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NEURAL PROSTHESES FOR SPINAL CORD INJURED SUBJECTS[†]

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Abstract

A functional electrical stimulation system with surface electrodes and four stimulation channels was developed. The proposed system was used to design two neural prostheses for spinal cord injured subjects and stroke subjects. One prosthesis was used to restore a grasping function in high lesioned tetraplegic subjects. The other prosthesis was used to eliminate the 'drop foot' problem in incomplete spinal cord injured subjects and stroke subjects. The preliminary results obtained with these two neural prostheses indicate that they can significantly improve the quality of life of spinal cord injured subjects, and that the subjects with such prostheses are more independent in daily living activities.

Introduction

Spinal cord injured (SCI) subjects often have limited or no control over their upper and/or lower body extremities. This deficiency frequently renders SCI subjects dependent on other people's assistance in everyday activities. The main objective in rehabilitating SCI subjects is to help them become as much independent from other people's assistance as possible. One way to accomplish this task is to provide the SCI subjects with assistive devices, such as neural prostheses, which could help them regain limb functions lost as a result of spinal cord injury. A neural prosthesis is a device that generates a series of short electrical pulses in order to cause a muscle contraction [1]. By activating a particular group of limb muscles a neural prosthesis can enable an SCI subject to control a motion of the stimulated limb which he or she otherwise cannot voluntarily move. The technique that is used to activate muscles in SCI subjects using the electrical stimulation is known as functional electrical stimulation (FES) [5].

The University Hospital Balgrist and the ETH Zurich have successfully developed two neural prostheses for SCI subjects. One of these two prostheses can be used to restore a grasping function in high lesioned SCI subjects[1]. The proposed FES system enables an SCI subject to restore either a key or a palmar grasp by stimulating finger flexion and finger extension muscles [7]. The prosthesis is an open-loop controlled system that generates a desired electrical stimulation upon SCI subject's command. The subject uses the electromyogram[2] (EMG) activity of the muscles, he or she can voluntarily control, to initiate and regulate the activity of the prosthesis. The subject constantly monitors how the prosthesis operates, and by providing input signals to it he or she regulates its performance. Hence, the

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[1] SCI subjects with C4 and C5 lesions [7].
[2] The electromyogram is the electrical activity of an active muscle. Every active muscle generates a significant level of electical activity which can be measured [1].

overall ‘man-machine’ system represents a closed-loop FES system with the SCI subject performing the control function. Except for visual feedback and the stimulation sensation, the SCI subject does not have any other sensory feedback from the stimulated hand (subject’s afferent nerves are often damaged as a result of a spinal cord injury).

The second FES system developed by our team can be used to restore walking function in incomplete SCI and stroke subjects. This neural prosthesis monitors subject’s activity and once the subject initiates a walking sequence it automatically sends an array of electrical pulses to the muscles of the leg affected by the disability. The proposed prosthesis stimulates the peroneal nerve and the tibialis anterior muscle of the affected leg. This FES system enables an SCI subject to eliminate a ‘drop foot’ problem and to successfully ambulate using a walker or crutches. In some SCI subjects in order to eliminate the ‘drop foot’ problem it is required to stimulate some additional muscle groups besides the peroneal nerve and the tibialis anterior muscle. Our FES system is designed to provide that capability since it has four stimulation channels. The proposed prosthesis uses an ‘intelligent’ foot sensor to determine the gait phase[3] and the moment when the stimulation sequence should be sent to the leg.

These two FES systems have been already tested in hospital environment and were found effective in restoring walking and grasping functions in SCI subjects [7]. Currently, the proposed systems are upgraded and prepared for ‘in field’ tests that are scheduled to begin at the end of April 1998. The preliminary results obtained with these systems indicate that they are robust and that they should not experience any problem during the tests.

Functional Electrical Stimulation

A methodology that uses a burst of short electrical pulses to stimulate muscles and cause them to contract is called functional electrical stimulation (FES) [1]. A muscle can be stimulated either by a direct stimulation or by stimulating its motor-neurons [1]. Since the direct muscle stimulation requires significantly more energy than the motor-neuron stimulation, while the end result is the same, in practical applications the stimulation of the motor-neurons is used to produce the muscle contraction [2]. This infers that the subject’s motor-neurons have to be intact. Otherwise they could not be used to stimulate the muscle [2]. In general, the muscles are stimulated using rectangular current pulses that have both positive and negative phases (balanced asymmetric biphasic waveform) [2]. The positive phase is used to activate the muscle while the negative phase is used to discharge static electricity induced by the positive pulse phase [4]. The positive phase of the pulse is short and has a large amplitude while the negative phase of the pulse is long and its amplitude is significantly lower [4]. By selecting a proper set of motor-neurons and by stimulating those motor-neurons with the proper pulse sequence one can cause a desired motion of otherwise paralyzed extremities or body parts [2].

The motor-neurons can be stimulated in two ways. One approach is to use surface electrodes (*epidermal stimulation*) which are placed on the subject's skin above the area where the motor-neuron is [2]. The other approach is to use implanted electrodes (*percutaneous stimulation*) which are attached to the motor-neuron or are attached to the stimulated muscle close to its motor-point[4] [3]. Stimulation using implanted electrodes provides more selectivity than the stimulation with the surface electrodes [3,4]. In other words, with the implanted electrodes one can choose exactly which muscle or muscle group

[3] The exact position of the foot and the lag during walking sequence.
[4] The electrode location where maximal contraction is generated [2].

he/she wants to stimulate, while with the surface electrodes this is much more difficult to achieve [3,4]. Although the implanted FES systems from this point of view are superior compared to the surface FES systems, they have one major disadvantage. In the case the implanted FES system fails the subject with the system would require a major surgery in order to restore the system's function. This is not the case with the surface FES systems. Because of that in our experiments we have used only surface FES systems.

Currently the FES systems are used to restore walking and grasping functions, bladder voiding function, and breathing function in SCI and stroke subjects [2,3,5,6]. In this paper we shall discuss the FES system developed by the ETH Zurich team at the University Hospital Balgrist which is used to restore walking and grasping functions in SCI and stroke subjects [7].

The ETHZ-Balgrist Functional Electrical Stimulation System

The proposed neural prosthesis consists of: Myolab II® EMG electrodes [8]; FSR force sensors[5]; goniometers; input signal amplifiers; data processing unit; control unit; stimulator unit; and self adhesive surface stimulation electrodes (see Figure 1 and Table 1). The EMG electrodes, the force sensors and the goniometers are used as input signals to the controller. Depending what is the condition of these input signals, the rule based controller selects the stimulation sequence that should be generated by the stimulator. The stimulator generates the stimulation sequence and sends it to the electrodes which deliver the electrical pulses to the desired motor-points. The motor-points further deliver these pulses to the selected muscles which through contraction cause a desired motion of the subject's limb.

4 stimulation channels:	current regulated
	pulse frequency 20-50Hz
	pulse amplitude 0-100mA
	pulse width 0-500μs
6 analog input channels:	EMG, FSR and goniometer inputs
programmable controller:	custom-made applications
	200Hz control frequency
power:	2.8Ah/7.2Vdc Li-ion battery (8h of stimulation)
dimensions:	length: 200mm; width: 120mm; thickness: 56mm
weight:	≈ 500g

Table 1: ETHZ-Balgrist FES system data sheet

The Grasping FES System

The grasping FES system consists of 2 EMG electrodes, 3 pairs of stimulation electrodes and the controller-stimulator unit (see Figure 2). The EMG sensors placed on the ventral and dorsal branches of the contralateral deltoid muscle[6] were used to control the neural prosthesis. Note that the subject could voluntarily control the deltoid muscle. When the ventral activity of the deltoid muscle was stronger than the dorsal activity the finger extension was generated (hand opening). In the case the dorsal activity was stronger than the ventral activity, finger and thumb flexion were performed (grasping). The amplitude of the difference between the ventral and the dorsal EMG signals was used to control the force exerted by the subject's hand

[5] Force Sensing Resistor manufactured by Interlink Electronics, USA.
[6] A deltoid muscle of the arm that was not stimulated.

during the grasp. The finger flexion was performed by stimulating the flexor digitorum superficialis and the flexor digitorum profundus. The thumb flexion was performed by stimulating the thenar muscle of the thumb or the median nerve. In order to perform finger extension, the extensor digitorum and the ulnar nerve were stimulated.

The proposed system was tested with a C4 to C5 SCI male subject. The prosthesis allowed the subject to perform either a palmar or a key grasp, but not both of them. The palmar grasp was used to grasp bigger and heavier objects such as cans, bottles and an electrical shaver (see Figure 4). The key grasp was used to grasp smaller and thinner objects such as keys, paper sheets and floppy disks. The pinch grasp, which is used to hold a pen, was obtained using the palmar grasp strategy (see Figure 5). The following is the list of the tasks the subject was able to perform with the proposed prosthesis:

- to grasp, to lift and to place a cylindrical object which was 5cm in diameter and weighted 250g;
- to lift a telephone receiver, to dial a number, to maintain a conversation for a minute and to hang up;
- to pour 3dl liquid out of a bottle into a glass and to drink the liquid out of the glass;
- to grasp an apple and eat it;
- to grasp a pencil and write with it for 2 minutes;

The Walking FES System

The walking FES system consists of a foot sensor, 2 pairs of stimulation electrodes and the controller-stimulator unit (see Figure 3). The foot sensors, consisting of 3 FSR sensors placed in the shoe sole of the stimulated leg, was used to detect a moment when the foot is in the lift off phase of the gate. The sensor would provide this information to the controller-stimulator unit which would stimulate the peroneal nerve and the tibialis anterior muscle. By stimulating the peroneal nerve and the tibialis anterior muscle the FES system would invoke a walking sequence (toe off and foot dorsiflexion) of the leg the subject cannot voluntarily control.

The proposed system was tested with a C6 to C7 incomplete SCI male subject (see Figure 6). The following is the list of the tasks the subject was able to perform with the proposed prosthesis:

- to walk safely using a walker;
- to walk up to 500m without the break, with an average speed of 1.5km/h;
- to walk uphill;

Discussion

The experiments conducted with the grasping and walking FES systems indicate that the proposed systems are easy to use and that subjects can intuitively learn how to control them. After two months of training the C4 to C5 SCI subject showed significant improvement in grasping ability as a result of using the grasping prosthesis. Also, the C6 to C7 SCI subject, which was using the walking prosthesis, showed significant improvement in his walking ability after three weeks of training with prosthesis. Both subjects expressed an interest to take the FES systems home and use them in daily activities. The proposed FES systems have been tested in hospital environment and were found very effective in restoring walking and grasping functions in SCI subjects. Currently, the proposed systems are upgraded and are prepared for ‘in field’ tests that are scheduled to begin at the end of April 1998.

There is a number of issues which still need to be resolved with these FES systems before they can be provided to the SCI patients on regular basis. One of the issues is a long time needed to place the stimulation and the EMG electrodes on the subject's skin (up to 10min). Second, the foot sensor often has a difficulty to distinguish if the subject is shifting its weight from one leg to another during standing, or the subject is actually walking. This problem could potentially cause an undesirable activity of the walking prosthesis while the subject is standing. These and other issues such as: improving the way in which the surface electrodes are mounted on a subject's skin, improving the systems reliability, and developing ‘fail safe’ features for the system, will be addressed in our future work.

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Figures:

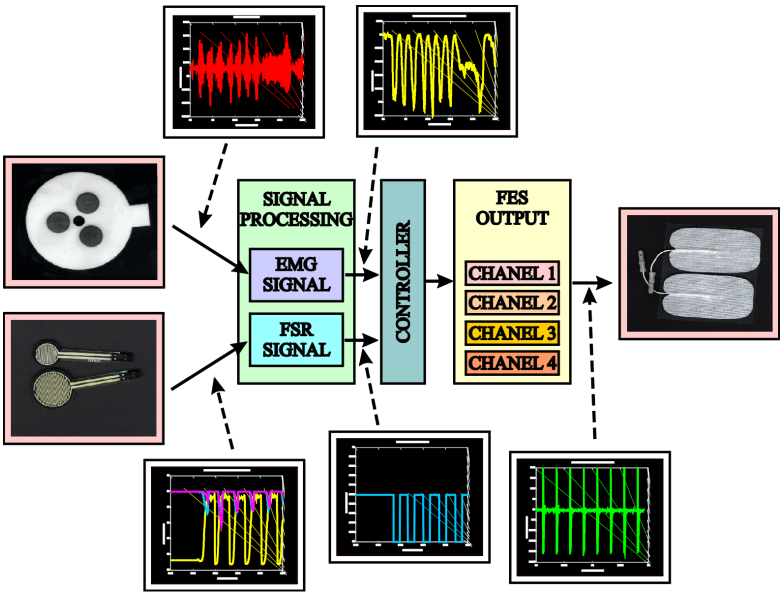

Figure 1: Schematic diagram of the proposed FES system

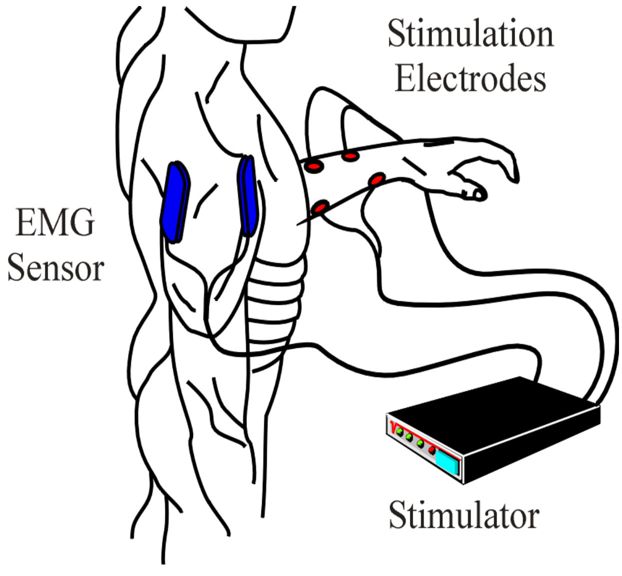

Figure 2: The grasping FES system

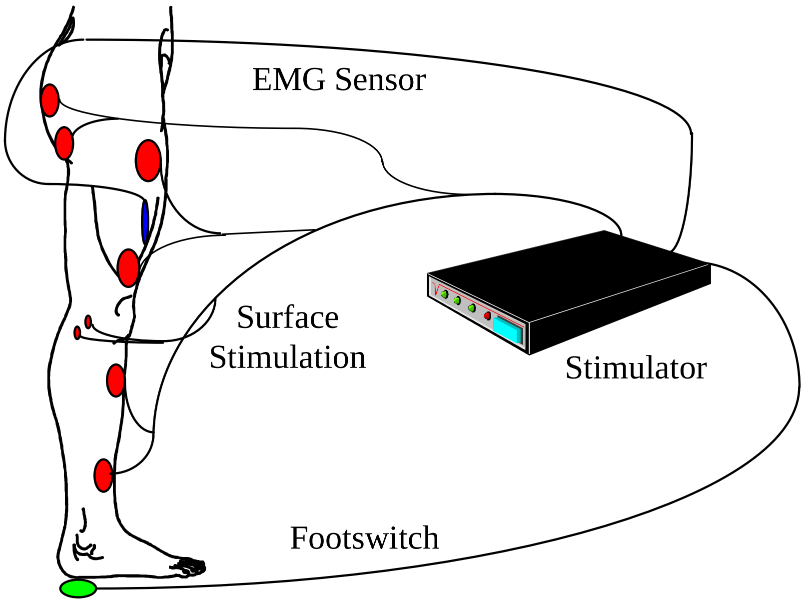

Figure 3: The walking FES system

Figure 4: C4 to C5 SCI subject performs a palmar grasp using the proposed grasping neural prosthesis

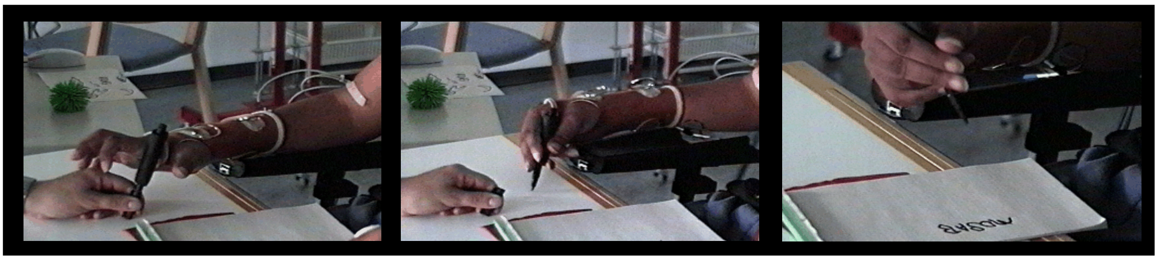

Figure 5 C4 to C5 SCI subject performs a pinch grasp using the proposed grasping neural prosthesis

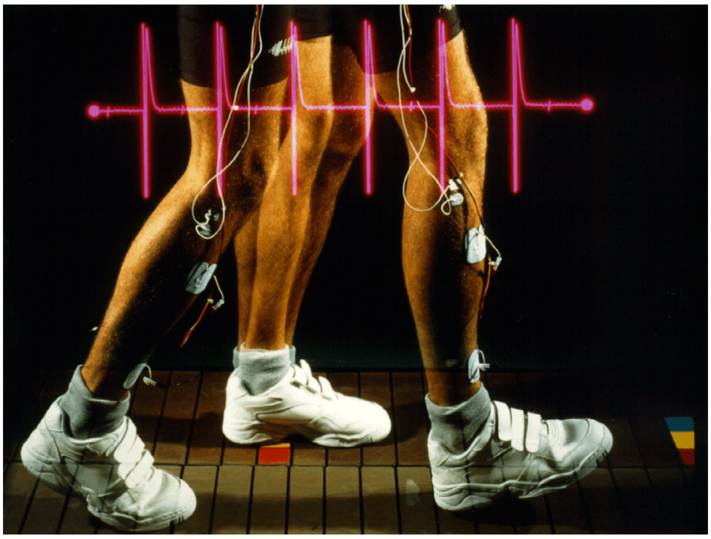

Figure 6: C6 to C7 incomplete SCI subject using the proposed walking neural prosthesis