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GRASPING IN HIGH LESIONED TETRAPLEGIC SUBJECTS USING THE EMG CONTROLLED NEUROPROSTHESIS

Thierry Keller*, Armin Curt*, Milos R. Popovic, Volker Dietz*, Annelies Signer***

*Swiss Paraplegic Center, University Hospital Balgrist, Zurich, Switzerland

**Automatic Control Laboratory, Swiss Federal Institute of Technology, Zurich, Switzerland

Author responsible for correspondence:

Thierry Keller
Swiss Paraplegic Center
University Hospital Balgrist
Forchstrasse 340
CH - 8008 Zurich
Tel.: +41 1 386 37 36
Fax: +41 1 386 39 09
e-mail: kellert@balgrist.unizh.ch

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ABSTRACT

A four channel functional electrical stimulation system with surface electrodes was developed and tested to give individuals with complete C4 and C5 tetraplegia a possibility to perform a grasping function. The proposed neuroprosthesis is EMG controlled, and it is voluntarily activated using the deltoid muscle of the contralateral arm. The duration of the processed "above the threshold" EMG signal was used to control the duration of the grasp, and the amplitude of the EMG signal was used to control the grasp strength.

The following are the benefits of the proposed system: 1) restoration of the lost grasping function; 2) natural and easy to train control of hand opening and closing; 3) smooth adjustment of the grasping force; 4) a subject can use natural control strategies to control the prosthesis; and 5) the control algorithm is easy to integrate into a micro-controller device.

Functional tests with a subject with C4 to C5 complete tetraplegia showed that the system significantly increased subject's independence in performing everyday tasks. The limiting factor for using the proposed neuroprosthesis was the fatigue of the proximal arm muscles. Surprisingly, the fatigue of the finger flexors, finger extensors and the contralateral arm deltoid[1] muscles were not the limiting factor.

KEYWORDS: rehabilitation, functional electrical stimulation (FES), EMG control, grasping, tetraplegia

[1] Note that the deltoid muscle of the contalateral arm was used to control the prosthesis.

INTRODUCTION

The restoration of grasping is one of the main concerns in the rehabilitation of individuals with tetraplegia. Commonly applied technique to control grasping in individuals with C5 to C7 spinal cord injury (SCI) is to use the tenodesis effect [5]. Another option is to use functional electrical stimulation (FES) [6]. The majority of the FES systems that are already available or will become available in a recent future use either position transducers (shoulder position transducers [1] and wrist extension/flexion transducers [2]) or push-buttons [3] to control grasping. The push-button approach is the simplest and easiest to implement, but it can only allow a control of the grasping time and not a control of the grasping force. Although, the existing shoulder transducers allow control of both grasping time and force they require an unnatural limb movement to activate the system [1]. This motion makes the system somewhat unattractive for the potential users. The best of these three methods is the wrist extension/flexion transducer, but its limitation is that it can only be used for individuals with C6 or lower level SCI. Since we were looking to design a FES system for individuals with C4 to C5 SCI we could not use the wrist extension/flexion transducers. Instead we proposed to use EMG activity to control our prosthesis. The EMG activity of two independently and voluntary controlled muscles was used to control the prosthesis.

The results presented in this paper were obtained with a 34 years old male subject T.M. with C4 to C5 SCI. The subject was trained for two months with the proposed prosthesis before the published results were recorded.

METHODS

The proposed neuroprosthesis consists of three main parts:

1) the EMG amplifiers and data processing unit;

2) the control program written in Lab-VIEW® which was running on a Pentium PC;

3) the FES device with surface electrodes;

The commercially available Myolab II® system [4], from the Motion Control Inc., was used to measure the EMG activity. The active EMG electrodes were placed on the ventral and dorsal branches of the contralateral deltoid muscle. For each recorded muscle three Niko® pre-gelled disposable surface electrodes were used. The subject was trained to activate two deltoid muscle branches independently. He achieved a very good selectivity with the proposed system. Co-contraction occurring as a result of support activities of the upper body were suppressed by subtracting the processed EMG signals from both deltoid muscle branches. The stimulation artifacts were suppressed using the same approach. The output of the Myolab II® system were two rectified and lowpass filtered analog signals proportional to EMG activity of both branches of the deltoid muscle. The EMG system was battery powered and was galvanically separated from the PC. The setting of the gains of both EMG signals was done with the Myolab II® hardware. The EMG signals from the Myolab II® were AD converted and processed with a software package written in the LabVIEW®.

Finger extension was initiated when the ventral activity was stronger than the dorsal activity of the deltoid muscle. On the other hand, if the dorsal activity was stronger than the ventral activity, finger and thumb flexion were performed. The amplitude of the difference between the ventral and the dorsal EMG signals was used to control the width of the stimulation pulses, which varied from 0 to 300 μs. The pulse width of the stimulation signal was used to control the force exerted by the subject's hand. Flexibility, provided by the control program, to sequence stimulation channels to perform co-contraction, allowed the subject to generate a more ergonomic hand configuration and better grasping strategy. For each stimulation channel the pulse amplitude, the pulse frequency and the maximum pulse width were set independently.

The stimulator was capable of stimulating four muscle groups with surface electrodes. The amplitudes of the stimulation pulses were in the range from 0 to 120 mA and the pulse widths were in the range between 0 and 500 μs (in our experiments the maximum pulse width was set to 300 μs). The stimulation frequency ranged from 20 to 50 Hz. Self-adhering surface electrodes from Pals® were used to stimulate the desired muscle groups. The system is now being redesigned in order to obtain a portable version of the system (see Figure 1).

The finger flexion was performed by stimulating the flexor digitorum superficialis and the flexor digitorum profundus, and 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.

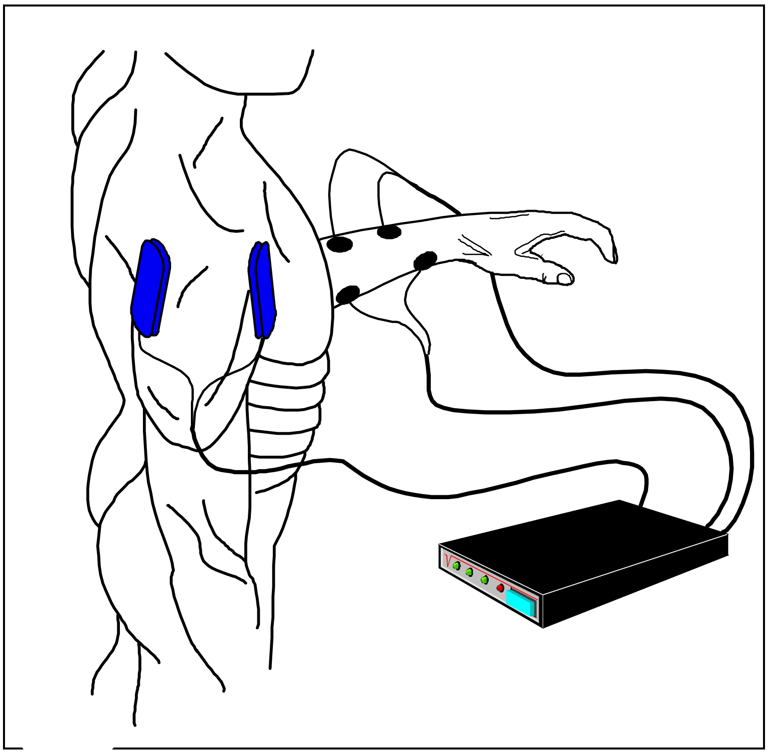

Figure 1: The proposed microcomputer that controlled FES grasping system

RESULTS

As a first step, the subject was trained to voluntarily control the deltoid muscle of the contralateral arm, which EMG signals were used to control the proposed prosthesis. After a training period of two weeks the subject was able to activate two branches of the deltoid muscle selectively, even when the subject was moving the arm in the transverse plane. This was a very important feature which allowed the subject to reach and grasp an object simultaneously. Without it, the subject would be restricted to either perform the reaching function or the grasping function, not both of them. In addition, the subject often used the contralateral arm to stabilize the upper body during reaching and grasping motions, which caused additional EMG activity of the deltoid muscle. Even though an additional EMG activity of the deltoid muscle was present (the subject used a co-contraction of both branches of the deltoid muscle to stabilize its upper body), the subject was able to selectively control the prosthesis.

To find the best positions for the electrodes and to prepare the subject for stimulation through a muscle strengthening program, a time period of five weeks was required.

The subject with the proposed prosthesis was able to perform either palmar or lateral grasp, but not both of them. The palmar grasp was used to grasp bigger and heavier objects such as cans, bottles, electrical shaver, etc. (see Figures 2 and 3). The lateral grasp was used to grasp smaller and thinner objects such as keys, paper sheets, floppy disks, etc. The pinch grasp, which is used to hold a pen, was obtained using the palmar grasp strategy.

Figure 2: The subject with complete C4 tetraplegia performs an EMG controlled grasping of a phone receiver: 1) finger extension was controlled by the EMG signal from the ventral branch of the contralateral deltoid muscle; 2) and 3) palmar grasp was controlled by the EMG signal from the dorsal branch of the deltoid muscle;

Performance of the palmar grasp prehension required the following stimulation pattern: the stimulation amplitude for the flexor digitorum superficialis and the flexor digitorum profundus was set to 27 mA, and the stimulation amplitude for the median nerve was set to 14 mA. The pulse width varied from 0 to 300 μs. Performance of the prehension for lateral grasp was generated with the following stimulation pattern: the stimulation amplitude for the flexor digitorum superficialis and the flexor digitorum profundus was set to 27 mA, and the stimulation amplitude for the thenar muscle was set to 14 mA. In the lateral grasp the activation of the thenar muscle was initiated only when the deltoid EMG signal exceeded 60% of its maximum amplitude.

To release an object or to open the hand, the extensor digitorum muscle was stimulated with a pulse which amplitude was 25 mA and its width was in the range from 0 to 300 μs. To prevent wrist extension and flexion the subject wore a leather cuff (see Figure 3).

Figure 3: The subject with complete C4 tetraplegia performs an EMG controlled grasping of a milk containing, Tetra-Pack®.

Since the subject had some afferent nerves intact, a compromise between best comfort and the grasping force had to be made. The maximum force of 10.2 N for palmar grasp could be measured (Table 1). This maximum force declined exponentially and within seconds reached the half of its initial value. Once the force reached one half of the maximum value it remained at that level for a prolonged period of time (60s). It is important to mention that the stimulation frequency during these trials was set to 30 Hz.

In practical tests the patient was able to grasp, lift and place a cylindrical object which weighted 250 g and had a diameter of 5 cm. The following skills could be achieved with the proposed grasping neuroprosthesis: 1) lifting of a telephone receiver, dialing a number, maintaining a conversation for a minute and to hanging up; 2) pouring 3 dl of a liquid out of a bottle into a glass and drinking it; 3) grasping an apple and eating it; 4) grasping a pencil and writing for 2 minutes.

One hour session	initial force	end force	meas. time
staring session	10.2 N	7.6 N	4.3 s
middle of session	7.4 N	5.7 N	9.9 s
end of session	9.9 N	5.9 N	14.4 s

Table 1: Palmar grasping force measurements

The above results were obtained with the subject that was trained for 12 weeks (including the EMG training and the muscle strengthening program), twice a week for an hour. We believe that much better results could be obtained with the subject if he was allowed to take the system home and use it in daily activities.

DISCUSSION

The experiments with the subject indicate that the proposed FES system is easy to use and the subject can intuitively learn how to control it. After two months of training with the prosthesis the subject with C4 to C5 SCI showed significant improvement in grasping ability as a result of using the proposed neuroprosthesis. It is important to mention that the proposed system is designed for SCI subjects that have at least some control over one arm's biceps and shoulder.

The limiting factor for using this FES system is neither the fatigue of finger flexor and extensor muscles, nor the fatigue of the muscles used to control the prosthesis, but the fatigue of the proximal arm muscles. Therefore, the stronger the proximal arm muscles are the longer the prosthesis can be used.

Our future work is aimed at improving the way in which the surface electrodes are mounted on a subjects skin. In addition, we plan to develop a portable version of the proposed neuroprosthesis that SCI individuals could use to perform a variety of daily activities.

ACKNOWLEDGEMENTS

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FIGURES

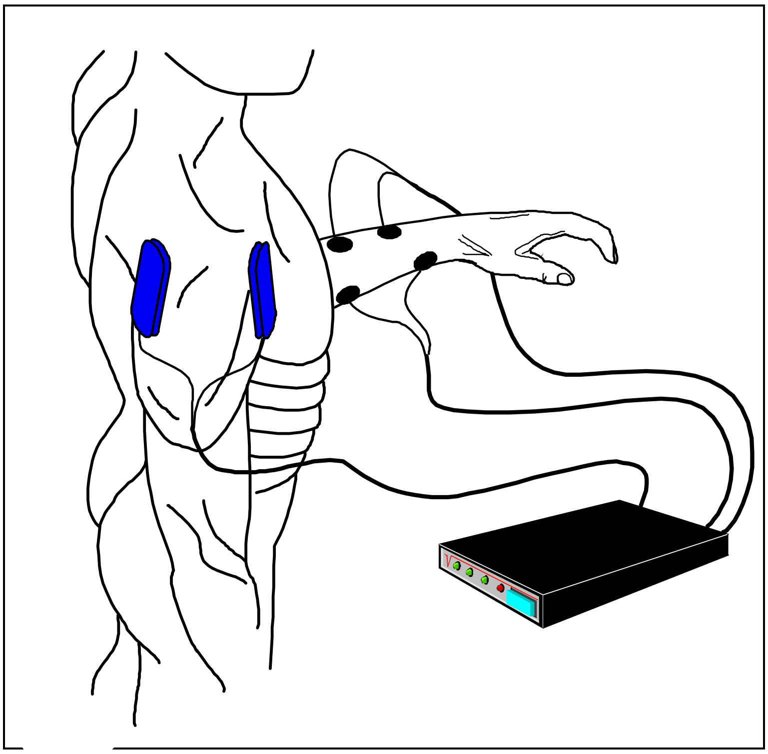

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Figure 3: The subject with complete C4 tetraplegia performs an EMG controlled grasping of a milk containing, Tetra-Pack®.

FIGURE LEGENDS

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TABLE

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