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Status of elbow myoelectric prosthesis: CINVESTAV-IPN prosthesis

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ABSTRACT

Advances of the prostheses had allowed people who lost an extremity to win back their normal life and live it with fewer limitations. Traditional commercial elbow prosthesis has at least two degrees of freedom: flexion-extension and humeral rotation; but the human arm has 22 degrees of freedom. Thus, it is important to realize that the prosthetics have a long way to go. Furthermore, the higher the amputation level, the greater the demands on the fitting technique. This work describes some elbow myoelectric prostheses of different characteristics, which have advantages and drawbacks. Also a current status of CINVESTAV-IPN prosthesis is described. The prosthesis is formed with a parallel mechanism of actuators. That allows an increase in the number of active degrees of freedom and therefore the range of motion. This enhancement let it carry out natural movements, which is a challenge in the evolution of prosthetics devices. Finally, a comparison of CINVESTAV-IPN prosthesis with others is discussed.

Key Words: Elbow myoelectric prosthesis, degrees of freedom, parallel mechanism, natural motion.

RESUMEN

Los avances en el diseño de prótesis han permitido a las personas que perdieron una extremidad regresar a su vida activa subsanando algunas limitaciones. Las prótesis de codo comerciales tienen al menos dos grados de libertad: flexión-extensión y rotación humeral; pero una extremidad humana tiene 22 grados de libertad. De esta manera, es importante comprender que la protésica tiene un largo camino por recorrer. Además, mientras más alto es el nivel de amputación, es mayor el nivel de funcionalidad que la prótesis requiere. En este trabajo se describen algunas prótesis mioeléctricas de codo con diferentes características, cada una tiene ventajas y desventajas. También, se describe el estado actual de la prótesis que se está desarrollando en el CINVESTAV-IPN. El mecanismo de está prótesis es un arreglo paralelo de actuadores. Esta innovación permite un incremento en el número de grados de libertad activos y por lo tanto el rango de movimiento. Además, con este sistema paralelo de actuadores la prótesis puede llevar a cabo movimientos de una forma natural, lo cual es un nuevo reto en la evolución de los dispositivos protésicos. Finalmente, se hace una comparación entre la prótesis del CINVESTAV-IPN y otras prótesis comerciales.

Palabras clave: Prótesis mioeléctrica de codo, grados de libertad, mecanismo paralelo, movimiento natural.

INTRODUCTION

Worldwide, every year the number of amputees increases in 150,000 to 200,000, which are added to the existing 4 millions; thirty percent of these amputees have suffered an upper limb amputation. Sixty percent of the arm amputations affect people between 21 and 64 years old; while a ten percent are patients under 21[1].

Myoelectric prostheses are powered by the muscle electric signals taken of the residual limb. The ideal solution for amputation would be the biological regeneration of the limb lost. So far, the technological advances do not allow this biological solution, so it is necessary to develop artificial systems to collaborate in the rehabilitation of the amputee in order to improve his or her quality life.

The needs that upper limb prosthesis must cover depend on the type of amputation that the patient had suffered. The degree of the amputation goes from the fingers, the hand, the wrist disarticulation, under the elbow with long, medium and short stump, elbow disarticulation, above the elbow with long, medium and short stump, shoulder disarticulation and scapular – thoracic disarticulation. Each one of them has different remnant movements and anatomic structures that allow different possibilities for prosthesis design.

Since 1948, Dr. O. Häfner has been experimenting with high level arm amputations and shoulder disarticulations using carbon dioxide for pneumatic prosthesis. In 1955 Dr. Ernst Marquardt joined the group and continued the prosthesis work. They confronted lots of troubles at the time; such as the external power supply, the type of control, the quality of the union between the body and the prosthesis, etc. this prosthesis had five basic requirements: 1) It must give all joint movements energy as close as possible to that of the natural power of an arm. 2) It must be capable of fine graduations and allow smooth and flexible transmission. 3) For small movements the control should require little power. 4) No power should be lost through continuous loading of joints. 5) The material used to provide power should not be expensive, heavy or bulky; it should be easily replenished and should last for at least one day without refilling when the prosthesis is in full time use.

In 1965, Dr. Marquardt had fitted more than 350 adults, juveniles and children, among them sixty small children, with pneumatic prostheses and in detailed follow-up examinations[2].

Myoelectric prostheses for amputations above the elbow present a particular difficulty: they have to substitute the functions of the hand, the wrist, the forearm and the elbow. These types of prostheses are called multifunction although they are limited to some movements due to difficulty of providing a simple control for the patient which, at the same time has to be trustworthy enough to be able to differentiate the instruction to activate each movement.

The challenge of the above elbow prosthesis is to cover all the functions mentioned above and, furthermore to give a natural appearance to the execution of the movements.

Currently, a myoelectric prosthesis for amputations above the elbow is being developed at the Bioelectronics Section from the Electric Engineering Department from the Center of Research and Advanced Studies from the National Polytechnic Institute (CINVESTAV-IPN), Mexico, D. F., (Figure 1). This prosthesis is made by different parts created in our laboratory of myoelectric prosthesis; and which are an electronic system for muscular training trough visual feedback, aimed to train the user of the prosthesis[3]; an interpreter of myoelectric signals[4]; and a system of activation of motors that move the mechanical structure[5].

In this work, the characteristics of the Utah arm and the Boston elbow are presented. Also, the current status of the CINVESTAV-IPN prosthesis is described. All advances presented solve some points which have been not considered in other prosthe-

Figure 1. Parallel system of the CINVESTAV-IPN prosthesis.

ses, for instance to add more actives degrees of freedom. Finally, a comparison of these and CINVESTAV-IPN prosthesis is discussed.

DEVELOPMENT

In this section of the paper, different kind of myoelectric prostheses are described; a brief history and their main characteristics are mentioned.

Otto Bock

Until the 1970's, the socket design and attachment essentially consisted of gluing together and laminating the wooden parts of the prosthesis. Since then, a steady movement toward a more modular-type prosthesis has taken place.

For many years the Otto Bock Company based in Germany held the exclusive patent to the pyramid and ball attachment system that was the foundation to endoskeletal modular system prosthesis. Over the years, other manufacturers have adapted their components, thus offering the prosthetist the ability to hybridize the Bock endoskeletal modular system to include several manufacturers' components.

These interlinking components make possible the multifunctional, multinational prostheses we see in use today by amputees around the world. Without these innovative components, such hybridized prostheses would not be possible[6].

Also, the German company Otto Bock[7] manufactures myoelectric prostheses of hands. The Otto Bock hand weights 540 g and can perform a force of 140 N.

These kinds of devices developed by Otto Bock are useful for the myoelectric prosthesis available in the market. Actually, the myoelectric hand of Otto Bock is a terminal device which is preferable for elbow prosthesis designers. For instance, Utah arm and Boston elbow are compatible with this terminal device.

Utah arm

Brief history

The Utah artificial arm was developed at the University of Utah in a laboratory started in 1974 by Dr. Stephen C. Jacobsen, Ph.D., and now called the Center for Engineering Design. The first version of the self-contained myoelectric elbow unit was introduced in December 1980.

The artificial arm evolved like follows: 1974, University of Utah research begun by S.C. Jacobsen, Ph.D.; 1975, multiple degree of freedom arm control experiments; 1978, prototypes of self-contained Utah Arm design; 1980, first Utah Arm fittings (myoelectric elbow); 1982, combines elbow/hand proportional control introduced; 1985, Utah Hand Controller introduced for below-elbow prostheses; 1988, Utah Arms fitted regularly at center in the United States, Canada, and Europe.

Currently, the Utah artificial arm can be provided by nearly any prosthetic fitting center, after a certified prosthetist had attended a 1-week training course conducted by the manufacturer, Motion Control, Inc.

Since 1985, amputees have been fitted with the proportional 12 V Utah Hand Controller, which is used with the Otto Bock hand mechanism. The 6V version replaced it in 1989. In contrast to the commonly used «myo switch» type of control, which simply turns the hand «ON» in one direction or the other, the proportional control provides the user with more sensitive slow and fast control of the hand, depending on the strength of muscle contraction. Below-elbow fittings of the system have installed the control circuitry just proximal to the wrist, with battery packs placed on the side of the forearm. By then, the system was appropriate for middle forearm or shorter amputations and for candidates of juvenile age or older. Powered wrist rotation was also available using the Otto Bock electric wrist. Control might be transferred between the wrist and hand using an external switch. The next version transferred control between hand and wrist by a rapid muscle contraction.

Since 1981, the Utah Arm has been the premier myoelectric arm for above elbow amputees[8]. In 1987, Motion Control released the Utah Arm 2, and in 2004, Motion Control introduced microprocessor technology into the Utah Arm 3 (U3), which delivers the same sensitivity, proportional control of elbow, hand and wrist letting the patient move the arm and hand slowly or quickly in any position. This functionality provides a more natural response with less effort for the patient than the traditional on/off movement. Since the Utah Arm 3 has two microprocessors, two functions can be controlled at once, producing a more natural movement.

Characteristics

The appropriate selection of the muscle to work with is highly important. Wrist flexor and extensor muscles are typically used, although supinator muscles have also been utilized in some very short below-elbow amputees. When fitted to above-elbow patients, biceps and triceps sites are typically used. Higher level amputees may require training and careful muscle selection.

About the socket, there are different kinds of fitting; the total contact socket in which suspension is provided by an harness, a silicon acromial cap with chest strap suspension which transfers more of the prosthesis load to the shoulder, a self-suspending, suction type, socket.

The size and strength of the prosthesis represent important characteristics that will impact whether the patient uses the prosthesis or not. The forearm length can be shortened up to 20.32 cm. It supports a load, during activity, of 1 kg in the terminal device, hand or hook. The arm weights 913 g without hand, and the hand weights 450 g, plus glove; the individual should be capable of supporting this amount of weight. The load limit is 22.7 kg with the elbow in a 90° flexion and 15.9 kg in the extended arm. The active lift is 1 kg in the terminal device and using a fully charged battery. The operation temperature is from 0 °C to 44 °C; the standard length of the forearm is 27.3 cm.

Currently, the Utah Arm elbow[8], without load, can rotate from 0° up to 135° in 1.2 seconds, approximately. The last model of the Utah Arm, distributed by Motion Control Inc., emulates simultaneous movements of the arm and the hand and connects to the body by using surface electrodes; plus a computational interface to carry out the arm calibration.

Training

Utah Arm user training should begin with muscle conditioning, then progress to control of the prosthesis, and then, finally, to progress to usage of the prosthesis in practical activities.

Learning to control the elbow and/or the hand of the prosthesis with the muscle signals may be very straightforward for many patients or it may require much practice by the amputee to develop smooth control. In the first step the patient learns differentiation of the two control muscles for elbow flexion/extension, or hand open/close. The hand, being the more sensitive component, may be the easiest to use initially, and the hand itself gives direct feedback to the patient. The second step involves learning elbow locking and unlocking with the Utah elbow control. For most patients we prefer to begin simply, with one component; we then add components and complexity as each level is mastered. Minimizing frustration and failure during the early stages is essential.

The practical use of the prosthesis can begin once control is mastered sufficiently to allow the performance of simple tasks. In step 1, simple tasks are approached, involving control of prehension with the terminal device. Step 2 of use training begins the performance of two-handed activities such as holding a paper while cutting with scissors and holding a glass while pouring into it. Attention should be paid to pre-positioning the passive joints for best performance of each task, including the wrist rotation and flexion and humeral rotation. Step 3 involves mastering the function of unlocking the elbow of the Utah Arm. Step 4 in the training process involves performing tasks appropriate to the amputee's daily life and should be tailored to the types of tasks performed in his work or home environment[9].

Boston elbow

Brief history

The Boston Elbow is an upper limb cybernetic prosthesis, and mathematician Norbert Wiener is considered its «godfather». Wiener's orthopedist at Massachusetts General Hospital, Melvin Glimcher had found in his work for Liberty Mutual Inc. that below-elbow amputees were using prostheses to recoup much more of their lost functioning than were above-elbow amputees. Even with the most advanced body-powered prosthesis, the above-elbow amputee had to: position and open or close the terminal device sequentially. The single-cable design did not allow for simultaneous execution of these two functions, and the result was unnatural body movements that were unattractive and inefficient.

The Boston Elbow Version I was produced in 1968 and made its debut at fall, with a press conference at Massachusetts General Hospital. They manufactured 18 Elbows Version 1, all with failures. The most serious problem was that the first Boston Elbow ran on a battery so large it had to be mounted on the wearer's belt. In 1974, modifications have been made and 25 working prostheses were manufactured. A batch of 100 Boston Elbows followed in 1976; these featured a slimmer forearm and more reliable electronics. In 1983, approximately 100 amputees wore Boston Elbows, which allowed elbow flexion and operation of the terminal device simultaneously.

The Boston digital arm system was introduced in 2001. The system incorporates microprocessor technology for improved performance and patient adjustment. It can control up to four other prosthetic devices in addition to the elbow itself, like hands, wrist rotators, shoulder lock actuators, etc. The terminal device is compatible with Otto Bock electric hand, Centri electric hand, Steeper electric hand, Otto Bock Greifer, Steeper powered gripper, body powered split-hooks, and Otto Bock electric wrist rotator.

The Boston digital arm system evaluates the patient for suitable muscle sites and then tries various control strategies until a proper one is found. This is accomplished through user-friendly graphical interface screen software. The software actualizes the control strategy by downloading it to the prosthesis, in less than 10 seconds. This software is also useful to easily diagnose problems and often fix it[10].

Characteristics

The Boston Elbow is a myoelectric prosthesis of elbow with one single active degree of freedom: the elbow flexion. It reproduces the active movement of the human elbow flexion and extension, but not, of course, other forearm movements such as pronation, supination and flexion or extension at the wrist. Also, it connects to the arm using superficial electrodes. The myoelectric hand and the wrist rotator of Otto Bock could be used as a terminal device. In addition, a divided hook terminal device activated by a cable could be used with this elbow. It is an endoeskeletal prosthesis.

The Boston Elbow looks like a complete arm, which extends from the wrist (to which various hooks and artificial hands may be attached) to a socket that fits the stump, but only the elbow joint moves.

Although any muscle can provide an EMG signal, the Boston Elbow is designed to tap residual biceps and triceps muscles, precisely those that would ordinarily flex and extend the arm. Thus an amputee's control of the prosthesis imitates control of the natural elbow[11].

The Boston Elbow is both myoelectric and proportional. So it moves at speeds directly proportional to the intensity of muscle contraction by the amputee. The forearm houses the batteries and electronics and offers the wearer a choice of terminal devices: a mechanical hook or hand controlled with a roll of the amputee's shoulder, or an electric or myoelectric hook or hand with switch control. The prosthesis has been designed so that hook and hand are interchangeable and may be used by the same wearer at different times[11].

The current Boston Elbow weighs 1.13 kg. It will lift 2.27 kg and hold something over 22.65 kg in a locked position. A fully charged battery will power the device for about 8 hours. The prosthesis has a range of 145 degrees, i.e., full flexion is 145 degrees from full extension, and this distance is traveled in a minimum of a second. The Boston Elbow has a 30-degree free swing that lends it a more natural appearance[11].

CINVESTAV-IPN MYOELECTRIC PROSTHESIS

Currently, a novelty myoelectric prosthesis prototype for above the elbow (Figure 1) is under development at the Bioelectronics Section of CINVESTAV-IPN, México. The project considers a myoelectric trainer[3], (Figure 2), mechanical structure and its control[5,12-14], and a myoelectric interpreter by mean of artificial intelligence[4]. Special actuators were designed for mechanical structure[13]. So, the structure of the prosthesis was formed by mean of an actuators parallel array. With this configuration 3 degrees of freedom at the elbow and the grasping function were obtained. All these are active movements: apprehension, prono-supination of forearm, flexion-extension of the elbow and humeral rotation[14]. It is important to notice that the prono-supination movements come from the elbow and not from the wrist as it happens for commercial prosthesis. Also, humeral rotation is a plus since it have not been reported on commercial prosthesis, and it is a movement that each amputated person loses.

The prosthesis prototype is shown in Figure 3 (it is mounted on a pedestal). In this prosthesis, the electronic instrumentation is contained at the level of the elbow, and the socket remains totally free to receive the patient stump.

The prosthesis dimensions fit within the range of dimensions of a human adult arm. It has a socket, made of polypropylene, long enough to receive long remnant limbs, like those of elbow disarticulation. The complete prosthesis weights 1,050 g; that is less than the recommendation of 1.5 kg for adults and less than some prosthesis available in the market. The prosthesis can be operated with batteries because its current demand is low, 400 mA with a 1 kg load[12-14]. The force is sufficient to realize everyday activities. The parallel mechanism allows enough mobility range to carry out activities of daily living. Therefore, the prosthesis has the possibility to develop natural movements as a healthy upper limb.

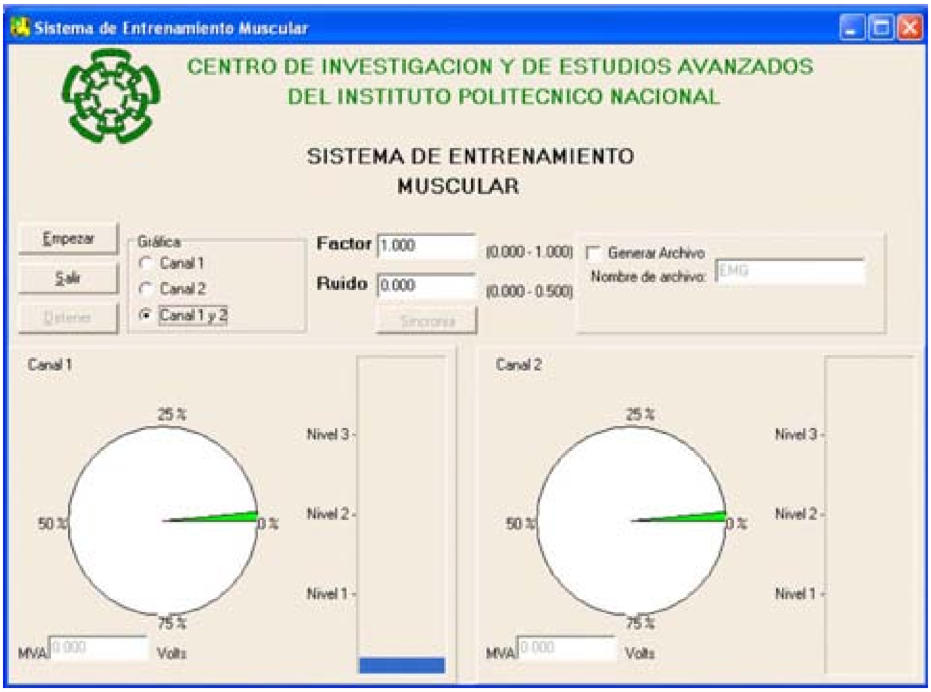

Figure 2. Myoelectric trainer. Muscular activity of each user is showed by mean of graphics.

Figure 3. CINVESTAV-IPN Prosthesis prototyped mounted on a pedestal and controlled by a RS-232 interface.

This prosthesis has some novel characteristics in the area: it is lighter and has more active movements than those commercially available of the same kind; it is the first prosthesis with parallel actuators and active humeral rotation; and its lineal actuators fulfil the needs of volume, weight and efficiency required in prosthetics[12-14].

Table 1 presents a comparison between commercial myoelectric prosthesis and CINVESTAV-IPN prosthesis. It shows the principal characteristics of each device. The active movements at elbow of CINVESTAV-IPN prosthesis were possible due to the parallel mechanism, which allowed us to emulate natural movements, proper of daily life activities.

DISCUSSION

Boston Elbow and Utah Arm are prostheses commercially available and have various characteristics that are suitable for diverse needs. They offer valuable features according to the requirements of the upper limb above the elbow amputees. So, they are considered functional prosthesis. From that point of view CINVESTAV-IPN prosthesis is functional too, since it can to carry out the same kind of movements. Another contribution is with respect to design, in these commercial prostheses, the motor responsible of the elbow flexion has to burden with the load of the other motors. In this way, seen from the elbow articulation, the motors that drive the grasping or the prono-supination are a death load. In this sense, in the parallel mechanism any motor has to lift any other since all motors are in the proximal side of the forearm, i.e., all motors are attached

Table 1. Comparison among myoelectric prosthesis.

Characteristics \ Prosthesis	Utah Arm Motion Control Inc.	Boston Elbow	CINVESTAV-IPN
Range of movement (Degrees)	Flexion 0° - 135° Prono-supination 360° Humeral rotation unlimited	Flexion 0° 145° Prono-supination 90°	Flexion 10°-115° Pronation 90° Supination 90° Internal humeral rotation 45° External humeral rotation 45°
Types of movement (P = Passive, A = Active)	Flexion-extension (A), Humeral rotation (P)	Flexion-extension (A)	Prono-supination (A), Flexion-extension (A), Humeral rotation (A)
Degrees of freedom at elbow	2	1	3
Weight	913 g without hand	1,100 g	1,050 g
Actuators movement	Sequential	Sequential	Parallel
Lifting weight	1 kg	2.3 kg	2 kg
Power supply	12 V	12 V	24 V

directly to the elbow. And, in order to move a load, at least two motors must work together in parallel.

Both Boston Elbow and Utah Arm can receive the Otto Bock myoelectric hand. The prototype of developed prosthesis is not compatible with this hand, but it has a terminal device, which perform grasping function. A common characteristic is that these elbow prostheses are just manufactured for adults.

Finally, a new challenge in the future of the elbow prostheses is the natural motion.

The aim is that the prostheses perform similar movements as a healthy upper limb. Boston Elbow and Utah Arm have been changing since its first design and the solution considered was the simultaneous activation of the elbow and the wrist or hand. This innovation has been presented in 2004[8]. By other hand, the configuration of the proposed prosthesis allows to perform natural motion. An important difference with respect to the others prostheses is that the prono-supination is evocated from the elbow not the wrist.

CONCLUSIONS

Two options of elbow prostheses available in the market were presented. Furthermore, a description of the CINVESTAV-IPN prosthesis was given. As a result, the prototype developed, satisfies functionality aspects considered by others.

Myoelectric prostheses eliminate control cables, this result in comfort to patient, they are easy to use even in high level amputees, and they have good hand functions and excellent cosmetic appearance. However, the soft and natural movements that a human arm can perform have an enormous complexity; the current prostheses have achieved the reproduction of lots of these movements in the last years.

The fact that the CINVESTAV-IPN prosthesis weights 1,050 g is an important result because it is lighter than the commercial ones. This is remarkable due to the fact that most of patient abandoned the use of prosthesis because of their weight, they are heavy. Furthermore, the parallel mechanism is useful for the reproduction of natural movements. This allows the prono-supination function at the elbow which is more natural. Normally, this function is at the wrist in the commercial prostheses.

As a part of the project CINVESTAV-IPN prosthesis a myoelectric trainer with visual feedback was developed (Figure 2). The system records the myoelectric signals in the remnant limb and shows the patient how much strength he or she is reaching. The software has 3 discernible levels of strength that the patient is asked to reach. The visual feedback helps the patient to accomplish these levels[3].

Summing up, CINVESTAV-IPN prosthesis has novel characteristics and is being developed as a complete system. We have a training system for the patient to reinforce the lost strength and control in the limb; we have prosthesis of light weight with 3 active degrees of freedom and grasping function;

it moves in a more natural fashion, evocating prono-supination from the elbow and activating actuators in parallel. Artificial intelligence is being used for the myoelectric signal processing in the interpreter, between the amputee and the prosthesis, associated to the control[4].

As a future work, it may be incorporated to this prosthesis movement prediction software that is in current develop.

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