EMG-BASED STIMULATION PATTERNS OF FES FOR THE PARALYZED UPPER EXTREMITIES

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Abstract

Stimulation patterns for restoring motor function of the upper extremities in the C4 quadriplegic patient by functional electrical stimulation (FES) is described. The standard stimulation patterns were obtained from the analysis of EMGs measured during upper extremity motion in normal subjects. Input of the maximum and threshold voltage data of muscles to be stimulated into the standard pattern automatically created stimulating data for each patient. This strategy realized well-coordinated and reliable movement of the paralyzed upper extremities. Patient's respiratory activities were utilized as volitional control commands and a C4 quadriplegic could control her upper extremity for activities of daily living (ADL) by using the EMG-based stimulation data.

1. Introduction

Programmed electrical stimulation can restore motor function of the paralyzed extremities induced by upper motor neuron disorders. Recent advances of computer technology have enabled to create very complicated multichannel stimulation patterns for controlling the paralyzed upper extremities with multi-degree of freedom (1-3). On the other hand, determination of temporal and spatial sequence of stimulation controlled by user's commands is required for precise and well-coordinated control of movements of the upper extremities in three dimensional space. However, empirical or textbook-based determination of stimulation sequence often failed to realize the coordination of the movements. Therefore, we have adopted to create standard stimulation patterns from EMGs of the upper extremities during motion in normal subjects (3-5). This paper describes electromyographical analyses of joint movements of the upper extremities in normal subjects and their application to functional electrical stimulation (FES) for the paralyzed upper extremities in a C4 quadriplegic patient.

2. System configuration

Fig. 1 shows a block diagram of a multi-channel FES system which we developed. This system was composed of a personal

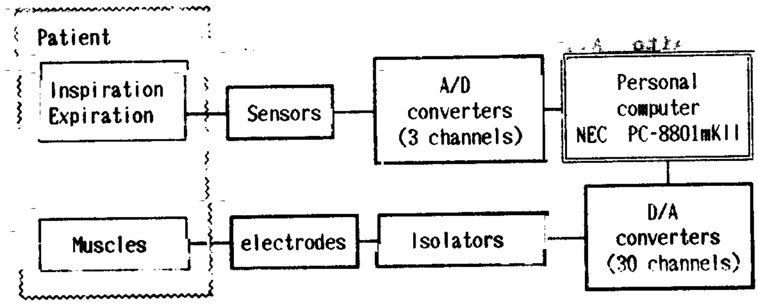

Fig. 1 A block diagram of our multichannel FES system

computer with dual floppy drives (NEC PC-8801 mkII) and a CRT display. For input of analog command signals to the system, 3 channels of A/D converters were used while 30 channels of D/A converters and isolators were connected to the system as stimulating outputs. The isolator consisted of a transformer to eliminate DC component from the stimulus for preventing electrochemical reaction. Amplitude-modurated multichannel pulse trains were used as stimulation waveform.

3. Analysis of EMGs during motion

EMG recordings during tasks of the upper extremities were obtained from 25 normal volunteers. Bipolar intramuscular electrodes made of Teflon-coated stainless steel wires were used for picking up EMG activities. Tip of the electrode was deinsulated and bent back into a hook. A 25 gauge needle was used for introducing the electrode to muscle belly to be examined. A reference electrode was put just above the styloid process of the ulna beneath the skin. Multichannel low noise amplifiers (28 channels) which we developed were used and the signals were fed into two data recorders (Shinkoh RCD-928, 14ch) and two pen recorders (NEC San-ei RECTI-HORIZ). EMG signals were rectified and averaged for analysis of temporal and spatial activities of each muscle during motion. Time constant of EMG averaging was 0.3 sec. Degree of activity of each muscle was represented as percentages by normalizing the averaged EMG values during motion by the value at the time of maximum contraction of that muscle.

Fig. 2 shows averaged EMG activities of muscles of the hand and wrist joint during prehension and release in cylindrical grasp. Opening of the hand was performed by extension of fingers II to V and abduction of the thumb, and resulted in 5-10 degrees of wrist extension. During this movement, the ED, AbPB, AbPL were acting as prime movers and the FCU and ECRB showed moderate activities for stabilizing the wrist joint. Grasp motion caused apparent increases in activities of the wrist extensors and decreases in those of the wrist flexors concomitant with agonistic activities of the finger flexors. Such

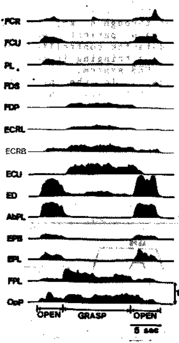

Fig.2 Averaged EMG activities of hand and wrist muscles during cylindrical grasp.

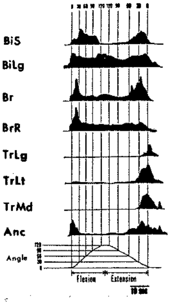

Fig.3 Averaged EMG activities of muscles relating elbow flexion and extension

activities of the wrist muscles seemed to be important for stabilizing the wrist joint to its functional position of 30 degrees of wrist extension.

Fig. 3 shows muscle activities of elbow flexion and extension during cylindrical grasp. This movement was performed in a mid position of the forearm and 45 degrees of shoulder flexion. As shown in this figure, initiation of the elbow flexion was achieved by transient increases in activities of the BiLg, Br, BrR and Anc. Steady activities were obtained in the BiLg, Br and BrR during flexion. Eccentric contraction of the BiLg, Br and BrR was observed during elbow extension. The triceps group was active only in final stage of the elbow extension.

4. Creation of multichannel stimulation data

Based upon analysis of the averaged EMG results, standard stimulation patterns were made by trapezoidal approximation obtained from the averaged EMGs. Fig. 4 shows standard stimulation patterns for tasks to hold a cylindrical object (Fig. 4-a) and to bring it to just in front of the patient's mouth (Fig

4-b). The ordinate and abscissa indicate stimulating voltage data and its memory allocation in each stimulation channel, respectively. For patient's use, the maximum and threshold voltages of each muscle were input through a key board, and thus, stimulation data for each patient were created automatically. The stimulation data for controlling one task such as holding a cylindrical grasp and bringing it to the mouth was registered as one "file" in our FES system. Furthermore, the file was divided into subfiles. In the present case, stimulation data for grasp motion by the wrist and hand was registered as subfile 1. Subfile 2 contained stimulation data for motion of the elbow.

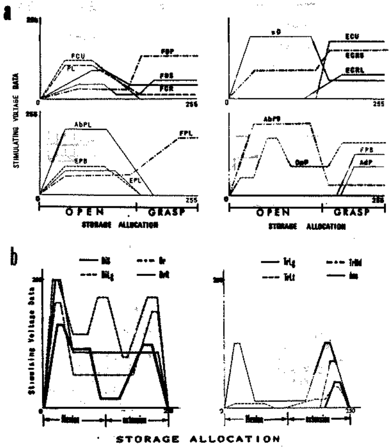

Fig.4 Standard stimulation patterns for cylindrical grasp (a) and elbow flexion and extension (b)

5. Control commands

Fig.5 Respiration sensors(S1,S2) for control commands.

Unidirectional(S1) and bi-directional (S2) ON/OFF sensors operated by inspiration and expiration were used in order to detect control commands for volitional control of the upper extremities (Fig. 5). Control logic for the control commands in the present system is shown in Table 1. S1 which was connected to input channel 1 was for selection and execution commands of the electrically-induced tasks of the upper extremities. Intermittent short expiration from once to four times could call the sub-file 1, subfile 2, "STOP" command and "CHANGE" command of the file, respectively. S2 connected to channel 2 and 3 was for controlling the movements of a subfile selected by expiration of S1. Continuous expiration and inspiration of S2 resulted in readout of memory allocation of the selected subfile with increasing manner (from 0 to 255) and with decreasing manner (from 255 to 0), respectively, and the corresponding multichannel stimulating voltage data were sent to electrodes through D/A converters and isolators. Thus, hand opening and grasp or elbow flexion and extension were controlled independently by the patient herself. Holding of the presently obtained position or task of the upper extremity was provided by stopping the expiration or inspiration of the S2. Stop of the stimulation was performed by S1 expiration three times.

Table 1 Command table

			Number of times			
S1	Ch 1	intermittent	1	2	3	4
		expiration	Subfile 1	Subfile 2	Stop	File select
S2			Subfile 1		Subfile 2	
	Ch 2	expiration	Hand opening		Elbow extension	
	Ch 3	inspiration	Grasp		Elbow flexion	

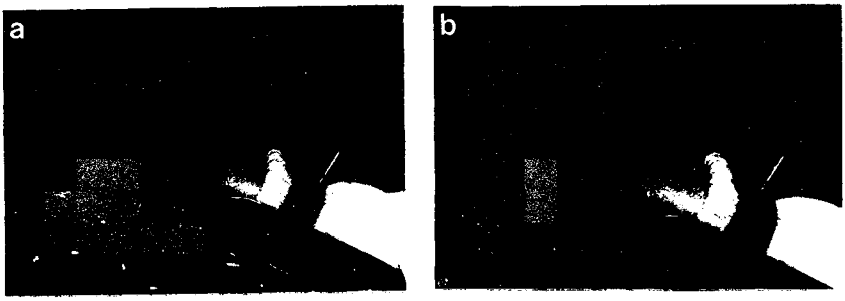

Fig. 6 FES-induced hand movements in a C4 quadriplegic by using stimulation data for cylindrical grasp.
a:hand opening, b:grasp

6. Clinical application

The multichannel FES computer system with a EMG-based stimulation data file was applied to a quadriplegic in order to evaluate system function for restoring motor function of the paralyzed upper extremity. The patient was a C4 quadriplegic whose cervical cord was injured by a car accident 7 years ago. Since active contraction of muscles relating to the right shoulder were not sufficient to perform tasks for activities of daily living (ADL), a balanced forearm orthosis (BFO) was used for helping shoulder movements. Although the elbow flexors were active, their contractile force was not enough to flex the elbow sufficiently even with the aid of BFO usage. The other muscles of her right upper extremity were almost completely paralyzed.

Helically coiled wire electrodes were percutaneously implanted with needles for venous canulation into the paralyzed muscles to be stimulated. For the task by using cylindrical grasp, electrodes were implanted into the following muscles:

1) for the fingers II-V; FDS, FDP, ED
2) for the thumb; EPB, AbPL, AbPB, OpP, FPL, FPB, AdP, PL
3) for the wrist; ECRL, ECRB, ECU, FCR, FCU
4) for the elbow; each head of the triceps and biceps, Br, BrR

Fig. 6 shows hand opening and grasp for holding a cylindrical object by using stimulation data for the hand and wrist muscles which were stored into the subfile 1. As shown here, the wrist joint showed extension of about 10 degrees during hand opening, whereas grasp caused an increase in the angle of wrist extension to about 35 degrees. Such wrist movements during grasp motion induced by FES corresponded to those observed in normal subjects.

Fig. 7 shows an example of FES-induced ADL in the paralyzed upper extremities. When the patient blew the S1 twice, the subfile 2 was selected so that she could extend her elbow by expiration of the S1. Expiration of the S2 following one S1 expiration for the subfile 1 selection resulted in hand opening with the elbow extended (Fig. 7-b). Then she could grasp a can by inspiration of the S2 (Fig. 7-c). After selecting the subfile 2, inspiration caused elbow flexion under the usage of the BFO (Fig.7-d) and she could drink canned tea by her own hand (Fig. 7-e).

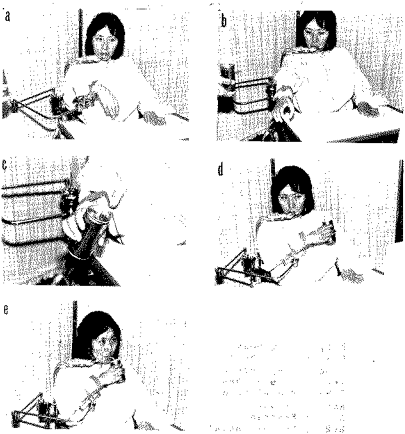

Fig. 7 FES-induced motions for drinking canned tea. a:before stimulation, b:hand opening with the elbow extended, c:holding the can, d:flexing the elbow, e:drinking

7. Discussion

It was found that electromyographical analysis of muscle activities during motions of the upper extremities in normal subjects provided practically useful information in order to restore motor function of the paralyzed upper extremities by FES. This method reproduced almost the same movements of normal EMG volunteers in the paralyzed upper extremity of a C4 quadriplegic by our open-loop FES system. It is noteworthy that coactivation of antagonists, synergists, stabilizers in addition to prime movers of which data were obtained from the EMG analysis realized not only well-coordinated and graded movements but also joint stability of the upper extremities as previously reported (3,6).

In this C4 quadriplegic, however, voluntary shoulder activities was not sufficient to control position of the upper extremity even with the aid of BFO. Setting of the BFO was the most important factor to utilize the FES-induced motion to ADL but was very complicated and time-consuming. Therefore, control of the shoulder by FES is necessary to improve controllability.

Method for picking up the control commands is also responsible for the improvement of controllability. Residual voluntary function of the high cervical cord injury patient is very limited, so that movement of the head (3,7,8) and/or shoulder (2, 3,7,8), voice (8,9) or myoelectric signals (7) have been utilized as control commands. For this C4 patient, however, respiration was thought to be the easiest and most reliable way to control her upper extremity as compared with the other methods mentioned above.

FES for the paralyzed extremities has many problems to be solved. We hope that this would be also one step for dissolving such problems.

Abbreviations

BiLg : Long head of the biceps brachii;
BiS : Short head of the biceps brachii;
TrLg : Long head of the triceps brachii;
TrLt : Lateral head of the triceps brachii;
TrMd : Medial head of the triceps brachii;
Anc : Anconeus;
Br : Brachialis;
BrR : Brachioradialis;
ECRL : Extensor carpi radialis longus;
ECRB : Extensor carpi radialis brevis;
ECU : Extensor carpi ulnaris;
FCR : Flexor carpi radialis;
FCU : Flexor carpi ulnaris;
PL : Palmaris longus;
EPL : Extensor pollicis longus;
EPB : Extensor pollicis brevis;
FPL : Flexor pollicis longus;
FPB : Flexor pollicis brevis;
AbPL : Abductor pollicis longus;

AbPB : Abductor pollicis brevis;
OpP : Opponens pollicis;
AdD : Adductor pollicis;
ED : Extensor digitorum;
FDS : Flexor digitorum superficialis;
FDP : Flexor digitorum profundus

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