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An EMG-controlled grasping system for tetraplegics

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Abstract—A two-channel, portable, battery operated, functional electrical stimulation (FES) system with surface electrodes to enhance grasping in tetraplegics was developed and tested. This system is meant for tetraplegics capable of grasping by tenodesis. Candidates for this system must retain some wrist extension, and have paralyzed but innervated finger flexors, and nearly normal shoulder and elbow coordination within the working space. The control signal that turns the stimulation of forearm finger and thumb flexors on and off is based on the detection of the threshold of the amplified, rectified, and integrated electromyographic recordings using surface electrodes positioned over the wrist extensors. The voluntary contraction of wrist extensors is suitable for triggering the stimulation, and it is reproducible enough for daily home use. The new device was tested on subjects with tetraplegia, and the general conclusions are: 1) the system increases the strength of the grasp; 2) no side effects or related problems were noticed; 3) the training period is short; 4) the reliability of the operation is good; and, 5) the design of the analog part of the system allows its easy integration into a computerized device. Functional tests of the system showed that some of the study subjects did not benefit from this approach due to disuse and denervation types of muscle atrophy of their finger flexors, lack of controllable wrist extension, curled resting position of distal and proximal interphalangeal (IP) joints, and/or inability to bring the thumb in the opposition of fingers.

Key words: *EMG control, grasping, tetraplegia.*

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INTRODUCTION

Functional electrical stimulation (FES) can restore limited control over absent or abnormal function in persons who have suffered spinal cord injury (SCI). In persons with tetraplegia, FES can provide grasping by external control of the paralyzed muscles in the forearm and hand (1). The Case Western Reserve University (CWRU) fully implantable FES device is the only one used for the assistance in daily living functions (2). The functional evaluation of the CWRU system has shown that there is substantial improvement in simple grasping tasks (3). More than 25 such systems are in use around North America. The CWRU system is meant for subjects with tetraplegia who retain some voluntary elbow flexion and extension, innervation of some forearm and hand muscles, and limited or no wrist control.

Wrist motion is essential for augmenting the fine motor control of the fingers and hand (4). Positioning of the wrist in the direction opposite that of the fingers alters the functional length of the digital tendons so that maximal finger movement can be attained; this is called tenodesis. Conversely, some flexion of the wrist puts tension on the long extensors, causing fingers to open automatically and aiding full finger extension. The wrist extension is caused by two groups of muscles: 1) extensor carpi radialis longus and brevis (extension of wrist, radial deviation); and 2) extensor carpi ulnaris brevis (extension of wrist, ulnar deviation). The range of wrist movement required for normal functioning is 10° flexion and 35° extension (5). This range was determined to be necessary for the following seven functional activities: lift glass to mouth, pour from pitcher, cut with knife, lift fork to mouth, use telephone receiver and push-button dialing, read newspaper, rise from chair; and seven personal care activities (touch

of head occiput and vertex, shirt neck, chest, waist, sacrum, and shoe). When the wrist was immobilized, the best performance was achieved having the wrist in a 15° extension (6).

Some persons with tetraplegia retain wrist movement and are able to grasp using a tenodesis. However, the grasp generated with a tenodesis is rather weak, and heavier object handling (e.g., opening a door, picking up a camcorder battery or VCR tape, holding a book, etc.) is frequently not feasible. In addition, in order to hold an object by using tenodesis, it is necessary to maintain the wrist extension during manipulation, and this is difficult or even impossible. Subjects who are able to use tenodesis for limited grasping typically have innervated finger flexors, but they are not controllable volitionally. The hypothesis tested in this research was that a rather simple system of myoelectric control signals from the same extremity can improve the grasping function by enhancing the flexion of fingers, including the control of a thumb position. In order to develop such a system, it is necessary to answer two questions: 1) What is the best location to record myoelectric activity? and 2) Which muscles and nerves are to be stimulated to elicit functional movement that enhances tenodesis grasp?

The literature dealing with this problem describes several possible approaches. FES systems to allow grasping can be divided among the origin of control signals to trigger or regulate the stimulation pattern: 1) shoulder control (7–9); 2) voice control (10,11); 3) respiratory control (12); 4) joystick control (1,2); and, 5) position transducers (13–15). A division can be made upon the method of delivering patterned electrical stimulation: 1) one to three channels to different muscle groups via surface electrode systems (14–16); 2) multichannel surface stimulation system (11); 3) multichannel percutaneous systems with intramuscular electrodes (7,10,12); and 4) fully implanted systems with epimysial electrodes (2).

Prochazka (15) suggested a very similar system that uses a wrist-controlled sensor to trigger the stimulation of muscles enhancing tenodesis grasp in a device called the Bionic Glove (patent pending). A glove with the sensor detects wrist movements and sets both the parameters of stimulation of each of three channels and the range of extension and flexion to turn the stimulation on and off. The glove contains the stainless steel mesh contacts for surface stimulation with conductive polymer-based electrodes. A microcomputer built into the battery-operated unit controls three channels of stimulation of the finger and thumb flexors and the thumb extensors. Everyday tuning of both the level of stimulation and the thresholds for control is automatic and requires only a voluntary wrist movement from neutral position to the maximal extension.

Since the introduction of myoelectric or electromyographic (EMG) control to limb prostheses, there have been many attempts to use myoelectric signals for the control of prostheses with multiple degrees of freedom (17–19). These attempts have been prompted because persons with high-level arm amputations frequently need multifunctional artificial arms but have limited muscle sites that are practical as myoelectric signal sources. The most successful myoelectric artificial limbs, below-elbow myoelectrically controlled hands, such as, the Utah artificial arm (20) and the Otto Bock myoelectric hand are in daily use.[1]

The EMG is a convenient control signal, because it does not need external energy, its activity follows the grasping process naturally, and eventually it will be possible to implant a system that will include both the stimulation and the recording electrodes. In this study we investigate the feasibility and preliminary functionality of an EMG-controlled FES grasping system applied to persons with SCI. This device employs surface stimulation of the finger flexors, and it is practical, portable, simple to don and doff, and easy to master.

The study was divided into four contiguous phases: 1) off-line analysis of the control signals; 2) design of the hard-wired electronic circuitry; 3) synthesis of the grasp; and, 4) testing of the device in tetraplegics.

OFF-LINE ANALYSIS OF CONTROL SIGNALS

The goals of this part of the study were to determine a processing technique suitable for control of the electrical stimulation of muscle nerves and to test the reliability of the device in subjects with tetraplegia.

Subjects

Six neurologically complete SCI subjects, between 20 and 45 years of age, were selected for the study from a group of 12 volunteers classified as complete or incomplete C4 to C6 levels. The volunteers were screened in an initial testing session to verify the presence of voluntary wrist movements (extension and flexion), voluntary control over biceps and triceps muscles function, normal passive range of movements, stability while sitting, and that the subjects had preserved ability to grasp using the tenodesis. The test

[1] Personal phone communication with Mr. Pike, November 1993.

included electrical stimulation of the forearm finger flexor muscles with surface electrodes using a custom-built stimulator. This test showed how a specific patient tolerates pain and discomfort (if any), and how the stimulation affects the wrist movements. The stimulating electrode (cathode) was positioned as close as possible to the wrist, while the anode was positioned at the middle of the forearm. The thenar muscle group was used for thumb flexion control. All subjects signed the informed consent approved by the local ethics committee.

The initial screening eliminated 6 of the original 12 SCI subjects for one or more of the following reasons: 1) limited or no response to stimulation (two subjects); 2) involuntary tremor while generating maximal voluntary contraction (MVC) of wrist extensors (two subjects); 3) lack of wrist extensor control (two subjects); and, 4) curling of the IP joints in the neutral position of the hand (three subjects).

Methods

The signals were recorded using three surface, disposable, self-adhering electrodes with 3.2 cm diameter (Encore Plus, Uni-Patch Inc., Wabasha, MN 55981), QT-5B low-noise preamplifier (Leaf Electronics, Edmonton, Alberta), and custom-designed biopotential amplifier (M. Gauthier, Edmonton, Alberta). The data were digitized at 10 kHz using an ADC 2838 (Data Translation, MS, USA) expansion board in a PC-IBM compatible computer (Gateway 2000-66E). The digital processing of the recorded signals included full wave rectification and low-pass filtering (21). We used DADiSP software (DSP Development Corporation, MA, USA) for the processing and analysis of these amplified, rectified, integrated, and smoothed EMG signals.

Results

All study subjects were asked to elicit MVC of their wrist extensors, maintain it for about 2 seconds, and then relax. This procedure was repeated in all subjects for several minutes during at least five sessions. The aim was to determine a reproducible, easy-to-elicit signal that can serve as the trigger for the commencement, as well as for the termination, of the stimulation of forearm finger and thumb flexors.

The EMG recordings depend upon the placement of the electrodes, skin, and electrode impedances (**Figure 1**). However, the analysis of the processed recordings in the same subject in day-to-day sessions, when mounting electrodes at more or less identical positions (the electrode positions were marked at the skin), showed a producible pattern of EMG recordings. No two EMG signals are identical: both amplitude and frequency spectrum vary. The rectified and amplified EMG recording always has a visible peak when the subject elicits and maintains a strong voluntary muscle contraction compared to the recordings made when resting the wrist extensors. The variability, even though very great (**Figure 1**), is not significant, as only a threshold method is adopted for control.

The effect of muscle fatigue has to be taken into account (**Figure 2**). During about 30 minutes of testing in the same subject, the peak of the integrated rectified EMG signal (RMS ≈ 100μV) dropped to about 60 percent compared to its maximal value (RMS ≈ 250μV) at the beginning of the test (22).

The use of the threshold method of the integrated, rectified, and amplified EMG signal emerged as an effective control signal. This strategy follows the adopted approach of voluntary control of turning the stimulation of

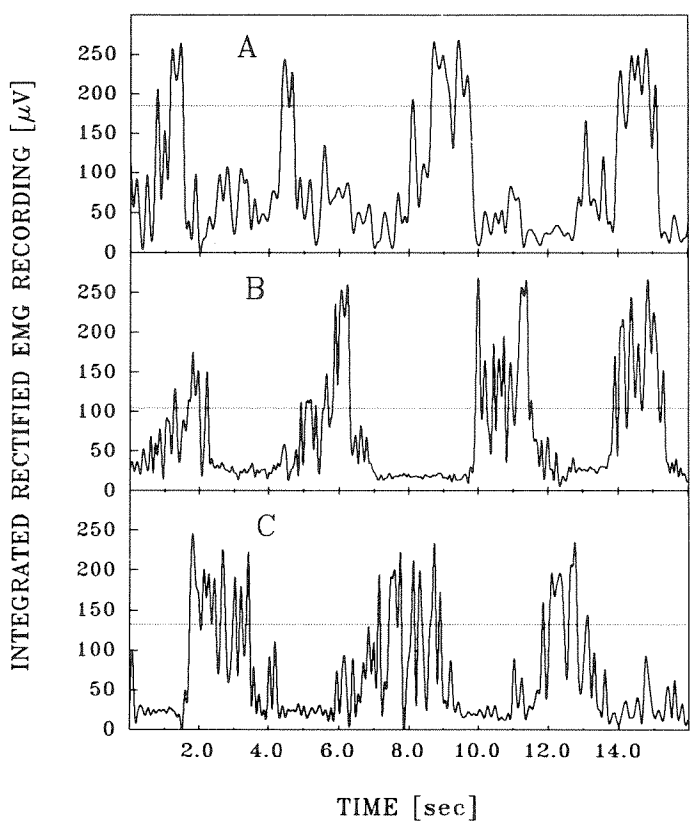

Figure 1.
The EMG from several consecutive contractions of three different subjects. Each of the recordings has a different threshold (dotted lines), showing that even though the activity varies from subject to subject, it is plausable to use the threshold method for triggering.

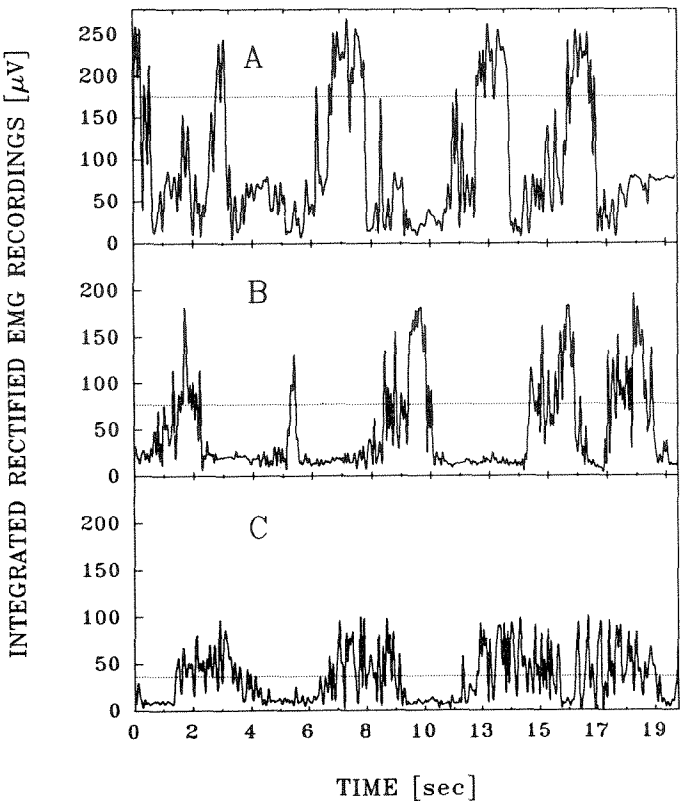

Figure 2.
The recordings from one untrained tetraplegic subject (C5/C6, complete lesion), 7 years after injury. The recordings show three short intervals from a long recording session (≈ 30 min). The top trace is from the first minute, the second is from the 15th, and the bottom one is from the last 20 seconds.

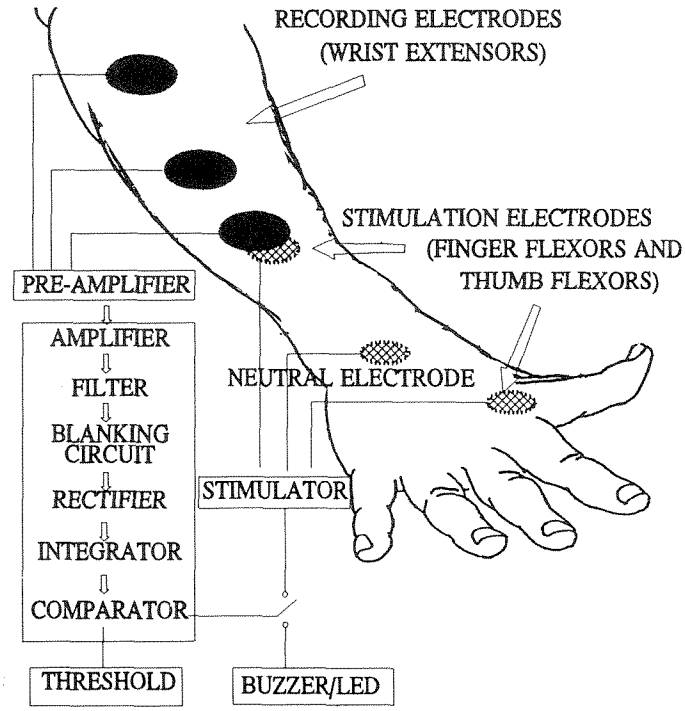

Figure 3.
The block diagram of the portable, battery operated recording and two-channel stimulation system. The first stage of the device includes a low-noise, high-common-mode-rejection ratio preamplifier. Optical isolation is used to separate the stimulating and the recording parts of the device. The stimulator controls the blanking device to ensure that the stimulation artifact and evoked potential are eliminated from the integrated EMG. The threshold level selection is realized with a simple voltage divider, and can be set any time during the operation. Visual (LED) and audio feedback (buzzer) are parts of the system to allow the setting of the threshold prior to functional use.

finger and thumb flexors on and off. The volar side of the forearm was found to be an appropriate location for recording when applying a system that uses an enhanced tenodesis for grasping, because it was possible to eliminate stimulation artifacts when the dorsal side of the forearm was stimulated.

DESIGN OF THE ELECTRONIC CIRCUITRY

Based on the off-line analysis using a bench system, a battery operated, portable, low-power device was designed (**Figure 3**). Three recording electrodes, described above, were connected to a custom-designed preamplifier characterized by a low-noise, high-impedance, high-common-mode-rejection ratio (CMRR). This preamplifier has a pair of junction field effect transistors (JFET) at the input, followed by the instrumentation amplifier (CMRR > 100 dB, A = 100, f∈100–10,000 Hz). The signal was fed to a cascade consisting of a response-conditioned (RC) high-pass filter with gain (f > 100 Hz, A = 100), a full-wave precision rectifier, and a blanking device. The blanking device switches the output of the amplifier to the ground when the stimulation pulses are delivered to the appropriate motor nerves. The blanking period is adjustable in the range of 100 μs to 20 ms. During the blanking period the input to the integrator is zero.

The signal was then binary integrated, with 10 ms intervals, and fed to the input of a comparator. The second input of the comparator can be set to a predetermined voltage level at any time during operation. Once the integrated EMG crosses this threshold level, the comparator output goes "high." This control signal changes the state of a flip-flop that triggers the stimulator. The following

MVC resulting with the EMG crossing the threshold turns the stimulator off. The timing circuit disables two consecutive trigger signals in an interval shorter than a preset time; that time is 2 seconds at present.

A custom-designed, two-channel, constant current stimulator, with variable parameters of stimulation within the following limits: I = 0–50 mA, f = 10–50 Hz, T = 10–500 μs was used. The output current can be regulated linearly by changing the value of the electrical resistance connected to the output.

The recordings with the designed device were comparable with recordings obtained using the bench system described previously. The results of each of the phases of processing are presented in **Figure 4** for a single subject, during a session in which the forearm finger flexors and thenar muscle group were stimulated with surface electrodes.

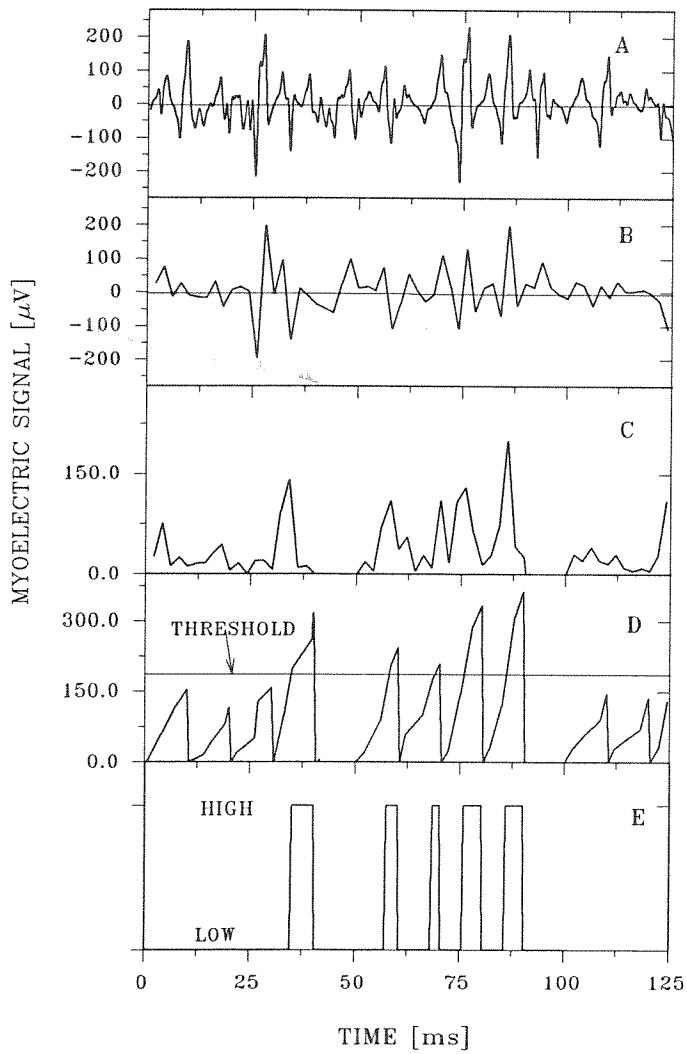

Figure 4.
The signal shape at various stages of the analog processing board. The top trace (A) shows the preamplified signal. This signal is then further amplified and filtered (B), full-wave rectified (C), and integrated with a time constant of 10 ms (D). The peak level that this integrated signal reaches is compared with a fixed predetermined threshold level. The reference level is shown in D. If the integrated EMG exceeds this level, then the output of the comparator is set high (E). Notice that every 50 ms, the rectified EMG is equal to zero for a period of 10 ms (i.e., the blanking circuit grounds the output).

SYNTHESIS OF THE GRASP

Subjects

The same population of subjects participated in this phase of the project, after signing a consent form.

Methods

Using a small probe electrode (1 cm^2) as a cathode, and a large neutral electrode positioned close to the wrist, the motor point of the finger flexors was determined and marked on the skin. Once the position of the stimulating electrodes for each user was determined, the parameters of stimulation were selected to cause a firm grasp without pain or discomfort. It was possible to use very similar parameters of stimulation in all subjects: T = 200 μs, f = 20 Hz, I = 35 mA, monophasic charged compensated pulses. The selective stimulation of finger flexors without activation of wrist flexors was not an easy task when surface electrodes were used. Positioning of the electrodes for the thumb flexors was simple, and small variations in the positions of the electrodes did not play a major role (**Figure 5**).

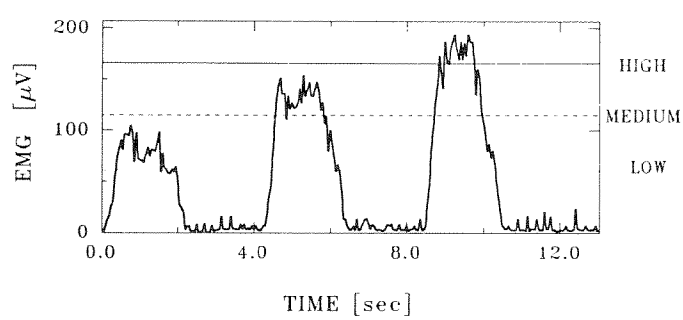

Figure 5.
Multi-threshold control strategy with three levels recorded in a C5 tetraplegic subject. He could control his wrist extension to elicit maximum voluntary contraction or only a fraction of it, but he was not able to maintain the desired level, and he had great difficulties in reproducing the preferred pattern. It was essential to provide him with three-stage feedback (three sounds from the buzzer).

The SCI subjects were trained to experience the stimulation of the finger flexor muscles, while volitionally contracting their wrist extensors simultaneously to generate maximum voluntary contraction. The stimulation was controlled by the physiotherapist. The device was designed with two modes to show when the EMG activity crossed the preset threshold level: an LED and a buzzer. These elements are used as a visual or audio feedback during the training period, as well as for everyday selection of the threshold levels. The SCI subjects were told during the training period to contract their wrist extensors in such a manner as to turn on the LED and buzzer, and to repeat a similar contraction when they wanted to stop the stimulation. Three 30-minute sessions were sufficient to train each of the subjects to control the system with a false triggering rate of less than 0.5 percent.

A potentiometer mounted at the front panel of the device allows the subject to select the threshold on his own, after the positioning of the recording electrodes and a few voluntary contractions of the wrist extensors. The subject adjusts the threshold according to the feedback from the LED or buzzer while volitionally contracting his wrist extensors. The potentiometer is used to adjust the gain of the amplifiers, in case the artifact pickup interferes with the voluntary activation of the device. The adjustment of the gain, if necessary, is done by the subject, when stimulation pulses are delivered, and the recording system is turned on. If the stimulation can turn the system on or off without the contraction of wrist extensors, the gain of the amplifier has to be turned down. It is rarely necessary to change the gain of the device because the artifacts are relatively constant in a given subject. Setting the threshold allows adaptation to effects of impedance changes (drying of electrodes), muscle fatigue, and similar events.

The device has independent control of the stimulation level for each stimulation channel. The subject controls the stimulation delivered to his motor nerves by changing pulse amplitudes. The level of stimulation was selected by the patient when he used video or audio feedback during the stimulation while performing some routine activities. The level of stimulation stayed very much the same, and the adjustments were typically done to reduce effects of muscle fatigue only when the system was used for longer periods. However, once the muscle had fatigued it needed several hours to fully recover, and increased stimulation strength did not improve the grasp.

Results

The subjects were asked to perform a set of typical daily activities selected following the evaluation of the shoulder control in the multichannel implanted functional neuromuscular CWRU stimulation system (3). Ten activities were studied; the final score for each task, both with and without the assistive system was defined from interview data, video recordings done during the sessions, and patient files maintained during the testing (**Table 1**). It was

Table 1.
Activities performed with (Yes) and without (No) the system.

Functional Task	Subject 1			Subject 2			Subject 3			Subject 4			Subject 5			Subject 6		
	No	Yes	Δ	No	Yes	Δ	No	Yes	Δ	No	Yes	Δ	No	Yes	Δ	No	Yes	Δ
Eating With A Fork	1	1+	+	1	1		1	1+	+	0	1	1	1	1+	+	0	1	1
Drinking From Glass	1	1+	+	1	1+	+	1	1+	+	1	1		1	1+	+	1	1+	+
Eating Finger Foods	1	1+	+	1	1+	+	1	1+	+	0	1	1	1	1+	+	1	1+	+
Brushing Teeth	0	1	1	1	1+	+	0	1	1	0	1	1	1	1+	+	0	1	1
Applying Toothpaste	0	1	1	0	1	1	0	1	1	1	1		0	1	1	0	1	1
Using Telephone	0	1	1	1	1+	+	1	1+	+	1	1		1	1		1	1+	+
Handling A Disk	0	1	1	1	1		0	0		0	0		1	1		0	0	
Holding A Book	1	1+	+	1	1		1	1+	+	1	1		1	1		1	1+	+
Writing	1	1+	+	1	1+	+	0	0		0	1	1	1	1+	+	0	0	
Drinking From Mug	1	1		0	0		1	1		1	1		0	0		1	1+	+
TOTAL(S)	6	10	4 (5)	8	9	1 (5)	6	8	2 (5)	5	9	4 (0)	8	9	1 (5)	5	8	3 (5)

Δ = difference in performance by using system; numbers in parentheses = functions where noticeable improvement was seen; numbers without parentheses = functions performed with the system only; 1 = success; 0 = failure; + = noticeable improvement

found that grasping was improved for most of the activities; hence, this device improved the quality of daily living in a selected group of subjects with tetraplegia. The performance of each activity was scored only as **success** marked "1," **failure** marked "0," and **noticeable improvement** marked "+."

Noticeable improvement was given as a grade in the following cases: 1) firmer and stronger grip when manipulating objects (pronation, supination, elbow flexion and extension); 2) enabling the prolonged holding pattern for at least 30 percent compared with no system; and, 3) shortening the time needed to grasp the object by at least 30 percent compared to tenodesis only. The maximum score for each individual subject was 10; hence, the total score for the 6 patients is between 0 and 60. The total score for all study subjects tested without the device was $S = 38$ ($S_{mean} = 6.33$, $\sigma = 1.36$), compared to the score when using the FES system $S = 53$ ($S_{mean} = 8.62$, $\sigma = 0.75$). This score does not include the noticeable improvement in performance. Improvement in grasping function ("+" signs, **Table 1**) was noticed in 25 of 38 function tests (65.68 percent).

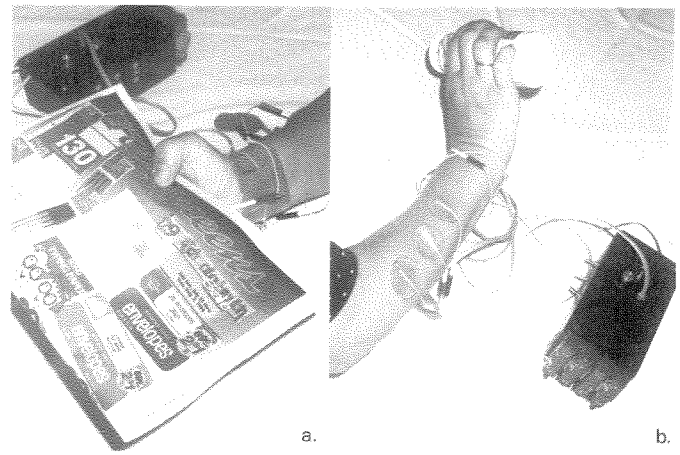

Figure 6.
A forearm of a subject instrumented with the EMG controlled tenodesis enhancement orthosis while holding the newspaper (left), and the little bottle (right). Note neutral and thumb electrodes for stimulation (left), and EMG recording electrodes (right).

DISCUSSION

The designed device works using an on-off controller, and there is no gradation in the force. The use of disposable polymer electrodes that can stay on the skin for several days is very effective, and no side effects have been noticed so far (23). Donning of the system requires minimal help of a somewhat trained person to connect the electrodes to the stimulator and position recording and stimulating electrodes on the forearm. The subject, if necessary, can set the threshold and the gain to suitable levels by using the LED or buzzer feedback.

Prolonged clinical and home use of the device showed that there are no side effects and that SCI subjects may want to use such a system on a daily basis.

It was feasible to grade the strength of the stimulation using the recordings (**Figure 6**) and multi-threshold triggering; hence, the performance can be improved. However, subjects who participated in our study seemed to prefer the single threshold device, because of the simplicity of the application.

It was possible to stimulate motor nerves with variable pulse width using a multi-threshold control strategy, but it required fine tuning of the gain of the device and thresholds. Experiments with this technique are not practical at this point, because the subjects had great difficulty selecting the appropriate EMG level and maintaining it when pronating and supinating.

The device presented has a hardware processing circuit suitable to be incorporated in a micro-computer system. A programmable micro-controller can easily integrate the self-tuning of the sensory part of the system based on initial recordings of the EMG when the wrist is relaxed and when an MVC is generated. In our recent design, with one threshold, it was possible to avoid daily fitting and to use the device for several days on the same subject without any tuning. Adjustment of the threshold of the comparator and the gain of the amplifier was necessary from subject to subject.

The hardware can be replaced with a fully implanted system, and many of the problems (selectivity of stimulation, decreased power consumption, stimulation of several motor nerves to allow controlled thumb flexion and extension in addition to finger flexion, and ease of daily donning and doffing) will be resolved (24).

CONCLUSIONS

The general conclusions are: 1) the system increases the strength of the tenodesis grasp; 2) training period for the use of the system lasts about 30 minutes per session; 3) side effects and related problems were not noticed; and, 4) reliability of the operation is good. Functional tests of the system showed that some subjects do not benefit from this approach, because of the disuse and denervation types

of muscle atrophy of their finger flexors, the lack of controllable wrist extension, the curled resting position of IP joints, and the inability to bring the thumb into opposition.

Another approach to enhance grasping is to use a mechanical brace, but this was intentionally omitted as our approach was to develop a functional device to maximize preserved functions, and eliminate any complicated, custom-fitted, hardware. In addition, the device is: 1) minimally invasive, 2) mounted on one forearm, 3) voluntarily controlled by the same arm, 4) applicable for individuals who are not benefiting from the fully implantable multichannel FES system sufficiently to be encouraged to undergo the implantation, and 5) easy to maintain and apply on a daily basis.

This paper described the feasibility study; hence, a clinical evaluation and comparison with other assistive systems are needed to confirm its performance. The myoelectric tenodesis enhancement device was given to three of the six subjects who participated in the study, for their daily use.

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