Proceedings of the Eighth International Symposium on ECHE,
1984, Dubrovnik

ELECTRICALLY INDUCED HAND MOVEMENTS AND THEIR APPLICATION FOR DAILY LIVING

Y. Handa, Y. Shimada, S. Komatsu, A. Naito,
M. Ichie, Y. Nakatsuchi, R. Yagi, Y. Sugimoto,
K. Iijima, R. Futami and N. Hoshimiya

Abstract

Electrical stimulation was applied to the nerve innervating the extrinsic and intrinsic hand muscles via percutaneous wire electrodes in hemiplegic and/or tetraplegic patients. Movements of the paralyzed hand were investigated by a ten-channel electric stimulator. Based upon these data, functional hand movements were restored in a C6 tetraplegic by multichannel functional electrical stimulation (FES) system developed by us. By this system, the patient could select one mode of prehension from lateral pinch, power grasp and prehension for grasping cards by switch operation and could proportionally control prehension and release by sliding a lever back and forth by himself. Activities of daily living (ADL) obtained by using the hand such as eating, writing, shaving and so on were achieved by the FES system.

Introduction

Functional electrical stimulation (FES) is a powerful means for the restoration of function of paralyzed extremities. Since Liberson and his associates [1] reported FES to the drop foot, much work on the clinical application of FES for the lower extremity has been described [2-4,5-7]. However, the problems of upper extremity FES are considerably more complex than those of lower extremity for the following reasons:

(1) The upper limb has a greater degree of freedom than the lower.

(2) Locomotive movement of the lower extremities is much influenced by primitive reflexes, while conscious awareness and visual concentration are extensively required for the movement of the upper extremities.

(3) The desired movements of the hand are relatively difficult to obtain because the source of control signals utilizing residual voluntary movements of the patient is limited.

In case of C5 or C6 tetraplegics or some of hemiplegics, some function of the upper extremities except the hand remains relatively intact. In these patients, restoration of the hand movements may induce functional usage of the upper extremity for activities of daily living (ADL).

The purpose of this paper is to describe the analysis of the hand movements by electrical stimulation of the nerves innervating the hand muscles and the coordinated hand movements induced by programmed electrical stimulation. In addition, effects of a multichannel FES system developed by us on practical use for ADL are also mentioned.

Materials and Methods

[1] Electrode

A modified Caldwell type of percutaneous electrode described by Peckham et al. [8,9] is used for nerve stimulation. This electrode is a helical coil wound from a teflon-insulated seven strand stainless steel wire (type 316;AM systems) of which basic characteristics on the security as an implanting electrode have been examined by animal experiments. The outermost diameter of the coil is about 0.7 mm, and five millimeters at the tip of the electrode are deinsulated for applying the stimulus to the nerve.

Before implantation of electrodes, approximate location of the nerve to be stimulated was determined by applying electrical stimulation to the skin surface. Then, the electrodes are introduced into the points to be stimulated by means of a hypodermic needle with the hook protruding over the needle tip. This hook is suitable for anchoring the electrode tip to the stimulating point when the needle is removed.

For opening of the hand, electrodes were implanted to the deep branch of the radial nerve innervating the wrist and finger extensors. Motor branches of the median nerve distributing to the opponens pollicis (OPP), flexor digitorum superficialis (FDS) and profundus (FDP) were selected for electrode implantation in order to get palmer prehension and lateral pinch. An electrode was also implanted to the ulnar nerve at the wrist for the motion of grasping cards or newspapers. As indifferent electrodes, one was located just beneath the skin on the forearm on the volar side and another was on the dorsal side.

The skin surface penetrated by the electrode was disinfected and was covered with a sterilized tape.

[2] Stimulating waveform

Figure 1-a shows the relationship between the stimulus pulse width and resulting force of muscle contraction in a C4 tetraplegic who has suffered excercise of electrical stimulation for about two years. The contractile force increased non-linearly accompanied with an increase in stimulus pulse width and reached plateau when the pulse width exceeded more than 0.1 msec. On the other hand, Fig. 1-b shows the relationship between the stimulus frequency and the contractile force when the stimulus pulse width was fixed at 0.2 msec. Although an increase in the frequency caused an increase in the contractile force, it resulted in a time dependent decrease in the contractile force. From these reasons, amplitude modulated rectangular pulses with width of 0.2 msec, of which frequency was 20 Hz, were used for stimulation. In order to prevent the electrochemical reaction at the electrode surface which can cause tissue damage and even electrode failure, charge balance at the electrodes was achieved by using a CR low cut filter.

[3] Design of the multichannel FES system

A block diagram of the FES system developed for prehension and release in the C6 tetraplegic are shown in Fig. 2. In this system, control signal input for the hand movement was achieved by sliding the control lever connected to a potentiometer back and forth (Fig.3-a). When the patient moved the lever forward, the stimulating voltage for release increased. Backward sliding of the lever resulted in a proportional control of prehension. In addition, three switches were prepared for power supply of the system and selection of a prehension mode by patients themselves as shown in Fig.3-b. The patients could select three kinds of prehension modes such as lateral pinch, power grasp and prehension for holding cards or newspapers. These control boxes were mounted on an electric wheel chair as seen in Fig.3-c.

For lateral pinch, activation of FDP and FDS was followed by the contraction of FPL. In case of power grasp, opposition of the thumb preceded the activation of FDS, FDP and FPL caused by the stimulation of the corresponding nerves. The stimulation of the ulnar nerve at the wrist level resulted in prehension for holding cards or newspapers.

[4] Patients

Three patients were selected for the analysis of the hand movements by electrical stimulation of the nerves innervating both intrinsic and extrinsic hand muscles. One was a hemiplegic whose unilateral upper extremity showed almost complete flaccid paralysis without contracture. The second was a C4 tetraplegic with extension contracture of the fingers. The third was a tetraplegic patient at the level of C5 in the left and C6 in the right. The results of the manual muscle testing of the third demonstrated in Table 1. His right fingers had flexion contracture.

The multichannel FES system presented here can be used by the patients who can voluntarily control the elbow and shoulder joints. The third patient, therefore, was selected for applying this FES system.

Results

Figure 4 shows the movements of the hand by the electrical stimulation of each nerve. Stimulation of a deep branch of the radial nerve at middle of the forearm elicited extension of all fingers accompanied by passive extention of the wrist joint (Fig. 4-a). Although complete extension of the interpharangeal(IP) and metacarpal(MP) joints was not obtained in the patient with moderate flexion contracture of the hand, this contracture did not interfere the hand function restored by FES. Opposition of the thumb was obtained by stimuli to a branch of the median nerve to the opponens pollicis (Fig. 4-b). However,the flexors and extensors of the thumb sometimes participated in the thumb movement due to stimulation of a main recurrent branch of the median nerve. Flexion of the IP joit concomitant with flexion of the MP and carpometacarpal (CM) joints of the thumb was clearly observed by the stimulation of a branch of the median nerve distributing to FPL (Fig.4-c). Flexion of the fingers except the thumb was achieved by activation of FDS and FDP (Fig.4-d). Stimulation of the ulnar nerve at the wrist provided flexion of MP joints of II-V fingers and adduction of the thumb (Fig.4-e).

Coordinated movements of the hand were investigated by a ten-channel stimulator developed by us. Activation of FPL following FDS and FDP resulted in lateral pinch (Fig.5-a). In case of the extension contracture, however, the same sequential stimulation failed to restore this prehension pattern because of incomplete flexion of the indicis. Power grasp was achieved by the activation of FDS, FDP and FPL preceded by opposition of the thumb(Fig.5-b). This power grasp was functionally useful in all cases presented here.

In the C6 tetraplegic, his right upper extremity might be functional for ADL if hand movement could be restored, because his supinator and elbow flexors were active as shown in Table 1. For this reason, the paralyzed hand of this patient thought to be applicable to the multichannel FES system mentioned before. For the usage of this system for ADL, sufficient electrical excercise was introduced to this patient in order to get enough muscle force and fatigue resistance.

For the operation of the switch box for power supply and selection of the prehension pattern, movements of the right upper extremity of the patient were used while his left hand with a conventional cock-up splint was for the operation of the control lever. After training of this system, the patient could easily operate the system with minimum visual attension and conscious awareness.

Figure 6 shows the functional movements of the upper extremity for ADL restored by the multichannel FES system. He could utilize the power grasp for holding relatively large objects such as a cup, an electric shaver(Fig. 6-a)and so on. In this FES system, he could actually shave his face over five minutes. Lateral pinch was suitable for holding small and light objects. (Fig. 6-b). However, correct pinching between the thumb and indicis was sometimes difficult for following reasons. Firstly stability of the second and third fingers was not enough to continue to maintain their position against the thumb flexion. This problem was dissolved by binding both fingers. Secondly, if the IP flexion by activation of FPL was too strong, the patient failed to pinch the objects correctly between the side of the indicis and the pulp of the thumb. Participation of the other muscles might be necessary to flex the thumb for lateral pinch. A prehension pattern obtained by the ulnar nerve stimulation at the wrist caused a more powerful grasp which was suitable to hold writing and eating utensils (Fig. 6-c).

Discussion

In oder to control the hand with a number of degrees of freedom, a multichannel stimulator will be needed. Furthermore, well programmed electrical stimulation is required for coordinated movements of the upper extremity. The multichannel FES system presented here partly satisfies this problem. Nevertheless, this system is not sufficient for getting complete independence of the patient for ADL using the upper extremity. Recent advances in micro-computer technology make possible well coordinated multichannel stimulation (Handa et al. in preparation).

It is well known that relationship between muscle strength and stimulus intensity is a non-linear function [10-12] and, thus, effective proportional control of the paralyzed hand has some difficulties in our FES system. Introduction of the reversed function of this non-linear function to the FES system linearlizes the muscle response [10]. For more elegant control, a combination of the feedback control and preprogrammed feed-forward control will be necessary in the FES system. We have already examined the availability of closed loop control in an FES system [13,14]. Some investigators have already presented that an application of a feedback system resulted in optimum control of the paralyzed extremity [10,15,16].

During usage of the multichannel FES system, dynamic properties of the hand muscles was sometimes changed and, in the worst cases, we obliged to reimplant the electrode. Surgical implantation of the electrodes or application of adequate stimulating waveforms may be one of the solution. Nguyen and Vossius [17] have reported an adaptive control system for adjustment of change in the dynamic properties of the controlled system due to varying loads, muscle fatigue and displacements of the stimulating electrodes during movement. Such function may be also essential in the FES system.

As stimulating electrodes, surface [2-4, 18, 19] and implantable [8, 20-22] electrodes have been used in FES system. However, implantable electrodes are considered to be more suitable for an electrical orthotic system especially for the upper extremity because of the following reasons:

(1) Finer and more precise control of each muscle can be achieved.

(2) A sophisticated multichannel stimulating system can be developed owing to an explosive improvement of micro-computer performance.

(3) Power consumption for the stimulation can be lowered.

Since the implanting electrode terminates directly in the excitable tissue, its reliability and security are essential. Peckham et al. [8, 21] have been using the teflon-coated multistrand stainless steel (type 316) electrode which is almost the same as our electrode. They have achieved successful implantation over 540 days in animal experiments. After sufficient animal experiments, we surgically implanted the electrodes to the patients with tetraplegia. These electrodes have been used every day over three hours and no unfavorable problem was observed over 2 years.

Thus, the FES system for the paralyzed hand has been gradually developed toward clinical application.

This work was supported by a grant of the Welfare Ministry in Japan.

References

1) Liberson, W.T., Holmquest, H.J., Scott, D. and Dow, M. :Functional electrotheraphy :Stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. Arch Phys Med Rehabil, 42:101-105, 1961

2) Vodovnik, L., Stanic, A., Kralj, A., Acimovic, R., Gracanin, F., Grobelnik,S., Suhel, P., Godec, C. and Plevnik, S. :Functional electrical stimulation in Ljubljana. In :Hambrecht,F. T. and Reswick, J.B.(eds), Functional Electrical Stimulation :

Applications in Neural Prostheses, pp. 39-54, Marcel Dekker, New York, 1977

3) Vodovnik, L., Kralj, A., Stanic,U., Acimovic, R. and Gros, N. :Recent applications of functional electrical stimulation to stroke patients in Ljubljana. Clin Orthop, 131 :64-70, 1978

4) Vodovnik, L., Bajd, T., Kralj, A., Gracanin, F. and Strojnik, P. :Functional electrical stimulation for control of locomotor systems, CRC Crit Rev Bioeng. 63-131, 1981

5) Waters, R. and Montogomery, J. :Lower extremity management of hemiparesis. Clin Orthop, 102 :133-143, 1974

6) Waters,R.L., McNeal, D.R. and Perry, J. :Experimental correction of foot-drop by electrical stimulation of the peroneal nerve. J Bone Joint Surg(Am), 57 :1047-1051, 1975

7) Waters,R. :Electrical stimulation of the peroneal and femoral nerves in man. In :Hambrecht, F.T. and Reswick, J.B. (eds.). In Functional Electrical Stimulation :Applications in Neural Prostheses, pp. 55-64, Marcel Dekker, New York, 1977

8) Peckham, P.H. and Mortimer,J.T. :Restoration of hand function in the quadriplegic through electrical stimulation. In :Hambrecht, F.T. and Reswick, J.B.(eds.), Functional Electrical Stimulation :Applications in Neural Prostheses, pp. 83-95, Marcell Dekker, New York, 1977

9) Peckham, P.H., Mortimer, J.T. and Marsolais, E.B. :Controlled prehension and release in the C5 quadriplegic elicited by functional electrical stimulation of the paralyzed forearm musculature. Ann Biomed Eng, 8:369-388, 1980

10) Crago, P.E., Peckham, P.H. and Thrope, G.B. :Modulation of muscle force by recruitment during intramuscular stimulation IEEE Trans Biomed Eng, 27 :679-684, 1980

11) Crochetiere, W.J., Vodovnik, L. and Reswick,J.B. : Electrical stimulation of skeletal muscle-A study of muscle as an actuator. Med Biol Engin, 5 :111-125, 1967

12) Merletti, R., Acimojvic,R., Grobelnic,S. and Cvilak,C. :Electrophysiological orthosis for the upper extremity in hemiplegia, feasibility study. Arch Phys Med Rehabil, 56 :507-513, 1975

13) Hoshimiya,N., Takahashi,M., Handa,Y. and Sato,G. :Basic study on electrophrenic respiration. Part 1: Electrophrenic respirator synchronized with phrenic nerve impulses. Med Biol Eng, 14,387-394,1976

14) Handa,Y., Natori,N., Sato,G., Hoshimiya,N., Takahashi,M., Matsuo,T., Nitta,S., Ohkuda,K. and Nakada,T. :Basis study on electrophrenic respiration. Part 2: Assisted ventilation by the synchronous electrophrenic respirator. Med Biol Eng, 14, 395-401,1976

15) Crago,P.E., Mortimer,J.T. and Peckham,P.H. :Closed-loop control of force during electrical stimulation of muscle. IEEE Trans Biomed Eng, 27 :306-312, 1980

16) Stanic, U. and Trnkoczy, A. :Closed-loop positioning of hemiplegic patient's joint by means of functional electrical

Stimulation. IEEE Trans Biomed Eng, 21 :365-370, 1974
17) Nguyen,T.V.and Vossius,G., : An adaptive control system for the functional electrical stimulation of muscle. Proc World Cong Med Phys Biomed Eng, 12.05, Hamburg,1982 Annual Progress Report, Rehabilitation Engineering Center Ljubljana, 1 :71-72, 1978
18) Rebersek,S. and Vodovnik, L. :Proportionally controlled functional electrical stimulation of hand. Arch Phys Med Rehabil, 54 :378-382, 1973
19) Rudel,D., Bajd, T., Rebersek, S., Vodovnik, L. and Kolnik, L. :Proportionally controlled FES of quadroplegic patients. Annual Progress Report, Rehabilitation Engineering Center Ljubljana, 1 :71-72, 1978
20) McNeal, D.R., Waters, R. and Reswick, J. :Experience with implanted electrodes. Neurosurg, 1 :228-229, 1977
21) Peckham,P.H., Marsolais, E.B. and Mortimer, J.T. :Restoration of key grip and release in the C6 tetraplegic patient through functional electrical stimulation. J Hand Surg, 5 :462-469, 1980
22) Handa,Y., Komatsu,S., Nakatsuchi,Y., Yagi,R., Sugimoto,Y.and Hoshimiya,N. :Functional electrical stimulation for the paralyzed upper extremity. Shinshu Med J, 389-401,1983 (Japanese)

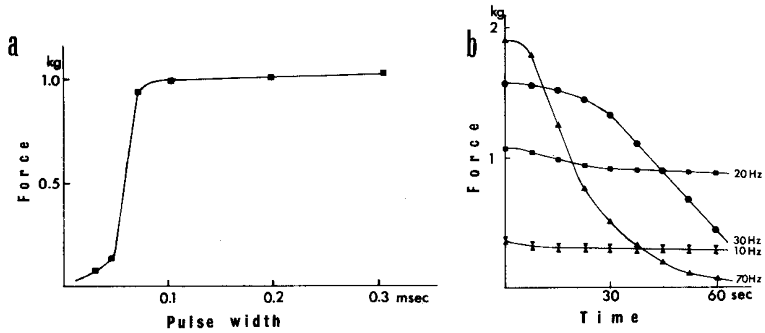

Fig. 1 Characteristics of muscle contraction of the extensor digitorum by electrical stimulation.
pulse amplitude = -4V

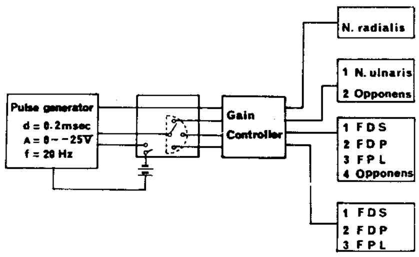

Fig. 2 Block diagram of the multichannel FES system.

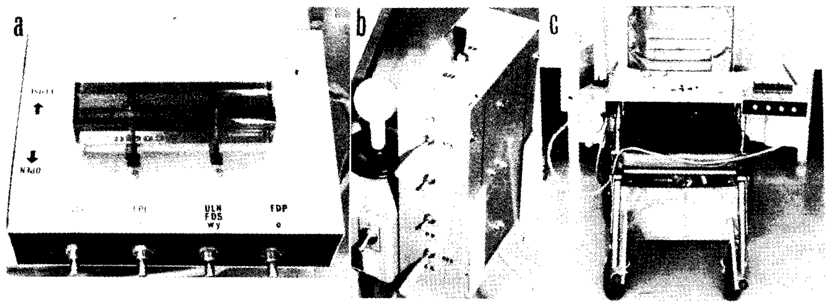

Fig. 3 Multichannel FES system
a; control lever for prehension and release
b; switch box for power supply and selection of a prehension mode
c; the FES system on an electric wheel chair

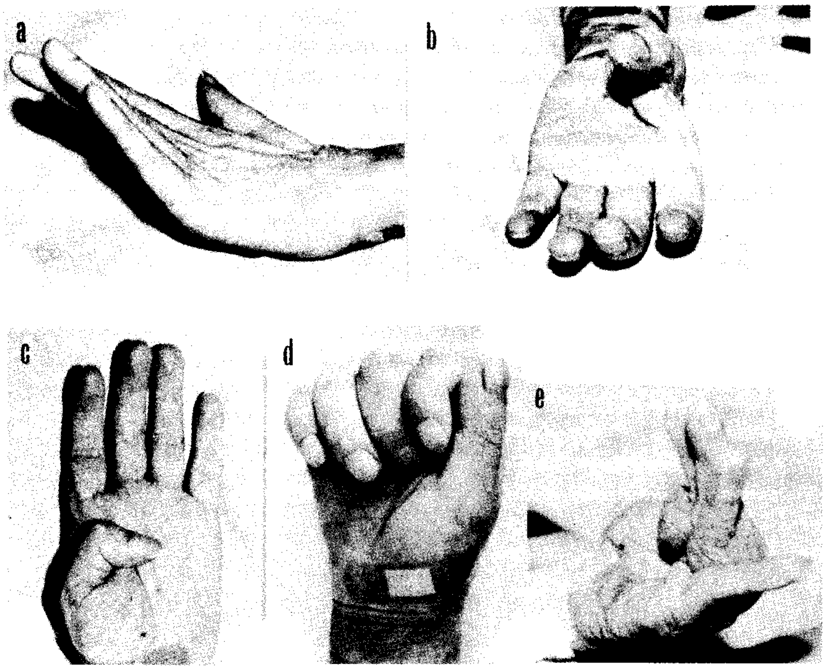

Fig. 4 Effect of single nerve stimulation through percutaneous electrodes. Stimuli were given to a deep branch of the radial nerve (a), branches of the median nerve to the opponens pollicis (b), the FPL (c) and the FDS and FDP (d) and the ulnar nerve at the wrist (e).

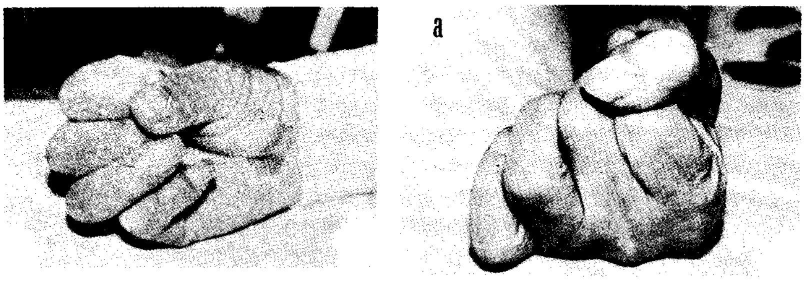

Fig 5. Coordinated hand movements induced by multiple nerve stimulation. a; lateral pinch, b; power grasp

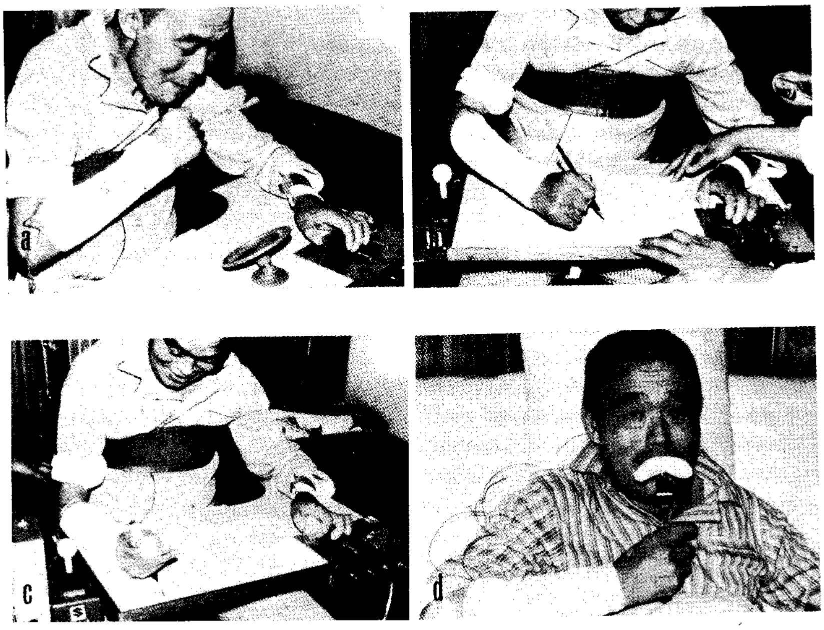

Fig. 6 Application of the multichnnel FES system for ADL. a; face shaving by power grasp. b; writing with a pencil by lateral pinch. c; writing by ulnar nerve stimulation. d; eating by ulnar nerve stimulation (the FES system was set to a bed table in this case).

Table 1. Manual muscle testing in a quadriplegic patient involved in development of multichannel FES system.

		right	left
level of injury		C_6 upper	C_5 lower
muscles tested	trapezius	5	5
	deltoid	4-	3
	elbow flexors	4	3
	triceps	0	0
	supinator	4	3
	pronators	0	0
	wrist extensors	3	0
	wrist flexors	0	0
	finger muscles	0	0