Neuroprostheses for grasping

Milos R. Popovic*[†], Dejan B. Popovic[‡] and Thierry Keller[§¶]

*Institute of Biomaterials and Biomedical Engineering, University of Toronto, Canada
[†]Toronto Rehabilitation Institute, Canada
[‡]Center for Sensory–Motor Interaction, Aalborg University, Denmark
[§]Automatic Control Laboratory, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
[¶]ParaCare, University Hospital Zurich, Switzerland

In recent years a number of neuroprostheses have been developed and used to assist stroke and spinal cord injured subjects to restore or improve grasping function. These neuroprostheses clearly demonstrated that the targeted group of subjects can significantly benefit from this technology and that functional electrical stimulation (FES) is a viable method for restoring or improving grasping function. In this article the FES technology is briefly explained and some of the better known neuroprostheses for grasping are discussed. Furthermore, a typical population of subjects that can benefit from this technology is indicated as well as the methodology to select and train these subjects to apply the neuroprosthesis in daily living activities. This article also provides a brief summary of the achieved results with the existing neuroprostheses for grasping and discusses some of the challenges this technology is currently facing. [Neurol Res 2002; **24**: 443–452]

INTRODUCTION

One of the most promising developments to improve grasping function in subjects with cerebro vascular accident (CVA – stroke) and spinal cord injury (SCI), who have permanent hand impairment, is Functional Electrical Stimulation (FES). In recent years a number of neuroprostheses for grasping have been introduced and some of these systems, such as the Freehand system[1] and the Handmaster[2], have achieved significant success. Despite these successes the neuroprostheses for grasping are seldom used in rehabilitation centers and thus far have made a limited impact on rehabilitation in stroke and SCI subjects. The general perception among clinicians is that this technology is not fully matured and that its application is often labor intensive while the favorable outcome cannot be guaranteed. The limited application of the FES technology in rehabilitation could be explained by the fact that both patients and their families often have over-expectations from the assistive systems, yet after initial enthusiasm become disappointed since results do not match their aspirations and hopes.

Nevertheless, the neuroprosthesis for grasping is an important tool in the rehabilitation of stroke and SCI subjects, and these subjects in most cases benefit greatly from this technology because of the training and the short- and long-term changes that occur within the central nervous system[3]. Our experience strongly suggests that the neuroprosthesis for grasping can be successfully used either as a neurorehabilitation system that promotes recovery and better hand function in incomplete SCI and stroke subjects, or as a permanent orthotic device for complete cervical lesion SCI subjects to augment the grasp and manipulation functions required for typical activities of daily living (ADL). This article highlights the actual state of art in the field and suggests both the indications and the limitations of this technology in restoring grasping function.

TECHNICAL BACKGROUND

A neuroprosthesis for grasping is a device that could improve or restore the grasping, holding, and reaching functions in subjects with stroke and SCI[4]. The neuroprosthesis applies FES to artificially generate muscle contractions required to perform reaching and grasping tasks in subjects who have lost voluntary control of these muscles through disease or injury. The FES is a technique that uses bursts of short electric pulses (pulse width 0–250 μsec and pulse amplitude 10–150 mA) to generate muscle contraction by stimulating motoneurons or reflex pathways. The key element for achieving synergistic activity of muscles that results with reaching and grasping is the appropriate sequencing of bursts of electrical pulses.

The available neuroprostheses for grasping enable the restoration of the two most frequently used grasping styles, the palmar and the lateral grasp[5]. The palmar grasp is used to hold bigger and heavier objects such as cans and bottles, and the lateral grasp is used to hold smaller and thinner objects such as keys, paper, and floppy disks. The lateral grasp is generated by first flexing the fingers to provide opposition, which is followed by the thumb flexion. The palmar grasp is generated by first forming the opposition between the thumb and the palm, which is followed by simultaneous flexion of both the thumb and the fingers. Finger flexion is performed by stimulating the *flexor digitorum super-*

ficialis m. and the *flexor digitorum profundus m.* Finger extension is obtained by stimulating the *extensor communis digitorium m.* Stimulation of the thumb's thenar muscle or the median nerve produces thumb flexion.

The FES can also be applied to generate elbow extension by stimulating the *triceps brachii m.*[6,7]. Such elbow extension in combination with the voluntary biceps contraction can be used to augment the reaching. The FES could be used to stimulate elbow flexion (*biceps brachii m.*), or even the shoulder muscles to provide upper arm movements, yet these systems have not been developed into practical devices.

To achieve a continuous contraction of hand and arm muscles (tetanization) a FES system has to deliver at least 16 stimulation pulses per second. These stimulation pulses elicit action potentials (AP) in the motor nerve, thereby causing the corresponding muscle to contract. If less than 16 AP per second are induced into the motor nerve the muscle generates a series of twitches that occur with delay and have the same frequency as the stimulation pulses, instead of fused smooth contraction. To have a tetanic contraction many muscles require more than 16 AP per second. Since generation of AP and their propagation occur in the axons, the motor nerves of the stimulated muscles have to be intact. If axons are missing, a muscle becomes denervated and it cannot generate functional force by means of FES[8]. The motor nerves can be stimulated using monophasic and biphasic current or voltage pulses[8]. The monophasic pulses are used only with the surface electrodes because they lead to unbalanced charge delivery to the tissues, potentially causing damage due to the galvanic processes. The majority of FES systems implement biphasic current or voltage pulses, or so-called monophasic compensated pulse shapes[8].

The motor nerves can be stimulated using either surface (transcutaneous), percutaneous, or implanted electrodes[8]. The transcutaneous stimulation is performed with self-adhesive or nonadhesive electrodes that are placed on the subject's skin in the vicinity of the motor point of the muscle that needs to be stimulated[4,8]. The percutaneous and fully implanted electrodes are placed close to the entry point of the motor nerve to the muscle which should be stimulated. Percutaneous electrodes are either epimysial[9] or intramuscular[10,11]. More recently cuff electrodes[12,13] have been introduced for FES systems. Implanted electrodes compared to surface electrodes guarantee higher stimulation selectivity with much less electrical charge applied, both being desired characteristics of FES systems[8,14].

PATIENTS, CLINICAL INDICATIONS AND APPLICATION

Patients

The neuroprosthesis for grasping is most frequently used to help SCI and stroke subjects to restore or promote the recovery of the grasping function. In the case of SCI subjects, the population that benefits the most from the

neuroprosthesis for grasping is C5–C7 complete SCI subjects. For this population of SCI subjects the hand function is essential for achieving a high level of independence in ADL. Typically, they have the function of the proximal upper limb muscles sufficiently preserved that allows them to perform the reaching tasks, while their impairment prevents them from voluntarily grasping and holding objects. The neuroprosthesis for grasping in SCI subjects is frequently used as a permanent orthotic device that provides them with the grasping function in ADL. Only a limited number of SCI patients uses the neuroprosthesis to retrain grasping and holding functions, and are later not obliged to wear it to perform these tasks in ADL[5,15].

To apply FES in SCI subjects to generate a function one has to ensure that the central paresis of the muscles that need to be stimulated is prevailing. In other words, there should not be a major degree of motoneuron or nerve-root damage of the stimulated muscles. In general, the C5–C7 complete SCI subjects frequently fall into this group of subjects and that is why the neuroprosthesis has been found effective in assisting and restoring grasp in these subjects. Since a considerable number of C5–C7 SCI subjects suffer from partial or complete peripheral nerve damage around the lesion (motoneurons and nerve-roots), one has to determine the extent of this damage as it restricts the application of FES[16–20]. The best way to assess the extent of peripheral nerve damage and consequently the potential application of FES is by means of neurographic recordings[21].

In stroke subjects one arm is fully functional while the other arm is affected because of the CVA. Hence, in these subjects the hand function of the more affected arm is not as critical as in the case of SCI subjects. The stroke subjects have a prevailing central paresis of the muscles that need to be stimulated and have no motoneuron or nerve-root damage. Hence, from the point of view of the neuroprosthesis application stroke subjects are ideal for the FES treatment. Note that these subjects, unlike the SCI subjects, often feel an unpleasant sensation during the electrical stimulation, because the sensory mechanisms are intact. Therefore, one has to carefully choose the stimulation intensity, pulse frequency and shape to achieve good functional results while the discomfort due to stimulation is minimized. It is also important to mention that stroke subjects often suffer from spasms that can result in contractions which can hinder them in performing grasping task. Since the stroke subjects still have one functional hand the neuroprosthesis in these subjects is mainly used as a neurorehabilitation tool to promote and speed the recovery of the grasping and reaching functions[3].

Grasping function

In principal, the grasping function can be differentiated into holding and object manipulation tasks that can be further differentiated in mono- or bi-manual handling tasks. Two main objectives in applying the neuroprosthesis for grasping are either to create a

reliable and long lasting power grasp or to generate a smooth pulp–pinch grasp that is used to manipulate small objects (for more details of how these grasps are generated with FES consult Technical Background section). Regardless of the applied grasping strategy it is essential that it can be easily commanded by the subject and that the strength of grasp can be adjusted during grasp.

The subjects that are trained to use the neuroprosthesis for grasping can be divided into two main groups, those who have a part of the grasp function preserved and those who cannot voluntarily contract any muscle below the elbow. In the case of the first group of subjects the objective is to use the preserved function as much as possible, and only to augment it by means of FES. For example, subjects who have voluntary control of the wrist extension can be trained to perform the tenodesis grasp. The tenodesis is a passive grasp obtained by extending the wrist. Due to shortening the length of finger flexors a voluntarily extension of the wrist leads to passive finger flexion (e.g. C6–C7 SCI subject). In these subjects the neuroprosthesis is used to enhance the tenodesis grasp by stimulating the finger flexors when the subject voluntarily extends the wrist. When the subject voluntarily flexes the wrist, the finger extensors are stimulated generating hand opening. In the case of subjects who cannot voluntarily contract muscles below the elbow the neuroprosthesis is used to generate the grasp as discussed in Technical Background section. Regardless of the type of subject and how the neuroprosthesis is used to assist grasp, while supporting the hand function the FES system should not interfere with the subject's preserved upper limb function, such as wrist extension or the ability to position the arm/hand at the desired place. Furthermore, the hand and arm movements generated by FES should be carried out in a physiological way and the FES-induced movements should not oppose natural joint movements (i.e. they should respect the anatomy of bone and soft tissue composition).

It is important to mention that one cannot simply predict the most appropriate neuroprosthesis for grasping for a treated subject from his/her level of neurological lesion. The acceptance of the devices very much depends on specific needs of the subject. Therefore, one has to evaluate various grasping strategies before the most functional FES grasp for the subject is identified. In addition, during FES training one can observe improvements reflected in better hand closure, more natural way of holding objects, stronger grasping force and reduced fatigue. For the subjects to fully benefit from these improvements the stimulation program and parameters should be constantly adjusted during the treatment such that efficient grasping function is obtained with the minimum stimulation intensity. In addition, both SCI and stroke subjects that are trained with the neuroprosthesis should be periodically assessed by scores in ADL such as the functional independence measurements (FIM), spinal cord independence measure (SCIM)[22] and Wuolle et al.'s grasp and release test[23] to quantitatively assess their functional improvements.

Type of FES application and its timing

Typically there are two approaches towards FES application and they are very much determined by the population of subjects that is treated and by the applied FES technology. In stroke subjects one can only apply surface FES systems since the objective of the treatment is to help patients relearn the grasping task rather than to provide them with a permanent assistive system. In SCI subjects there are two possibilities:

1. Use of an implanted FES system. These devices should only be applied once the patient reaches stable neurological status (neurological recovery is finished) and no further significant improvements of function are expected. Therefore, the implanted FES systems are usually applied to SCI subjects two or more years after trauma.
2. Use of surface FES systems. This approach allows one to introduce FES training during the early rehabilitation period because the technology does not require the subject to be 'neurologically stable' and the neuroprosthesis can be removed from the training program at any time without adverse effects on the subject.

Our experience indicates that an early application of FES treatment is preferred since subjects can train with the FES system during the early rehabilitation period[5]. If the FES treatment is administered in addition to conventional occupation and physical therapy during early rehabilitation phase, subjects tend to learn skills required to perform grasp much easier compared to the situation when a neuroprosthesis treatment is not administered. In addition, some of the SCI subjects who were trained with a neuroprosthesis for grasping during early rehabilitation sufficiently improved their function that they did not need a FES system to perform grasping in ADL. The subjects who were subjected to the 'early' FES training and were still dependent on the neuroprosthesis to perform grasp six months after the training onset, often performed better than the patients that were trained with the system two or more years after the injury. Patients that daily used a surface FES system to perform grasp in ADL six months after the training was completed, should be advised about the existing commercially available implanted neuroprosthesis. Medical doctors, occupational therapists and psychologists working with the subject should assist him/her and his/her family to decide which of the existing systems is most appropriate for the subject and his/her needs.

Application procedure

Typically, the application process starts with a muscle strengthening program that lasts from one to five weeks (depending on the subject's muscle condition and muscle response to electrical stimulation). Close to the end of the muscle strengthening program several grasping strategies are tested with the surface FES system to evaluate which one can be potentially applied to the patient in ADL. Once a decision is made regarding the
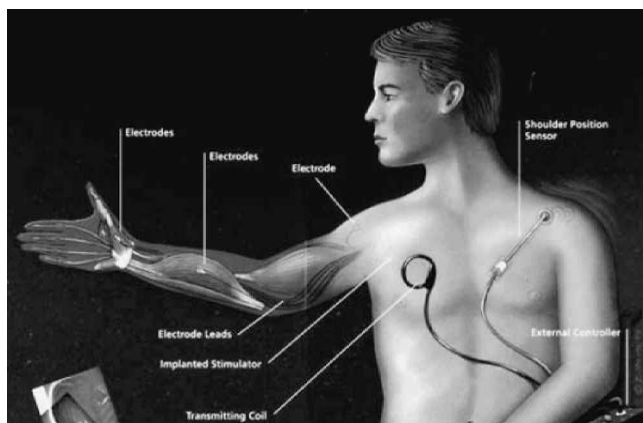
Figure 1: Freehand system by NeuroControl Corporation, USA (adapted from *The NeuroControl Freehand System*, NeuroControl Co.)

grasping strategy the functional training is introduced and the achieved function is repeatedly evaluated. During the functional training, which occurs daily, the stimulation intensity, duration and frequency is constantly adjusted to achieve best performance with negligible muscle fatigue. It is important to mention that in some subjects such as those who have partially denervated muscles one needs between one and two months of daily FES training before repeatable grasping function is obtained. It is essential to have a repeatable grasp prior to initiating functional training in ADL. Typically, we use this training phase to prepare the system for the subject to take it home. Once repeatable grasp is obtained, the subject should be only trained to apply the function in ADL and should be encouraged to use the system during the whole day.

Several follow-up measurements have to be carried out to provide evidence of whether the FES application improved the desired function and to which extent. Relevant criteria in assessing FES-assisted grasp are that movements are performed faster, with higher repeatability, and that the subjects perform them more easily compared to performing the same function without the neuroprosthesis.

NEUROPROSTHESES FOR GRASPING

Neuroprostheses for grasping are FES systems designed to restore or improve grasping function in tetraplegic and stroke subjects. The best known grasping neoroprostheses are the Freehand system[9], Handmaster NMS-1[2], Bionic Glove[24], NEC FESMate system[11], ETHZ-ParaCare neuroprosthesis[5], and the systems developed by Rebersek and Vodovnik[25] and Popovic et al.[7]. Except for the Freehand and NEC FESMate systems all other neuroprostheses for grasping are FES systems with surface stimulation electrodes.

Freehand system

The Freehand system[9] (NeuroControl Co, Cleveland, OH, USA), has eight implanted epimysial stimulation electrodes and an implanted stimulator (*Figure 1*). The stimulation electrodes are used to generate flexion and extension of the fingers and the thumb in C5 and C6 SCI subjects in order to provide them with lateral (key pinch) or palmar grasp. The stimulation sequences that are used to generate both palmar and lateral grasps are individually tuned and are pre-programmed in the form of a 'muscle contraction map'. The hand closure and the hand opening are commanded using a position sensor that is placed on the shoulder of the subject's opposite arm. The position sensor monitors two axes of shoulder motion, protraction/retraction and elevation/depression. The control strategy can be varied to fit different shoulder motion capabilities of the subject. Typically, the protraction/retraction motion of the shoulder is used as a proportional signal for hand opening and closing. The shoulder elevation/depression motion is used to generate logic commands that are used to establish a zero level for the protraction/retraction command and to 'freeze' the stimulation levels until the next logic command is issued. An additional switch is also provided to allow a user to choose between palmar and lateral grasp strategies. The shoulder position sensor and the controller are not implanted. Besides this sensor configuration, the Freehand system also allows one to use either external or implanted transducer mounted on ipsilateral wrist. This transducer measures the dorsal/volar flexion of the wrist and uses this motion to control hand opening and closing in a way similar to the shoulder position sensor (*Figure 2*)[26,27]. The output of the shoulder or the wrist sensor is sent to an external control unit that generates an appropriate stimulation sequence for each stimulation electrode. This sequence is then sent via an inductive link to an implanted stimulator that generates the stimulation trains for each implanted stimulation electrode.

The electrode leads are tunneled subcutaneously to the implanted stimulator located in the pectoral region. The surgical procedures to enhance both voluntary and stimulated hand functions are often performed in conjunction with the stimulator implantation. More than 200 tetraplegic subjects have received the Freehand neuroprosthesis at more than a dozen sites around the world. The subjects have demonstrated the ability to grasp and release objects and to perform ADL more independently when using the neuroprosthesis. The Freehand system is the first neuroprosthesis for grasping approved by the USA Food and Drug Administration (FDA). The FDA-approved Freehand system neither supports the above mentioned implanted transducer that is mounted on ipsilateral wrist nor the data transfer from the implanted stimulator to the external control unit. These features will be available in the next generation of the Freehand system.

One of the main advantages of the Freehand system is that it is implanted and the time needed to put on (donning) and to take off (doffing) the system is shorter compared to the majority of the surface stimulation FES systems (donning of the Handmaster system is faster). On the other hand, the patients are often subject to an additional surgery that is required to replace failed
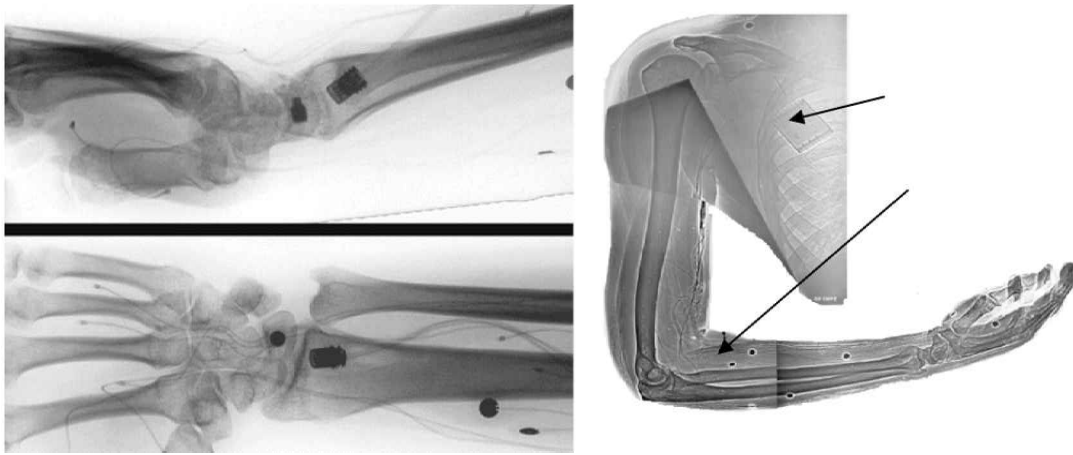
Figure 2: Xerogram of the implanted wrist joint transduced based on the Hall-effect sensor (left). The Freehand system with the Hall-effect sensor (right). (Adapted from reference 12 with permission)

hardware components or to correct the positions of the stimulation electrodes.

The next generation of the Freehand system is under development at the Case Western Reserve University, Cleveland, OH, USA. Its implantable stimulator/tele-meter system will extend the capabilities of the existing Freehand stimulator by increasing the number of stimulation channels and by allowing information about the muscle activation and the stimulator's operational status to be fed back to the computer via telemetry. The increased number of stimulation channels would facil-itate increased flexibility to control muscles and would allow the neuroprosthesis to facilitate reaching function in addition to the already existing grasping function. The system will also include a new implantable transducer that would allow the stimulator to sense movements of the wrist or the shoulder joint.

NEC FESMate

In the early 80s the Sendai FES group led by Handa developed a microcomputer-controlled neuroprosthesis for grasping and walking. Soon after that Handa's team proposed the second FES system with 16 percutaneous intramuscular stimulation electrodes that was both portable and programmable[11]. This system consisted of a NEC PC-98LT personal computer and an external microcontroller-based stimulator. The stimulator applies trapezoidal stimulation patterns to generate muscle contractions. The stimulation patterns were 'cloned' from the muscle activity recorded during voluntary grasping movements of able-bodied subjects. This early Sendar stimulator generates monopolar constant voltage stimulation pulses ranging from 0 to -15V, and the stimulation sequences are triggered with a push button or a pneumatic pressure sensor. The subsequent version of the same system had 30 stimulation channels. This system demonstrated that SCI subjects with complete C4–C6 spinal cord lesion could achieve both reaching and grasping functions[11].

Since 1994 in collaboration with NEC Inc. the Sendai FES team developed a fully implantable 16-channel electric stimulator NEC FESMate. Two hundred of these stimulators were manufactured[28]. The concept of the NEC FESMate system is similar to the preceding Sendai stimulator. The main difference is that the new system has an implanted stimulator and implanted stimulation electrodes. Unlike the Freehand system the NEC FESMate neuroprosthesis is not available outside Japan.

Neuroprosthesis developed by Rebersek and Vodovnik

The neuroprosthesis developed by Rebersek and Vodovnik[25] was one of the first FES systems for grasping. This neuroprosthesis has three stimulation channels (two stimulation electrodes per channel), which are used to generate the grasping function by stimulating the finger flexors and extensors, and the thumb flexors. Although this device was developed almost three decades ago it is one of the rare FES systems that allows a subject to control the stimulation intensity via different sensory interfaces such as EMG sensor, sliding resistor and pressure sensor. As a result, the subject can choose the most appropriate command interface to control the neuroprosthesis. The option to choose the neuropros-thesis control interface is important since it allows one to tailor the neuroprosthesis to the subject. The main disadvantages of this neuroprosthesis are that donning and doffing times are long, and that the selectivity of stimulation is rather low. A modification of the system was applied by Merletti *et al.*[29] in stroke subjects. Merletti *et al.* applied a two-channel functional elec-trical stimulation (FES) in order to augment the elbow and finger/wrist extensions. The conclusions were that FES contributed greatly to recovery of hand and elbow movements in five stroke subjects, yet in the remaining three the improvement was significant only at the elbow joint. To the best of authors' knowledge the neuropros-thesis developed by Rebersek and Vodovnik and later modifications are not commercially available.
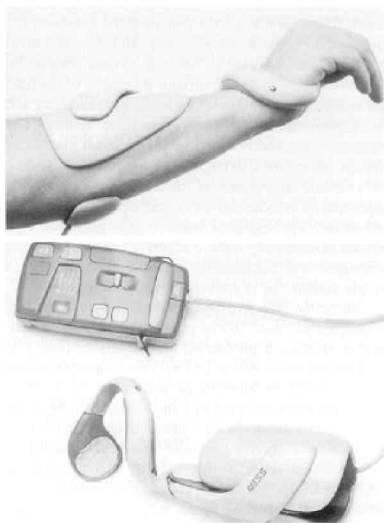
Figure 3: Handmaster neuroprosthesis by NESS Co., Israel (courtesy of Dr Roger Nathan)

Handmaster – NMS-1

The Handmaster (Ness Ltd., Raanana, Israel) is a neuroprosthesis for grasping with three surface stimulation channels that was developed by Nathan *et al.*[2,30] (*Figure 3*). The system is used to generate grasping function in tetraplegic and stroke subjects. One stimulation channel is used to stimulate the *extensor digitorum communis m.* at the volar side of the forearm. The second channel stimulates the *flexor digitorum profundus m.* and the *flexor digitorum superficialis m.* The third stimulation channel generates the thumb opposition. The Handmaster is controlled with a push button that triggers the hand opening and closing functions. Two switches are connected in parallel, one mounted at the stimulator box and the other at the plastic ortosis that houses the electrodes. The subject pushes one or the other button according to his activity and abilities. By pressing the push button the stimulator turns on and after a short time delay extends the subject's fingers for a short period of time followed by the thumb and finger flexion. The fingers and thumb remain flexed until the subject presses the push button for the second time. The consecutive activation of the push button generates finger extension that lasts a predefined period of time followed by switching off of the stimulator. An additional sliding resistor, which is built into the control box, allows the subject to regulate the intensity of the thumb opposition stimulation. This feature helps the subject to adjust the grasp to the size and the shape of the object he/she wants to grasp. In addition, the subject can increase or decrease the grasping force using two additional push buttons on the control box.

Originally the Handmaster was envisioned as an exercise and rehabilitation tool, but it is also used as a permanent orthotic system. One of the advantages of the Handmaster is that it is easy to don and doff. The Handmaster is predominately used as an exercise tool

for stroke subjects and is commercially available in several countries around the world. One of the disadvantages of the Handmaster is that it does not provide the user with sufficient flexibility to vary the position of the stimulation electrodes. Another limitation of the Handmaster is its stiff orthosis that fixes the wrist joint angle. In particular, the subject cannot perform full supination when he/she wears the system. Despite these shortcomings the Handmaster is exceptionally well designed and is one of the best neuroprosthesis for grasping that is commercially available.

Bionic Glove

The Bionic Glove[24] is a neuroprosthesis designed to enhance the tenodesis grasp in subjects that have a voluntary control over the wrist flexion and extension (*Figure 4*). These subjects can by extending a wrist cause passive finger flexion due to the limited length of the finger flexors. Typically C6–C7 SCI subjects are able to apply tenodesis grasp. The grasp generated with tenodesis is rather weak and its strength is very limited. In addition, to hold an object using tenodesis grasp it is necessary to maintain the wrist extension during the entire duration of the object manipulation, and that is often very difficult to do. By stimulating finger flexors and extensors during tenodesis grasp, the Bionic Glove can significantly enhance the strength of the grasp. The Bionic Glove applies a position transducer attached to the wrist to detect voluntary wrist flexion and extension. When the patient flexes the wrist, the finger extensors are stimulated causing hand opening. When the patient voluntarily extends the wrist the finger flexors are stimulated to provide hand closure. A dead-zone (hysteresis) allows movement of the wrist once the 'open' or 'close' stimulation pattern is activated. The

Figure 4: Bionic Glove developed by Prof Arthur Prochazka from the University of Alberta, Canada (courtesy of Prof Arthur Prochazka)

Figure 5: The Belgrade Grasping System (BGS) used by an incomplete C5 SCI subject for reaching and grasping (left). The position of electrodes for grasping function (right)

electrical stimulation is provided via three self-adhesive surface stimulation electrodes that are placed over the muscles' motor points, and a balancing (anodic) electrode that is placed proximal to the wrist crease. Each stimulation electrode has a metal stud on its back that is connected to one of four stainless steel meshes placed inside the neoprene glove above the expected electrode positions. The stimulator and the position sensor used by the glove are located on the forearm part of the glove. An easy-to-use interface with three pushbuttons on the stimulator is used to set the stimulation parameters and the optional audio feedback that facilitates faster learning.

Clinical evaluation of the Bionic Glove[15] indicated that this neuroprosthesis is beneficial to tetraplegic subjects but that the overall acceptance rate for long term use is at about 30% of potential users. In particular, the power grasp and the handling of big objects were significantly improved. One of the conclusions was that the control, and donning and doffing of the stimulator have to be improved, as well as its cosmetics. A clinical trial carried out at ParaCare located in Zurich, Switzerland, showed similar acceptance results but had also indicated that the location of the stimulator on the glove is not optimal since the forearm is exposed to frequent impacts against objects (our patients often use the forearm to hit doors and drawers in order to close them). The Bionic Glove was available only for clinical evaluation from the University of Alberta, Edmonton, Canada, and it is presently being modified into a new version of the system called Tetron. This new system should provide several grasping patterns and strategies, and should resolve several of the above-mentioned design problems.

Belgrade Grasping–Reaching System

The Belgrade Grasping–Reaching System (BGS) proposed by Popovic *et al.*[7], represents a neuroprosthesis for grasping that also provides reaching function (*Figure 5*). The BGS has four stimulation channels, three of which are used to generate the grasping function, and the fourth channel is used to stimulate the triceps brachii muscle to allow the subject to extend the elbow in order

to reach objects he/she otherwise cannot reach. The grasping function is controlled via a push button that triggers the hand opening and closing. The grasping is separated into three phases: prehension that forms the correct aperture; relaxation that allows the hand to get in good contact with the object; and closing the hand by opposing either the palm and the thumb, or the side of the index finger and the thumb. The releasing function includes two stages, opening of the hand and resting. The reaching function is achieved by measuring the subject's shoulder velocity with a goniometer and by generating a synergistic elbow motion by stimulating the triceps brachii muscle. The BGS allows one to select the duration of each of the phases of the grasp–release task to fit the individual needs and preferences of the subject. The BGS system, similar to the system proposed by Rebersek and Vodovnik[25], requires more time to place the electrodes compared to the Handmaster system[2] and it is not yet commercially available.

The BGS system was not the only neuroprosthesis that facilitates both reaching and grasping functions. The Cleveland group also successfully combined the grasping and reaching functions using the Freehand system[6,26]. Unlike the BGS their neuroprosthesis measures the position of the arm in space and for certain arm positions it automatically triggers stimulation of the triceps brachii muscle. In parallel with the triceps brachii muscle stimulation, the subject has to voluntarily contract the biceps muscle to control the position of the arm.

ETHZ–ParaCare neuroprosthesis

The ETHZ–ParaCare neuroprosthesis was designed to improve grasping and walking functions in SCI and stroke patients[5] (*Figure 6*). This surface stimulation FES system is programmable, has four stimulation channels, and can be interfaced with any sensor or sensory system. The ETHZ–ParaCare neuroprosthesis is used to develop the custom-made neuroprosthesis that can be used in ADL. The ETHZ–ParaCare neuroprosthesis for grasping can provide both palmar and lateral grasps. The system can be controlled with proportional EMG, discrete EMG, push button, and sliding resistor control strategies[5,31,32].
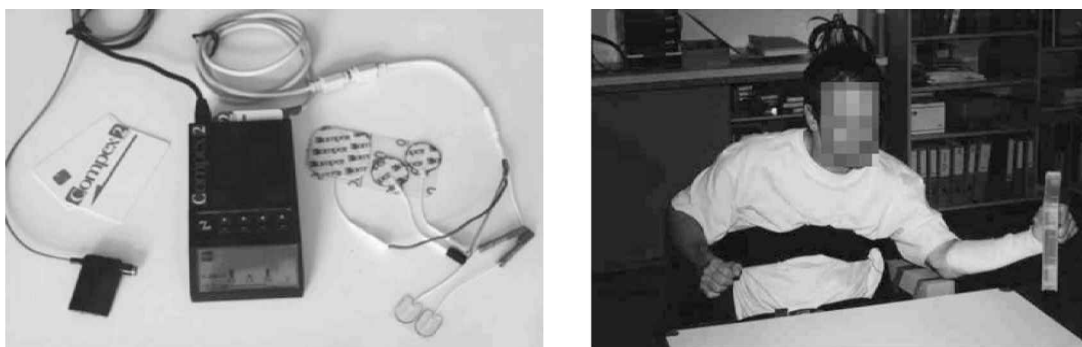
Figure 6: The ETHZ-ParaCare neuroprosthesis for grasping. Left, complex motion stimulator; right, tetraplegic subject

Thus far, more than 12 patients used the system. Four patients used the neuroprosthesis at home in daily living activities. One of the main disadvantages of this system is that it requires between 7 min and 10 min to don it and doff it. This problem is currently being addressed with the development of a glove that will house the stimulation electrodes and the command sensors. The system is not yet commercially available. Current efforts are aimed at completing a new generation of the neuroprosthesis that could be used for all FES applications involving surface stimulation electrodes. This is a collaborative project between ParaCare and the University Hospital Zurich, the Rehabilitation Engineering Group at the Swiss Federal Institute of Technology Zurich, and Compex SA, all located in Switzerland. The new neuroprosthesis is called Compex Motion and its beta version was scheduled to become available at the end of 2002[33].

DISCUSSION

Achieved results

The neuroprostheses for grasping discussed above have all demonstrated in clinical trials that they can improve grasping function in stroke and/or SCI subjects. These systems confirmed that the FES technology can facilitate comfortable and secure grasp. Subjects that successfully applied this technology were able to grasp, hold and manipulate various objects. Except for the Bionic Glove, which was designed to enhance the tenodesis grasp, all other systems were able to facilitate both palmar (power) grasp and lateral (fine) grasp. To control the neuroprosthesis the subjects are using either 'on–off' type of switches, or have to apply simple analog sensors to generate desired control commands. As a result, a time delay of 1–2 sec can be observed between the time the command is issued and the moment the grasp is executed. This time delay restricts the speed with which the subject can grasp and release objects. Hence, the neuroprostheses for grasping can only be used to support slower grasping tasks. Tasks such as grasping a falling object are not achievable with the current FES technology. The existing neuroprostheses for grasping were all used as permanent orthotic systems. Recently, the Handmaster, BGS system and the ETHZ–ParaCare

neuroprostheses have been applied successfully as rehabilitation tools used to restore grasping function instead of being used as permanent orthotic systems. These trials were carried out with stroke and incomplete SCI subjects.

The most widely accepted and used neuroprostheses for grasping are the Freehand system and the Handmaster. The success of these two systems can be contributed to their excellent design and to the major effort their companies put into making the FES technology accessible to the wider population of end users. All other neuroprostheses mentioned in this article are mainly used in experimental trials and for research purposes.

Challenges

Although the neuroprosthesis for grasping is already established as one of the most promising rehabilitation devices that stroke and SCI subjects can use to retrain or support grasping and reaching functions, its impact in clinical applications is still limited. The reasons for poor acceptance are various, such as technical, cultural and psychological. Although many of the problems that limit the application of the FES technology were already identified, a number of them still remain unclear. In this section we would like to draw attention to some of these issues hoping that this discussion will stimulate researchers in the field to revisit these problems and contribute towards their solution.

One of the main problems with the existing neuroprostheses, is that their success very much depends on strong engineering support. The FES technology requires intensive maintenance that cannot be provided by people with limited technical background. As a result, the neuroprosthetic systems were found effective in hospitals that have strong engineering support but were less successful in institutions that lack such support. To resolve this problem some neuroprostheses were designed to minimize technical assistance. That was achieved by simplifying the functions the system is generating and the system's donning and doffing were made easier. As a result, such systems required less technical support but often failed to address needs of a wider subject population. This often left an impression

that these FES devices are inadequate for clinical applications. Balance between the technical complexity and the 'ease-of-use' still remains to be resolved.

The second problem pertinent to all neuroprostheses, not only to grasping systems, is inadequate reliability. The majority of the neuroprostheses were either designed in laboratory environment or were developed by spin-off companies that originated from university laboratories. Consequently, the reliability of the systems is often inconsistent with actual needs, which often aggravates patients and therapists that use the FES technology. This problem can be eliminated with better manufacturing processes, stricter safety and reliability analysis, and better component selection.

Grasp strategies that can be provided with the existing neuroprostheses for grasping are very limited and can only be used for a restricted set of grasping and holding tasks. Hence, after initial excitement and enthusiasm a subject that uses a neuroprosthesis for grasping begins to complain that he/she can only use it for a restricted set of tasks, for example palmar or lateral grasp. This is one of the more challenging problems and it cannot be easily resolved. There are two technological improvements that have to be achieved before this problem can be eliminated. First is to design a neuroprosthesis that can facilitate more dexterous hand motions. This means that one would need to increase the number of stimulation channels. That in turn introduces the question of how to synchronize stimulation of all these additional channels (muscles) to generate appropriate hand movements. At the same time this complexity introduces the question of how one can facilitate control of such complex grasping strategies such that the subject can command them in a simple, reliable and fast way. Providing a solution to these two problems would represent a major milestone in the improvement of the FES technology.

The existing neuroprostheses for grasping that apply surface stimulation technology are often not accepted by the end users as a permanent orthotic system even though the improvement of the function is obvious and the user clearly benefits from the system in ADL. We believe that the main reason for the system rejection is psychological, and can be explained by the inappropriate cosmetics of the existing systems. One can also look at this issue in the following way: 'The system's performance is not sufficiently advantageous for the subject to outweigh the system's poor looks'. In the case of implanted systems, subjects often reject them because they have to be subjected to one or more surgical interventions before the system is fully functional. Many subjects dislike the idea of additional surgeries, in particular when they are already accustomed to their life with disability.

The last shortcoming of the FES technology we would like to mention is that to fully accept the system a subject has to train with it for extensive periods of time and the training has to be supervised by a therapist. Without supervised training few subjects are able to achieve a full function with the neuroprosthesis and only few subjects are able to apply in it ADL. This in turn means that this technology is labor intensive and therefore expensive. Many rehabilitation institutions are not willing to invest two or more months of daily training sessions to prepare a subject to use this technology if they are not fully convinced that the system is sufficiently reliable and that the subject will be provided with full engineering support many years after initial provision of the system.

CONCLUSION

The neuroprostheses for grasping can be successfully applied to rehabilitate stroke and SCI subjects assuming that the following criteria are respected:

1. The subject was carefully selected according to clinical and electrophysiological examinations.
2. The subject is motivated and fully supported by his/her family to join the FES program.
3. The FES training is supported and combined with the conventional occupational and physical therapy.
4. The function that is taught with the neuroprosthesis is physiological and resembles a natural limb function.
5. The training is initiated as early as possible after trauma, preferably during the early rehabilitation phase.

Under these conditions the FES treatment can give good results in retraining grasping function in stroke and SCI subjects.

During the acute rehabilitation phase the neurological condition of the patient is unstable and neurological recovery may occur. In this early phase flexible FES system should be applied to assist grasping function. For the success of such a system changes of the treatment objectives, adjustments of the stimulation sequences and stimulation parameters, repositioning of the stimulation electrodes, and implementation of different sensors for neuroprosthesis control must be effortlessly achievable. We firmly believe that the surface FES systems are the most appropriate to carry out functional training during early rehabilitation, due to their inherent flexibility. This flexibility also allows one to withdraw the FES treatment without any disadvantage to the patient. The functional training typically has three possible outcomes. One is that the system does not generate an adequate function or the subject is not motivated to use the system. The second outcome is that the subject recovers the function and does not need the FES system to perform it any longer. The third outcome is that the subject can generate the function only with the help of FES. In this case the subject should be encouraged to use the FES system as an orthotic device. If the subject accepts the system and is using it daily he/she should be informed about the existing commercially available FES system and should be encouraged to consider an implanted FES system if such a system can generate the function subject was trained to perform.

Although the neuroprosthesis for grasping is already established as one of the most promising rehabilitation technologies that stroke and SCI subjects can benefit

from, its impact in clinical applications is still limited. Further improvements in the FES technology and the increased awareness of the results recently achieved with the neuroprostheses for grasping could help bring this technology to a wider community of rehabilitation centers.

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