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Compex Motion: Neuroprosthesis for grasping applications

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Summary

The Compex Motion is a versatile electrical stimulation system with surface stimulation technology that can be used to develop various custom-made neuroprostheses, neurological assessment devices, muscle exercise systems, and experimental setups for physiological studies. This stimulator allows users to generate an arbitrary stimulation protocol that can be controlled or regulated using any external sensor, sensory system, or laboratory equipment. The Compex Motion system is modular, providing users with an unlimited number of stimulation channels, and promoting the application of complex sensory systems and user interfaces. This stimulator is specially designed to encourage sharing of stimulation protocols, sensors, and user interfaces. This feature promotes share-ware mentality, which, in our opinion, can be instrumental in accelerating technological developments in the neuroprostheses field. The Compex Motion system is especially designed for rehabilitation treatments administered during early rehabilitation (for example immediately after stroke or spinal cord injury), although it can also be applied as a neuroprosthetic system for patients to use in activities of daily living. In this chapter, an example is provided where the Compex Motion system was used to develop a neuroprosthesis for grasping for a 22-year-old, male, C5 motor complete, C4 sensory complete, spinal cord injured patient.

Case Study

A 22-year-old, male, C5 motor complete, C4 sensory complete, spinal cord injured (SCI) patient was admitted to the Toronto Rehabilitation Institute Lyndhurst Centre, Canada, two months after sustaining a SCI as a result of an automobile accident. On admission, the patient could place his left hand at almost any point in the arm's work space, but was unable to voluntarily grasp objects. The patient had good voluntary control of the left shoulder and *biceps m.*, while his *left triceps m.* was graded level 3 (patient could extend his arm against gravity when resistance was not applied to the arm). The patient had no voluntary muscle control on the left arm below the elbow. Furthermore, this right-handed patient had significant difficulty using his right arm, which could only voluntarily cover 30 to 40 % of the right hand's workspace. The patient had limited voluntary control of the right shoulder and *biceps m.* His right *triceps m.* was graded level 2 (patient could extend the arm against gravity when resistance was not applied to the arm). The patient had no voluntary control of any muscles below the right elbow. At the time the patient was admitted to the functional electrical stimulation (FES) program at Toronto Rehabilitation Institute, he had score A on the American Spinal Injury Association (ASIA) impairment scale which assesses sensory and motor function. Score A indicates complete injury, i.e. no sensory or motor function is preserved in the sacral segments S4-S5.

This patient was a good candidate for a left arm grasping neuroprosthesis. Neuroprosthesis is a device that applies short, low intensity electrical pulses to the paralyzed muscles to cause the muscles to contract on demand. By stimulating a desired group of muscles and by properly sequencing their contractions, neuroprosthesis can

generate functions such as hand opening and closing. In order to generate these functions, the muscles that need to be stimulated, must be enervated (motor neurons that project from the spinal cord towards the muscles of interest need to be intact).

This patient was fitted with a neuroprosthesis that allowed him to grasp both large and bulky objects, as well as small and light objects. The neuroprosthesis was developed using the Compex Motion electric stimulator manufactured by a Swiss based company, Compex SA. This stimulator has four stimulation channels and is fully programmable, i.e. the stimulation protocol can be tailored to fit any patient need. In this particular case, the stimulation protocol developed, allowed the patient to generate both lateral and palmar grasps on demand. Stimulation channel No.1 was used to stimulate the *flexor digitorum superficialis m.* and the *flexor digitorum profundus m.* to generate finger flexion. Stimulation channel No.2 was used to stimulate the *flexor pollicis longus m.* to generate thumb flexion. Stimulation channel No.3 was used to stimulate the *median nerve* to produce thumb adduction. Stimulation channel No.4 was used to stimulate the *extensor digitorium communis m*. to generate hand opening. The patient used a push button to command the neuroprosthesis. By pressing a push button for less than 0.5 s continuously, the patient would issue the lateral grasp command, and by pressing it longer than 1 s continuously, the patient would issue the palmer grasp command. Upon receiving the command, the neuroprosthesis would execute the desired grasping function instantaneously and would maintain this grasp until the next command is issued. By pressing a push button for the second time for less than 0.5 s, the patient would command hand-opening function. This system was deliberately designed so that the hand opening function did not preced the hand-closure function. We found that the patient had more

success in grasping an object if he first manipulated it with both hands and then prior to grasping it, oriented and placed the object in his left hand. In other words, the patient used the passive stiffness of his left hand and fingers to manipulate and orient the object before the FES grasp was executed. If the patient's hand was opened with FES prior to the grasp, the patient often experienced difficulties orienting the object properly, thus had difficulties preparing the object to be grasped.

Without the neuroprosthesis, the patient was not able to grasp any object. After two months of FES training (three to four sessions per week, lasting less than 45 minutes per session), the patient was able to significantly increase his grasping abilities and was able to reach, grasp, and manipulate a variety of objects such as a tea cup, paper sheet, pencil, video tape, can of coke, tooth brush, and fork. All these objects were used by the patient in the activities of daily living (ADL).

1. Neuroprostheses and Functional Electrical Stimulation

For more than 30 years, electrical stimulation of peripheral nerves has been applied to restore or improve body functions such as walking, hearing, bladder voiding, and grasping[(1)]. By applying bursts of low intensity electrical pulses, an electric stimulator creates action potentials in a stimulated nerve, which, depending on the nerve's function (nerve projected to a muscle or a part of the central nervous system), can cause muscle contractions, elicit a reflex, or help a deaf person to hear (Figure 1). Since action potentials that are elicited with electric stimulation propagate along the axons, the

stimulated nerves need to be intact. If a nerve is damaged, the degree of its damage will determine the efficacy with which electric stimulation elicits action potentials in the nerve. Severely injured or severed nerves prohibit the use of electric stimulation. Electric stimulators for medical applications are most frequently applied as orthoses or neuroprostheses that are used to assist patients in performing the above mentioned body functions in ADL. These devices are also called functional electrical stimulation (FES) systems. In this chapter, FES systems used for grasping will be discussed.

Figure 1 should be placed here

FES systems generate short repetitive electric pulses of 100 to 300 μs. Twenty to forty such pulses per second are required to generate a tetanic muscle contraction, necessary for a functional articulation of a limb. In principle, the nerves can be stimulated using monophasic or biphasic current or voltage pulses[(2)]. Since monophasic stimulation pulses can cause skin burns and tissue damage (due to galvanic processes), the majority of electric stimulation systems today implement either biphasic pulses or so called monophasic compensated pulses[(3)]. Many researchers and practitioners in the field prefer to use current, instead of voltage stimulation pulses, because current stimulation pulses allow full control over the amount of electric charge induced into the tissue. The electric stimulation pulses can be delivered to the nerve using surface (transcutaneous), inserted (percutaneous), or implanted electrodes. The transcutaneous stimulation is performed with self-adhesive or non-adhesive electrodes placed on the subject's skin in the vicinity of the motor point of the muscle that needs to be stimulated. A motor point is defined as

the region of easiest excitability of a muscle. Percuteneous electrodes, also known as intramuscular electrodes, are inserted into the muscle using epidermic needles[4, 5]. Implanted electrodes are subdivided into two main categories, epimysial[6], and cuff electrodes[7, 8]. The epimysial stimulation electrodes are placed on (sutured to) the muscles while the cuff electrodes are "wrapped" around the nerve that is stimulated. Compared to surface stimulation electrodes, implanted and inserted electrodes can provide higher stimulation selectivity while applying lower amounts of electric charge. These are desirable characteristics of electric stimulation systems[3, 9]. However, implanted electrodes, such as epimysical and cuff electrodes, require a surgical intervention to place the electrodes, and many subjects who could potentially benefit from the electric stimulation are reluctant to undergo a surgical intervention to be able to use this technology.

1.1 Neuroprostheses for Grasping

In tetraplegic and stroke patients, hand function is the most important function in achieving a high level of independence in ADL. The extent to which these patients can use their hands represents a measure of their independence. In principal, the grasping function can be differentiated into holding and manipulation tasks, which again can be differentiated in mono- or bi-manual handling tasks. The main objective in applying FES in tetraplegic and stroke patients is to improve the hand function by creating a reliable and long lasting power grasp, or a smooth pulp-pinch grasp that is needed to manipulate

small objects. Regardless of the grasping strategy, it is essential that the patient can easily command the grasp and adjust the strength of grasp. In supporting the hand function, the FES system must not interfere with the patient's preserved upper limb function, such as wrist extension or ability to position the arm/hand at the desired place. Furthermore, the hand and arm movements generated by the FES should not oppose natural joint movements and must respect the anatomy of bone and soft tissue composition.

The available neuroprostheses for grasping are able to restore two most frequently used grasping styles: the palmar and the lateral grasp[10]. 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, followed by the thumb flexion. The palmar grasp is generated by first forming the opposition between the thumb and the palm, followed by simultaneous flexion of both the thumb and the fingers. Finger flexion is performed by stimulating the *flexor digitorum superficialis m.* and the *flexor digitorum profundus m.* Finger extension is obtained by stimulating the *extensor digitorium communis m*. The stimulation of the thumb's *thenar muscle* or the *median nerve* produces thumb adduction, and the stimulation of the *flexor pollicis longus m.* or the *flexor pollicis brevis m.* produces thumb flexion. Typically, the stimulation sites and sequences of the neuroprosthesis for grasping have to be customized, and cannot be predicted simply from the neurological level of lesion. Therefore, various grasping strategies have to be evaluated to find the FES grasp that is functionally most useful for the patient.

The well-known neuroprostheses for grasping include the *Freehand system*[6], *Handmaster*[11], *Bionic Glove*[12], *NEC-FES system*[4], and the systems developed by *Vodovnik et al.*[13] and *Popovic et al.*[14]. A few years ago, our team also developed a neuroprosthesis for grasping, better known as the *ETHZ-ParaCare neuroprosthesis*[10]. With the exception of the Freehand and NEC-FES systems, all other neuroprostheses for grasping are FES systems with surface stimulation technology. Only the Freehand and Handmaster systems are currently available on the market while other neuroprostheses are primarily used in laboratory environments.

The *Freehand system* has up to eight implanted epimysial stimulation electrodes and an implanted stimulator. The stimulation electrodes are used to generate flexion and extension of the fingers and the thumb. One stimulation electrode is frequently used to provide a biofeedback to the subject, i.e. to stimulate subject's afferent nerves, informing him/her that the stimulator is working. 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 the 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 ("locking") 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.

The Freehand system was the first neuroprosthesis for grasping approved by the USA Food and Drug Administration (FDA). Thus far, the Freehand system has been made available to more than 130 patients and is commercially available. 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 of (doffing) the system is significantly shorter compared to most surface stimulation FES systems. On the other hand, the Freehand system can be applied only 18-24 months after the injury and is only suitable for SCI subjects and not individuals suffering from stroke. Therefore, the Freehand systems in not suitable for rehabilitation applications and can only be used as a permanent neuroprosthetic device. Furthermore, the patients are often subjected to additional surgery required to replace failed hardware components, or to correct the positioning of the stimulation electrodes.

The *Handmaster* is a neuroprosthesis for grasping with three pairs of surface stimulation electrodes. This system can be used to generate a grasping function in tetraplegic and stroke patients. Originally, this system was envisioned as an exercise and rehabilitation tool, but it is also used as a permanent prosthetic system. The Handmaster is controlled with a push button that triggers hand opening and closing, and the patient can regulate the way in which the thumb flexes with a sliding resistor. This feature allows a patient 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. One of the advantages of the Handmaster is that it is easy to put on and to take off. The Handmaster is predominately used as an exercise tool for stroke subjects and is commercially available in a limited number of countries. One of the disadvantages of the Handmaster is that it does not provide the user sufficient freedom to place the

stimulation electrodes. In addition, the Handmaster's orthosis is too short and does not allow stimulation of the finger flexors at a proximal position on the forearm. This location of stimulation electrodes provides good finger flexion with negligible wrist flexion activity. Another limitation of this system is its stiff orthosis that restricts the range of the wrist motion. In particular, the subjects can not perform full supination.

1.2 State of Art in the Functional Electrical Stimulation Field

Although implanted and surface electrical stimulation systems have been used extensively for more than three decades, the majority of these devices were developed with very specific FES applications in mind. Therefore, if one wanted to use an electric stimulator to carry out a different function (e.g. standing) other than the specific application that it was originally designed for (e.g. grasping), the user had to modify either the stimulator's hardware, software or both. Since such alterations are often impractical, many researchers and practitioners in the FES field were forced to develop their own stimulators. As a result, numerous electric stimulators have been developed, but FES practitioners and researchers continue to have overwhelming difficulties finding a standardized, programmable, reliable, and versatile electric stimulator that can be used for diverse FES applications. Thus, the level of success in the FES field is positively correlated to the amount of technical support available to the research team. In other words, rehabilitation centers which are able to provide substantial technical support to their FES teams often had successful neuroprostheses programs, while other institutions

without the necessary technical support, often close their FES programs after a brief period of experimenting with the technology. Consequently, FES technology has had limited impact on stroke and SCI rehabilitation and is found in only a few rehabilitation centers worldwide.

Another important issue in the FES field, is that many researchers believe that neuroprostheses should be used primarily as prosthetic devices. This means that each patient should have his/her own FES system to be used at home in ADL. This approach does have its merit, especially in the case of patients with complete SCI and is used as the basic premise for developing implanted FES systems. However, recent studies indicate that a significant population of stroke and SCI patients could also benefit from FES rehabilitation[15-17]. In particular, it was found that stroke and incomplete SCI patients subjected to intensive FES treatment post injury were able to recover grasping or walking function faster and better compared to patients who did not participate in the FES treatment. These results clearly indicate the need for a reliable, portable, programmable, and versatile surface FES system. Such a system could be used in early rehabilitation to promote functional recovery rather than being used as a permanent prosthetic or orthotic device. In addition, access to a stimulator that would allow FES practitioners to freely exchange stimulation protocols in the form of libraries (e.g. a protocol for hand grasp for C5 SCI subjects that applies EMG control or a protocol for treating subluxation in stroke patients) would dramatically simplify and encourage the application of this technology. This strategy of knowledge-sharing combined with reliable and versatile surface FES technology, could potentially become instrumental in making neuroprosthesis a more appealing rehabilitation tool for stroke and SCI patients.

In this chapter a new electric stimulator called Compex Motion is presented. The Compex Motion stimulator represents a further evolution and expansion of the ETHZ-ParaCare neuroprosthesis[10]. This electric stimulator exemplifies a type of technology that provides all the advanced FES application and control features, and yet, is simple to apply in a standard rehabilitation setting. The Compex Motion stimulator can be used to develop various custom-made neuroprostheses, neurological assessment devices, muscle exercise systems, and experimental setups for physiological studies. It can be programmed to generate any arbitrary stimulation sequence that can be controlled or regulated using any external sensor, sensory system, or laboratory equipment. Each stimulator has four output channels, and any number of stimulators can be combined to form a multiple unit with a greater number of stimulation channels (8,12,16,…). The stimulation sequences are stored on readily exchangeable memory chip-cards. By replacing the chip-card, the function of the stimulator is changed instantaneously to provide another function or FES treatment. The Compex Motion stimulator is being manufactured by the Swiss based company, Compex SA. A company is currently being sought to market this product.

2. Compex Motion: FES System with Surface Stimulation Electrodes

The Compex Motion stimulator was designed to serve as a hardware platform for development of diverse FES systems that apply surface stimulation technology (see Figure 2). One of the main design requirements for the system was that it can be easily

programmable and that even individuals with limited FES experience could generate useful stimulation protocols with the system. In addition, the stimulator is also capable of providing sophisticated stimulation protocols and control features commonly used in FES research. Furthermore, the system was designed to allow FES practitioners the ability to apply the same device to a number of different clients requiring distinct stimulation protocols, and to be able to treat one client after another with virtually zero "transition" time between treatments. To satisfy these needs, the stimulator was designed such that it is programmed with a graphical user interface software, which is installed on a personal computer (PC). As shown in Figure 3, a user can program the stimulation sequence using a PC and then transfer the complete stimulation protocol to the stimulator via serial port connection. During the transfer, the stimulation protocol is programmed onto a chip-card which is inserted into the stimulator. After the transfer is completed, the chip-card will contain all the relevant information that is needed to execute the stimulation protocol such as stimulation parameters, stimulation sequence, data about the sensors that need to be interfaced by the stimulator, signal processing that needs to be carried out with the input signals from the sensors, control strategies that need to be applied to regulate the stimulation sequences, etc. By simply replacing the chip-card, the function of the stimulator is changed instantaneously to provide a different function or FES treatment.

Figure 2 should be placed here

The main hardware and software features of Compex Motion stimulator are:

- The unit is portable

- Each unit has four stimulation channels, and any number of stimulators can be combined to form a multiple unit with a greater number of stimulation channels (8,12,16, …)
- The pulse amplitude, duration and frequency are independently controlled and can be changed during the stimulation in real time
- The stimulation channels are galvanically separated
- The stimulator is powered by a rechargeable battery and the only limitation in stimulation duration is imposed by the battery's capacity, which can support over eight hours of continuous stimulation per charging
- The stimulator can be interfaced/controlled with any external sensor, sensory system, or laboratory equipment
- The system's reliability matches the reliability of standard consumers electronic devices

Figure 3 should be placed here

3. Examples of Compex Motion Applications

Thus far, more than 30 SCI and stroke patients have used the Compex Motion stimulator at ParaCare, University Hospital Balgrist located in Zurich, Switzerland and Toronto Rehabilitation Institute located in Toronto, Canada. The system was primarily used as a neuroprostheses for grasping and walking. One patient used the device to treat shoulder

subluxation and a few others used it for muscle strengthening. The Compex Motion stimulator was also used to investigate muscle properties in animal studies and in closed-loop muscle control applications at ParaCare. Other applications of Compex Motion system such as neuroprosthesis for standing, breathing, and sitting are currently being explored. An example of a clinical application of Compex Motion is presented in this section. The example describes a neuroprosthesis for grasping applied to a C5, complete SCI patient. The performance and the impact of the neuroprosthesis on the patient will also be discussed in this section.

3.1 Neuroprosthesis for grasping

As discussed in the Case Study section of this chapter, a grasping neuroprosthesis was developed for a 22 year old, male, C5 motor complete, C4 sensory complete, SCI patient. The patient was admitted to our FES program two months after sustaining a SCI. The left arm was chosen for the neuroprosthesis application because the patient could place the left hand at almost any point in the arm's work space, and the muscles that needed to be stimulated were not denervated. The patient had good voluntary control of the left shoulder and *biceps m.*, while his *left triceps m*. was graded level 3. When the patient was admitted to the FES program at Toronto Rehabilitation Institute, he had ASIA score A.

The patient was fitted with a neuroprosthesis that allowed him to grasp both large and bulky objects, and small and light objects. Hence, a stimulation protocol was developed that allowed the patient to generate both lateral and palmar grasps on demand

(see Figure 4). Stimulation channel No.1 was used to stimulate the *flexor digitorum superficialis m.* and the *flexor digitorum profundus m.* to generate finger flexion. Stimulation channel No.2 was used to stimulate the *flexor pollicis longus m.* to generate thumb flexion. Stimulation channel No.3 was used to stimulate the *median nerve* to produce thumb adduction. Stimulation channel No.4 was used to stimulate the *extensor digitorium communis m*. to generate hand opening. The patient used a push button to command the neuroprosthesis. By pressing a push button for less than 0.5 s continuously, the patient would issue user interaction A command (UI-A in Figure 5) and by pressing it longer than 1 s continuously, the patient would issue user interaction B command (UI-B in Figure 5). The user interaction A was used to command the lateral grasp and the user interaction B was used to command the palmar grasp. By generating the user interaction A or B command, the neuroprosthesis would instantaneously produce the lateral or palmar grasp, respectively.

An important feature of this neuroprosthesis for grasping is that it also stimulates the *flexor pollicis longus m.*, which generates thumb flexion. An advantage of stimulating the *flexor pollicis longus m.* rather than stimulating the *median nerve* or thumb's *thenar muscle* alone, is that one can generate a proper thumb flexion. When the *median nerve* or thumb's *thenar muscle* is stimulated alone, the thumb produces adduction movement. This adduction movement combined with finger flexion is often used to generate the palmar grasp. However, this grasp is weaker and less stable than the grasp, which is generated with thumb adduction in addition to thumb flexion. Therefore, stimulation of the *flexor pollicis longus m.* is a beneficial and desirable feature. A combination of thumb flexion and adduction, together with finger flexion was used to generate the palmar grasp.

The lateral grasp is generated by combining finger flexion and thumb flexion. Stimulation of the *flexor pollicis longus m.* is a common feature in implanted FES systems, such as the Freehand system[6], but is very rarely found in surface FES systems because the *flexor pollicis longus m.* is difficult to access using surface FES due to its anatomical location in the forearm. The origin of the *flexor pollicis longus m.* is the anterior surface of body of radius below tuberosity, the interosseous membrane, medial border of coronoid process of ulna and /or medial epicondyle of humerous. The insertion of the *flexor pollicis longus m.* is the base of the distal phalanx of the thumb, palmar surface. The *flexor pollicis longus m.* in the proximal part of the forearm is a muscle located deep in the forearm and is difficult to access using surface FES. However, at the distal part of the forearm, the *flexor pollicis longus m.* comes close to the skin surface and is surrounded by the *radius*, *flexor digitorum superficialis m.*, *pronator quadratus m.,* and *flexor digitorum profundus m.* on one side (covering approximately 70% of the muscle surface), and surrounded by skin and *tendon m. brachioradialis* on the other side (covering approximately 30 % of the muscle surface). Since skin and *tendon m. brachioradialis* do not obstruct the surface electrical stimulation of the *flexor pollicis longus m.*, this site was selected for placement of the stimulation electrode. There are; however, some drawbacks to this stimulation site. When subjects perform pronation, the *flexor pollicis longus m.* and stimulation electrodes tend to shift and move with respect to one another. This movement may be problematic since it causes a reduction in the overall muscle force. In this particular case, the stimulation electrodes were positioned such that sufficient flexion force was achieved with the thumb during pronation and supination. In general, we were successful in

stimulating the *flexor pollicis longus m.* in a limited number of patients (two patients out of seven).

We should point out that the stimulation of the *flexor digitorum superficialis m.* and the *flexor digitorum profundus m.* caused patients to experience weak wrist flexion. We compensated for this side effect by providing patients with a wrist retainer that was integrated into a glove which patients used in combination with the neuroprosthesis.

3.2 Achieved results with the neuroprosthesis for grasping

When the patient was first admitted to the FES program he was unable to grasp any object. As a result of the FES training, the patient significantly increased his grasping abilities and was able to reach, grasp, and manipulate a variety of objects such as a telephone receiver, tea cup, mug, pencil, envelope, can of coke, and video tape. The patient was able to use all these object in ADL. However, there were some objects that the patient was unable to grasp and manipulate even while using the FES system. Typical examples of these objects include catheter, packaged gaze, lighter, and wallet. A common factor shared among all these objects were that they required two dexterous hands in order for the objects to be manipulated properly. Since the patient had only one arm instrumented with the neuroprosthesis, it was not unexpected that he would have difficulties manipulating these objects. Despite these limitations, the patient was content with the system's performance and requested a system for home use.

An unexpected and intriguing outcome resulted from this study. As we indicated earlier, prior to the FES treatment, the patient was unable to grasp any objects voluntarily, but with the neuroprosthesis, the patient was able to manipulate a significant number of tools and objects. However, after the completion of the FES training, it was found that the patient was able to manipulate 80% of these objects, in the absence of the neuroprosthesis. This is an important result, especially since the patient's neurological condition did not change, nor did the patient experience any neurological recovery during the treatment. Thus, by the end of the treatment, the patient was still classified as a C5 motor complete and C4 sensory complete SCI. At this time, we can only offer one explanation for this finding. As a result of FES training, the patient had learned a number of tricks and techniques to effectively approach and grasp objects. These tricks were easier to learn when the patient felt a sense of security that he would not drop the objects while manipulating them. The use of FES during grasping helps patients feel more confident that objects are safe and secure in the patient's hand while using or grasping them. An additional positive side-effect of FES treatment is that patient's muscles and tendons are strengthened, which in-turn provides additional passive stiffness to the hand and fingers. We have observed that stiffer hands and fingers frequently helped patients manipulate lighter objects and objects which have rougher surfaces. Our current work at Toronto Rehabilitation Institute will investigate the extent repetitive treatments with neuroprosthesis for grasping will have on C5 to C6 complete SCI patients and how this could improve grasping function. This approach represents a departure from the current trend in the FES field, where neuroprostheses for grasping was considered primarily as

prosthetic systems for C5 to C6 complete SCI patients. The preliminary study results obtained from this and two additional patients are very encouraging.

3.3 Impact of neuroprosthesis for grasping on SCI patients

Over the course of five years, more than 20 SCI patients have used the neuroprosthesis for grasping. In general, after the first few FES sessions, all patients expressed overwhelming enthusiasm and were impressed with the movement the system helped them generate in their otherwise paralyzed hands. However, as the patients became more familiar with the neuroprosthesis technology over time, their acceptance of this technology started to differ. To date, we were able to distinguish between three patient group views regarding the neuroprosthesis for grasping technology. The first group consisted of 60-70% of the patients who remained very enthusiastic about the FES treatment and eagerly participated in the treatment until completion. These patients were all informed that FES treatments would not help them achieve neurological recovery, yet they voluntarily continued to participate in the program. In fact, some of these patients expressed interest in taking these systems home to use in ADL. Overall, these patients were content with the treatment outcome and did not express disappointment when they were not offered a system for home use. On the contrary, despite the constant reminders that FES technology would not help individuals achieve neurological recovery, the second group of patients continued to believe that FES treatment will help them regain voluntary control of their arm and hand muscles. These patients were often disappointed

when they finally realized that their expectations were not rational. Due to the "awakening", some of these patients abandoned the program all together, while others took a short break from the program and resumed it a number of weeks later. Less than 10% of our patients belonged to this group. The third group consisted of patients who were very content with the treatment and its outcomes for the first four to six weeks. After which time, these patients requested for additional sophisticated features to be added to the system and were disappointed with the systems' overall performance. These patients were often disappointed that the system could only generate gross motor function and could not allow for more dexterous finger manipulations. These patients often got disenchanted with the treatment and after eight to ten weeks, withdrew from the program. We should point out that all individuals in this group expressed interest in resuming FES treatment once the technology became "more advanced" and could facilitate grasping tasks which they considered relevant. Approximately 20 to 30% of our patients belonged to this category.

Another interesting observation is that the majority of patients were very conscious of the aesthetic aspects of the neuroprosthesis. However, others patients were not concerned with the aesthetics at all, but were more interested with its performance. This later group consisted of individuals who were older or who had a SCI for two or three years prior to being admitted to the FES program. Without an exception, all patients provided good suggestions on the system design, including how to mount it on a wheelchair, and how to simplify its interfaces.

What was the overall impact of neuroprosthesis for grasping on our patients? This is a very difficult question to answer. Our impression is that the impact is positive and

significant, and we strongly believe that all our patients who participated in the program benefited considerably from the FES treatment. However, we have not yet conducted a study which confirms our subjective impressions. Our current efforts at Toronto Rehabilitation Institute and ParaCare are aimed at demonstrating how significant improvements to grasping function are, as a direct result of FES treatment, and how much this improvement correlates to the number of treatment sessions. In addition to this study, we intend to assess the consumers' perception on neuroprosthesis for grasping. This second study will be undertaken by a research team at Toronto Rehabilitation Institute which is independent of our group. These two studies should provide quantitative and qualitative measures of the impact neuroprosthesis for grasping technology has on consumers. This data will be used to assess the effectiveness of the device and to provide suggestions to further improving the Compex Motion and the neuroprosthesis for grasping systems.

4. Future Prospects

The Compex Motion electric stimulation system represents a versatile system that can be applied as a hardware platform to develop various custom-made neuroprostheses, neurological assessment devices, muscle exercise systems, and experimental setups for physiological studies. This stimulator provides all advanced FES application and control features, yet, it can be easily applied to standard rehabilitation settings. The Compex Motion stimulator can be programmed to generate any arbitrary stimulation sequence,

which can be controlled or regulated using any external sensor, sensory system, or laboratory equipment. We believe that this device can potentially resolve a number of challenges that are currently facing the FES field, such as:

- The Compex Motion stimulator allows one to generate any arbitrary stimulation protocol. Developed protocols can be easily exchanged among FES practitioners. This feature would allow the users to collectively test and incrementally improve the stimulation protocols with the objective of standardizing reliable and widely accepted stimulation protocols. This would allow FES practitioners to share their stimulation protocols with other FES users, and would promote share-ware and open-source mentality in the field. This approach was instrumental in developing numerous technically challenging fields, and would most certainly be beneficial to future developments in the FES field. This is currently impossible to do with the existing FES technology.
- Since Compex Motion can be controlled by any sensor and sensory systems, the existing "FES sensors" and man-machine interfaces can be configured to interface the stimulator. This would allow FES practitioners to share their sensor technology with other FES users as discussed above. Compex Motion user interface primitives and functions that allow regulation of stimulation amplitudes via analog input signals can dramatically simplify development of these interfaces. Thus far, our team has developed a number of sensory systems and man-machine interfaces that are reliable and can be used to control the stimulator. Some of these systems are: Gait Phase Detection System[18], EMG measurement sensor combined with the signal processing routines for stimulation artifacts

removal[19, 20], sliding resistor control strategy[10], and voice control module (not yet published).

- FES gloves, garments and other user interfaces can be developed for the stimulator. The sharing of successful user interfaces would further simplify donning and doffing of stimulation electrodes. Our team is currently developing a glove that will be used for quicker donning and doffing of stimulation electrodes for neuroprosthesis for grasping.
- Modularity of the Compex Motion system, which allows one to have an unlimited number of stimulation channels and promotes application of complex sensory systems and user interfaces, would allow practitioners to acquire modules one by one, instead of buying an expensive complex FES system all at once. This feature would allow institutions and laboratories with limited budgets to acquire a high quality FES system, in additional to allowing them to incorporate the system instantaneously into their research or rehabilitation environment. Later, if needed, they could add additional modules and sensory interfaces to the system, enhancing its capabilities.
- The final point is that the Compex Motion system is non-invasive and can be applied at various stages of recovery and rehabilitation. Since implanted FES systems are mainly suitable for long term FES treatments and should be used as prosthetic devices, we believe that Compex Motion is appropriate for rehabilitation treatments, especially those treatments that are administered during early rehabilitation (for example immediately after stroke or SCI). However, Compex Motion can also be used as a prosthetic system that the patient can apply

in ADL. Often surface stimulation systems are more appealing to patients, compared to implanted systems, since their application does not involve surgical intervention.

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References:

1. Popovic D, Sinkjaer T. Control of Movement for the Physically Disabled. London: Springer; 2000.
2. Baker LL, Wederich CL, McNeal DR, Newsam C, Waters RL. Neuromuscular Electrical Stimulation - A Practical Guide. 4 ed. USA: Rehabilitation Engineering Program, Los Amigos Research and Education Institute, Rancho Los Amigos Medical Center, 2000.
3. Mortimer JT. Motor Prostheses. In: Handbook of Physiology - The Nervous System II: American Physiological Society; Edited by Brooks VB; 1981. p. 155-187.
4. Hoshimiya N, Handa Y. A Master-Slave Type Multichannel Functional Electrical Stimulation (FES) System for the Control of the Paralyzed Upper Extremities. Automedica 1989;11:209-220.
5. Cameron T, Loeb GE, Peck RA, Schulman JH, Strojnik P, Troyk PR. Micromodular Implants to Provide Electrical Stimulation of Paralyzed Muscles and Limbs. IEEE Transactions Biomedical Engineering 1997;44(9):781-790.
6. Smith B, Peckham PH, Keith MW, Roscoe DD. An Externally Powered, Multichannel, Implantable Stimulator for Versatile Control of Paralyzed Muscle. IEEE Transactions on Biomechanical Engineering 1987;34(7):499-508.
7. Grill WM, Mortimer JT. Stability of the Input-Output Properties of Chronically Implanted Multiple Contact Nerve Cuff Electrodes. IEEE Transactions on Rehabilitation Engineering 1998;6:364-373.
8. Tyler DJ, Durand DM. A Slowly Penetrating Interfascicular Nerve Electrodes for Selective Activation of Peripheral Nerves. IEEE Transactions on Rehabilitation Engineering 1997;5(1):51-61.
9. Kobetic R, Morsolais EB. Synthesis of Paraplegic Gait With Multichannel Functional Neuromuscular Stimulation. IEEE Transactions on Rehabilitation Engineering 1994;2(2):66-78.
10. Popovic MR, Keller T, Pappas IPI, Dietz V, Morari M. Surface-Stimulation Technology for Grasping and Walking Neuroprostheses. IEEE Engineering in Medicine and Biology Magazine 2001;20(1):82-93.
11. IJzerman MJ, Stoffers TS, Groen FACGit, Klatte MAP, Snoek GJ, Vorsteveld JHC, et al. The NESS Handmaster Orthosis: Restauration of Hand Function in C5 and Stroke Patients by Means of Electrical Stimulation. Journal of Rehabilitation Sciences 1996;9(3):86-89.
12. Prochazka A, Gauthier M, Wieler M, Kanwell Z. The Bionic Glove: An Electrical Stimulator Garment that provides Controlled Grasp and Hand Opening in Quadriplegia. Archives of Physical Medicine and Rehabilitation 1997;78(6):608-614.
13. Rebersek S, Vidovnik L. Proportionally Controlled Functional Electrical Stimulation of Hand. Archives of Physical Medicine and Rehabilitation 1973;54:168-172.
14. Popovic D, Popovic M, Stojanovic A, Pjanovic A, Radosavljevic S, Vulovic D. Clinical Evaluation of the Belgrade Grasping System. Proceedings of the 6th Vienna

International Workshop on Functional Electrical Stimulation; September 22-24, 1998:247-250.
15. Popovic DB, Popovic MB, Sinkjaer T. Neurorehabilitation of upper extremities in humans with sensory-motor impairment. Neuromodulation 2002;5(1):54-67.
16. Field-Fote EC. Combined use of Body Weight Support, Functional Electrical Stimulation, and Treadmill Training to improve Walking Ability in Individuals with Chronic Incomplete Spinal Cord Injury. Archives of Physical Medicine and Rehabilitation 2001;82:818-824.
17. Wieler M, Stein RB, Ladouceur M, Whittaker M, Smith AW, Naaman S, et al. Multicenter evaluation of Electrical Stimulation Systems for Walking. Archives of Physical Medicine and Rehabilitation 1999;80:495-500.
18. Pappas IPI, Popovic MR, Keller T, Dietz V, Morari M. A Reliable Gait Phase Detection System. IEEE Transactions on Neural Systems and Rehabilitation Engineering 2001;9(2):113-125.
19. Biofeedback Version 2M4456. Ecublens, Switzerland: MediCompex SA; 1996.
20. Keller T, Popovic MR. Stimulation Artifact Removal Algorithm for Real-Time Surface EMG Applications. Proceedings 7th Vienna International Workshop on Functional Electrical Stimulation; September 11-13, 2001:118-121.

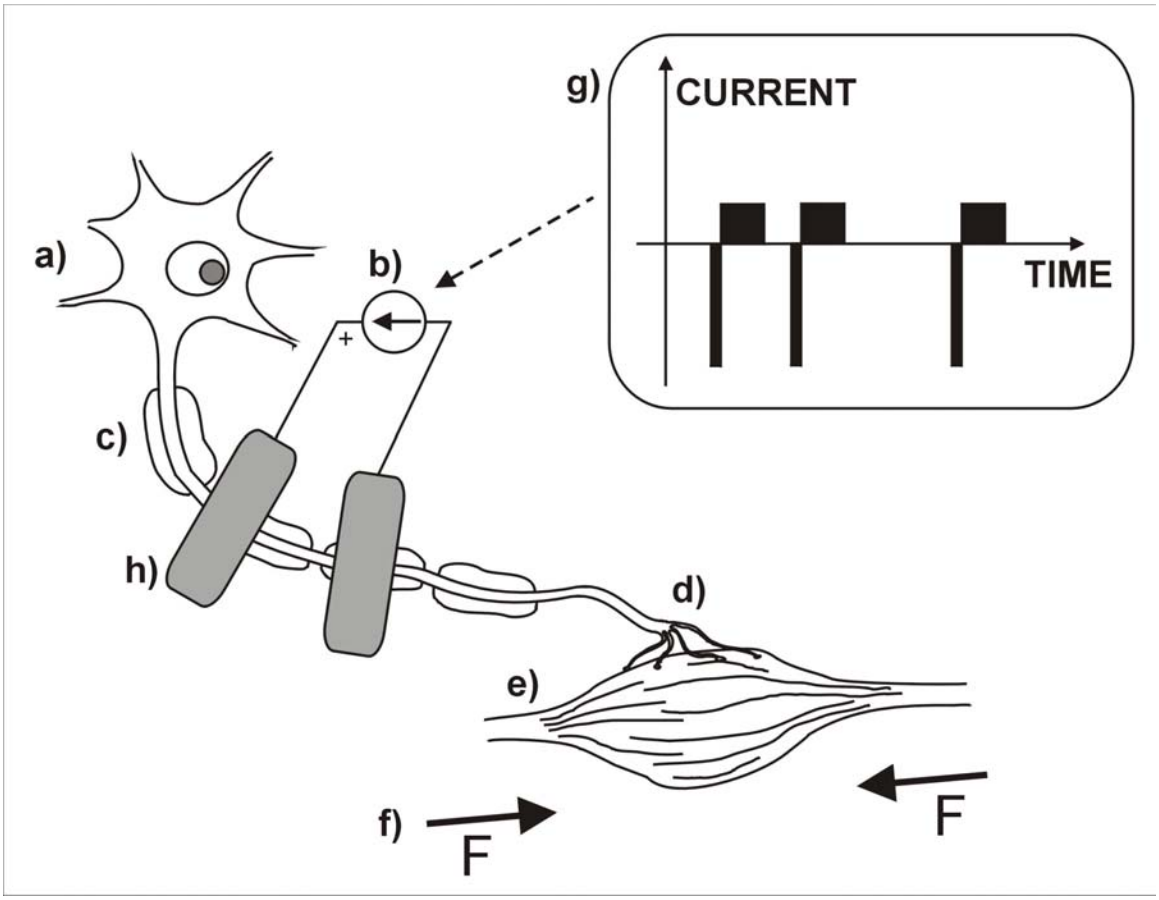

Figure 1: Simplified schematic diagram of functional electrical stimulation system. a) motorneuron that projects axon from the spinal cord towards a muscle; b) electric stimulator, i.e. current generator; c) nerve axon; d) axon terminals; e) muscle; f) contraction forces generated by electric stimulation; g) stimulation pulses (typical values for surface electrical stimulation are: pulse amplitude 10 to 100 mA, pulse frequency 20 to 40 Hz and pulse width 50 to 300 μs); and h) stimulation electrodes.

Figure 2: Compex Motion stimulator, three memory chip-cards, two EMG sensors and two stimulation electrodes

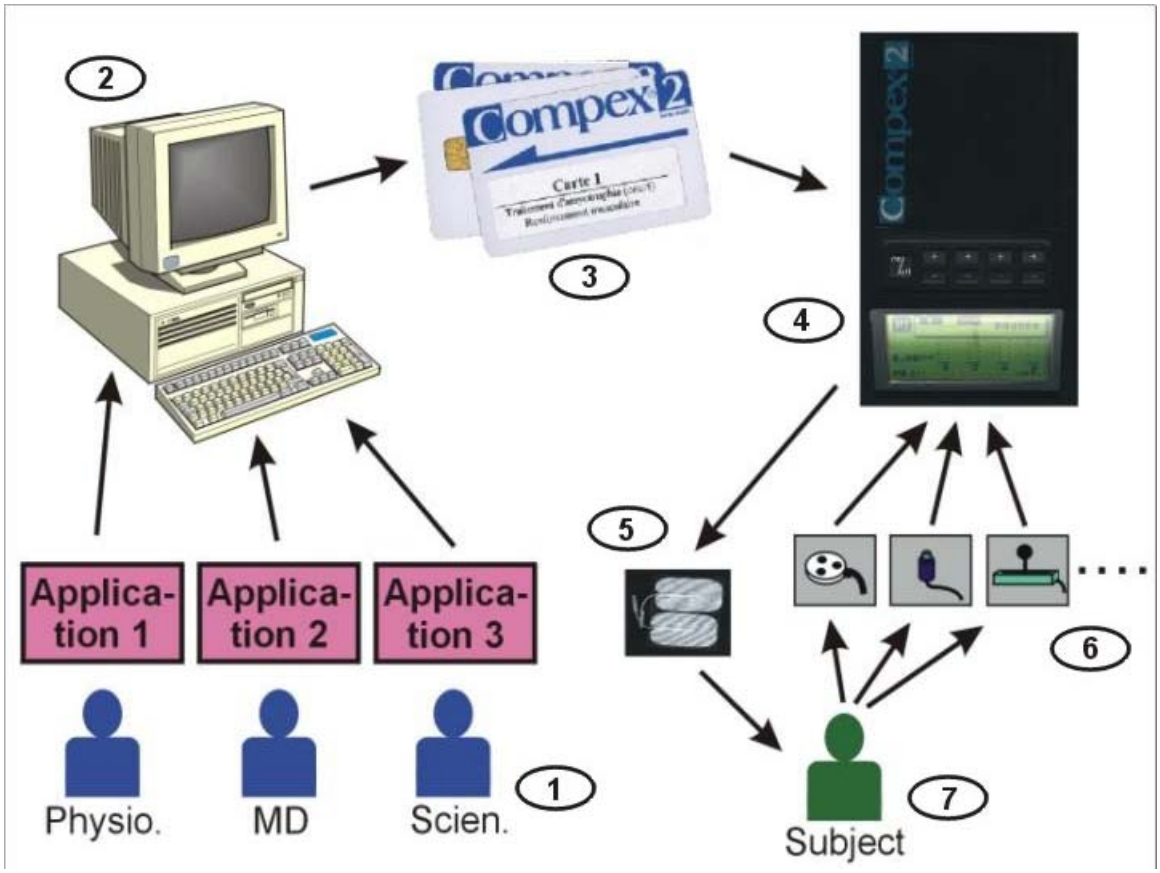

Figure 3: Compex Motion – Stimulator's concept: 1) FES practitioner, 2) PC used to program the stimulation protocol, 3) programmable chip-card, 4) stimulator, 5) surface stimulation electrodes, 6) sensors subject is using to trigger and control the stimulation sequences and intensity, and 7) end user

Figure 4.a

Figure 4.b

Figure 4: Patient with the neuroprosthesis for grasping; a) palmar grasp b) lateral grasp

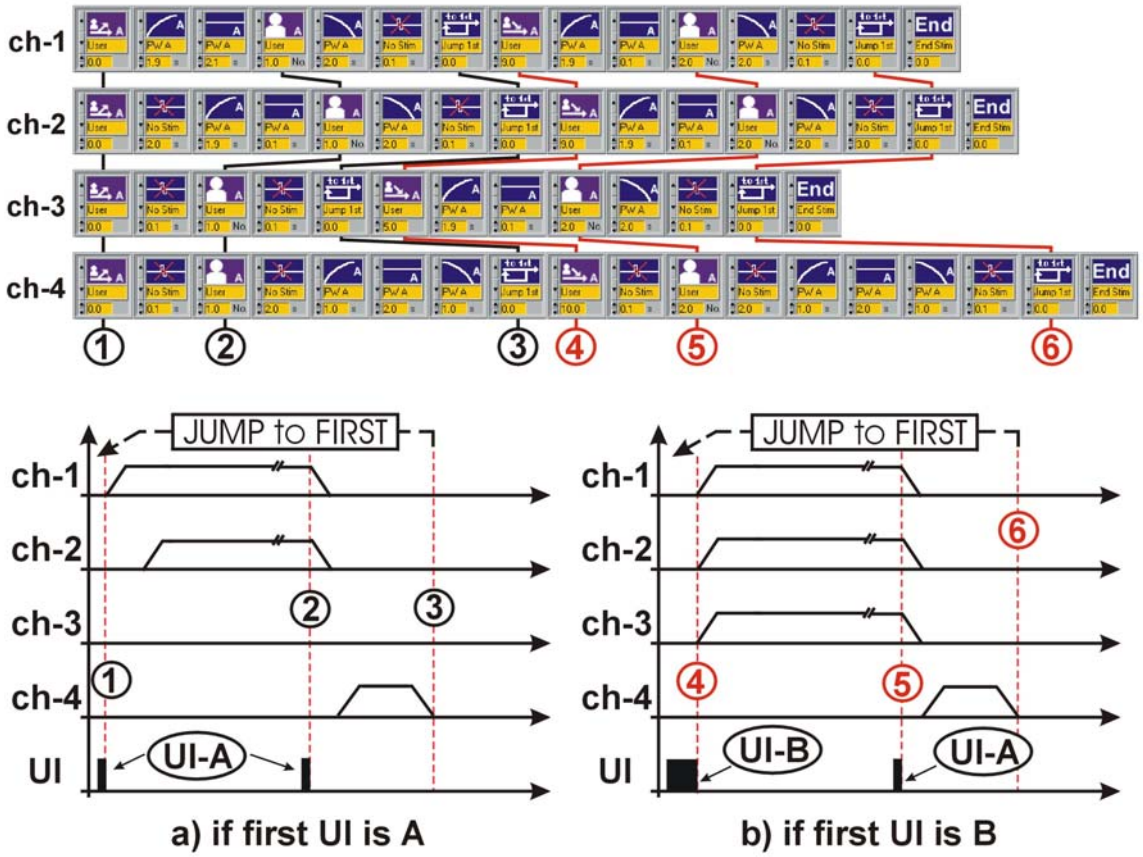

Figure 5: Grasping protocol that generates both a) lateral and b) palmar grasps on demand. The upper part of the figure presents primitives in time lines and the lower part represent the outputs for channels 1, 2, 3 and 4.

UI-A is user interaction A which is generated if the push button is pressed less than 0.5 s; UI-B is user interaction B which is generated if the push button is pressed longer than 1 s; ch-1, 2, 3 and 4 are stimulation channels; and labels ① to ⑥ are used to indicate which primitives in the time lines are responsible for certain stimulation protocol events.

CVs

Milos R. Popovic

In 2001 Milos R. Popovic was appointed Assistant Professor at the Institute of Biomaterials and Biomedical Engineering at the University of Toronto, as well as Research Scientist at the Toronto Rehabilitation Institute, both facilities located in Toronto, Canada. From 1997 until 2001, he led the Rehabilitation Engineering Group at the Swiss Federal Institute of Technology (ETH) and the Paraplegic Center of the University Hospital Balgrist (ParaCare), both in Zurich, Switzerland. From 1996 until 1997, he worked for Honeywell Aerospace in Toronto, Canada. In 1996, he received his Ph.D. degree in Mechanical Engineering from the University of Toronto, Canada in addition to the Dipl. Electrical Engineer degree from the University of Belgrade, Yugoslavia in 1990. Dr. Popovic's interests are in neuromuscular systems, assistive technology, and neuro-rehabilitation. In 1997, together with Dr. Thierry Keller, he received the Swiss National Science Foundation Technology Transfer Award - 1st place.

Thierry Keller

Thierry Keller received his Doctorate (Dr. sc. techn.) in 2001, as well as his Dipl. Ing. degree in electrical engineering (M.Sc.E.E.) in 1995, both from the Swiss Federal

Institute of Technology Zurich (ETHZ), Switzerland. He is currently working as a Visiting Research Scholar at the Department of Physical Therapy and Human Movement Science at Northwestern University in Chicago, and the Sensory Motor Performance Program at the Rehabilitation Institute of Chicago. In addition, he is in charge of leading the Rehabilitation Engineering Group at ETHZ and the Paraplegic Center of University Hospital Balgrist, in Zurich. Since 1995 at the Rehabilitation Engineering Group he has held the research engineer position and later he was appointed the research associate. He has developed various neuroprostheses used to improve walking and grasping functions in spinal cord injured and stroke subjects. His research interests are in the development and application of rehabilitation technology. In 2002, he was awarded the Swiss National Science Foundation (SNF) fellowship for advanced researchers and in 1997, together with Dr. Milos R. Popovic, he received the Technology Transfer Award - 1st place.

Glossary of Terms

- **Functional electrical stimulation:** Controlled, sequenced bursts of low intensity electrical pulses that are used to create action potentials which can cause muscle contractions
- **Neuroprosthesis:** A system that applies functional electrical stimulation to generate body functions such as standing, grasping and walking

- **Palmar grasp:** The palmar grasp is generated by first forming the opposition between the thumb and the palm, followed by simultaneous flexion of both the thumb and the fingers.
- **Lateral grasp:** The lateral grasp is generated by first flexing the fingers to provide opposition, followed by the thumb flexion.
- **Axons:** Are elongated nerve fibers of neurons, which allow transmission of nerve impulses from one neuron to another neuron or muscle.
- **Stimulation:** See functional electrical stimulation
- **Monophasic pulse (or simply pulse):** A rapid, transient change in the amplitude of a signal from a baseline value to a higher or lower value, followed by a rapid return to the baseline value.
- **Biphasic pulse:** Two consecutive monophasic pulses that have amplitudes that have opposite signs.
- **Voltage pulse:** A pulse of a voltage signal.
- **Current pulse:** A pulse of a current signal.
- **Surface stimulation technology:** Functional electrical stimulation applied using surface stimulation electrodes.
- **Supination:** Rotation of the lower forearm so that the hand faces forwards or upwards with the radius and ulna parallel.
- **Subluxation:** Partial dislocation of a joint, so that the bone ends are misaligned but still in contact.
- **Pronation:** Rotation of the lower forearm so that the hand faces backwards or downwards with the radius and ulna crossed.

- **Motor point:** A motor point is defined as the region of easiest excitability of a muscle.

Web Sites of Interest

www.utoronto.ca/IBBME/Faculty/Popovic_Milos/rel_uoft.html

www.aut.ee.ethz.ch/~fes

www.ifess.org

www.makoa.org/sci.htm

www.heartandstroke.ca

Index

- stimulation electrodes
    - implanted
    - percutaneous
    - transcutaneous
- stimulation pulses
    - biphasic
    - monophasic
    - current
    - voltage
- stroke

Clarification

I clarify that the patient cannot be identified and that no reprint permission forms are required for any of the figures included.