts
Seuil détection:	0,6	Volts
Pente forte:	2,5	Volts/s
Pente faible:	0,5	Volts/s
Saturation:	3,0	Volts
Capteur 2		
Seuil haut:	2,2	Volts
Seuil détection:	0,6	Volts
Pente forte:	2,5	Volts/s
Pente faible:	0,5	Volts/s
Saturation:	3,0	Volts

Fig. 7. The Titech software: Parameters adjustments for the two EMG sensors ("capteurs1" and "capteur2"): the slopes ("pente") and detection thresholds (seuil détection") for the strong and week signals generation

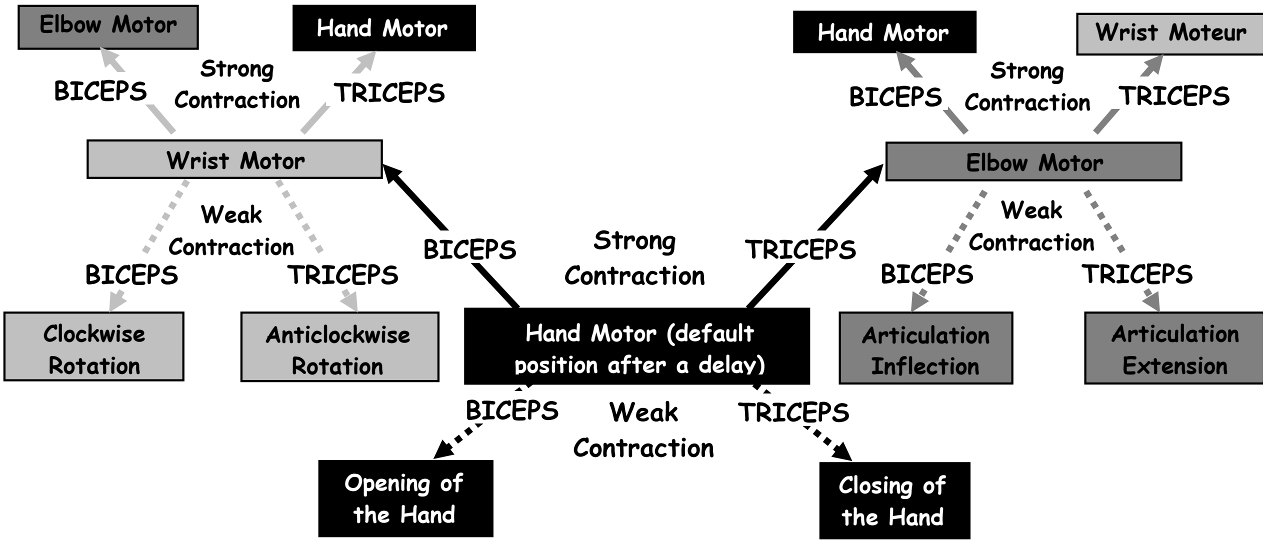


Fig. 6. Decision making process: diagram of the prosthesis movements according to the muscular activity [8]

contracted and guided her towards a better understanding and use.

V. EXPERIMENTAL VALIDATION AND SIGNAL VISUALISATION

For this experimental validation, we proposed a scenario in agreement with the user. In this scenario, we have written together the actions she has to carry out. To be able to realise de movement she wants, the first step is to easily choose the motor to actuate.

The figure 8 shows the patient using the Tech.Innovation prosthesis for experimental validation.

Fig. 8. Patient is using the prosthesis in accordance with the scenario written. The prosthesis is linked to the Titech software to recover and analyse the data.

In figure 9, the graph shows the signals resulting from the decision to choose the wrist motor. It is possible to see exactly the evolution of the muscular activity and the microprocessor signals in the same time.

On the graphs presented in figures 9 and 10, the first EMG electrode (*sensor1*) is placed on the triceps and the second EMG electrode (*sensor2*) on the biceps. The two lines named *high threshold* and *low threshold* symbolise the limits which serve to determine if the signal is interpreted as a strong or a week contraction.

The *motor state* line indicates if the selected motor is on or not. On these two figures, the *motor choice* line informs about the current active motor:

- 50 bits: elbow motor is selected
- 100 bits: hand motor is selected (after a delay, the control card selects automatically the opening/closing motor of the hand,
- 150 bits: the wrist motor is selected

On the graph in figure 9, we note that the user decides to choose the wrist motor with a strong contraction of her biceps. A minimal biceps/triceps co-contraction is inevitable; however, the patient has a dominant muscular activity which is interpreted by the microprocessor as a voluntary contraction of the biceps as expected. This action is more natural to realize for the patient than a voluntary co-contraction.

After a 2-seconds delay of non-activity, the control card system activates automatically the hand motor. Note that during the 2-second phase the motor state signal is always zero.

In figure 10, the graph represents the clockwise and anticlockwise rotation of the wrist. Firstly, the patient decides to choose the wrist motor with a strong biceps contraction. Then, with alternative biceps/triceps low contractions, she plays with the two rotation directions of the prosthesis wrist motor.

In this graph, the activity of the motor is only visible through the *motor state* line at the beginning of each weak contraction. Moreover, we note that the wrist motor is selected as long as some activity is detected.

These two figures illustrate two of the many experiments made with this patient. The muscles activities of the patient can be captured, treated and interpreted thanks to the microcontroller process chosen and the control strategy developed. These experiments allow the design team to put the user in real situation and to better understand the patients' requirements.

For the moment, this patient cannot move the elbow as she wants (this is for her a new EMG control function) but the rotation of the wrist and the movement of the hand are easier than before: the previous

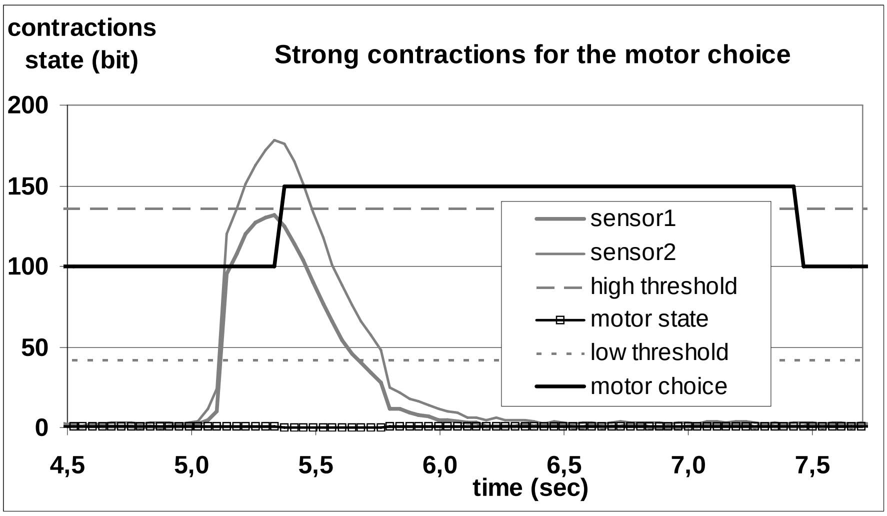


Fig. 9. Strong contraction activity of the patient to change the motor: strong contraction of the biceps (sensor2), rock to the wrist motor (100 bits to 150 bits) and go back automatically to the hand motor after a delay

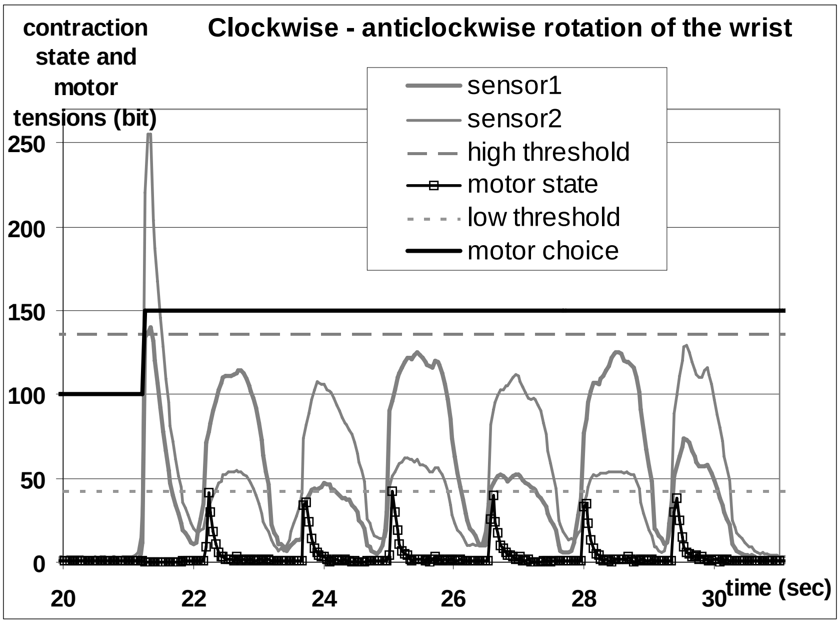


Fig. 10. One strong contraction and many weak contractions of the patient: selection of the wrist motor and activity of this motor during weak biceps.triceps contractions of the patient.

prosthesis used by the patient needed the triceps strong and weak contractions for the opening and closing of the hand and the biceps strong and weak contractions for the rotation of the wrist.

Finally, these experiments validate both the prothesis and the technological tools we have developed for an easy instrumentation of it.

VI. CONCLUSION AND PERSPECTIVES

In the medical world, a successful prosthesis is a prosthesis used. Today still 50% of the patients give up their prosthesis.

In this paper, we have described the different prostheses proposed by societies, some of their defaults and some patient requirements.

The Tech.Innovation proposal wants to be more in accordance with the users' requirements and to manufacture upper limb prostheses able to take into account the amputees' needs at a reasonable cost. Some advantages of our product are the aestheticism and the lightness due to new manufacture processes used. But the main advantages are the facility of instrumentation and the personalisation of the product both from a physical and electronic point of view.

The success of this work mainly results from the control strategy proposed and the Titech software developed.

A next planned innovation consists of a sonor feedback [17] which allows the patient to correct its contraction itself if the prosthesis doesn't react as he wants. We are also developing a hand with five mobile fingers. This product puts in action two additional fingers and allows a better catch (passive adaptability or passive compliance): the fingers will come to marry (changer) the objects' shape.

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