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Restoration of Shoulder Movement in Quadriplegic and Hemiplegic Patients by Functional Electrical Stimulation Using Percutaneous Multiple Electrodes

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Department of Anatomy and Advanced Medical Science Tohoku University School of Medicine, Sendai 980-8574, [1]Department of Electrical Communication, Faculty of Engeneering, Tohoku University, Sendai 980-8579, and [2]Department of Orthopeadic Surgery, Tohoku University School of Medicine, Sendai 980-8574

KAMEYAMA, J., HANDA, Y., HOSHIMIYA, N. and SAKURAI, M. *Restoration of Shoulder Movement in Quadriplegic and Hemiplegic Patients by Functional Electrical Stimulation Using Percutaneous Multiple Electrodes.* Tohoku J. Exp. Med., 1999, **187**(4), 329-337 —— The purpose of this study is to restore the motion of the paralyzed shoulder caused by upper motor neuron disorders using functional electrical stimulation (FES). Percutaneous wire electrodes were implanted into twelve muscles of the shoulder in six patients with stroke or cervical spinal cord injury. The motion of the paralyzed shoulder was controlled by a portable FES computer system, with the three standard stimulation patterns for restoring motion of 90° flexion to 90° horizontal abduction, 90° flexion to 20° horizontal adduction, and 90° abduction to 90° horizontal adduction. Shoulder movements were repeatedly controlled according to the created stimulation patterns in five of the patients. The two dimensional motion analyzer also confirmed shoulder control over a satisfactorily broad range of excursion. One hemiplegic patient, who was a signboard painter, had his paretic left upper extremity improved by FES, and he drew a large picture on a board with his normal right hand and, with his affected left arm against the wall, to support his trunk. This may be a world first case of producing shoulder motion through FES. ——— functional electrical stimulation; shoulder motion; quadriplegic patient; hemiplegic patient

In the 1963, Long and Masciarelli (1963) used functional electrical stimulation (FES) for the first time to restore the motor function in upper limbs paralysed by upper motor neuron disorders. Recently the FES method has been improved considerably thanks to the development of implantable electrodes which enable us

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to selectively stimulate paralyzed muscles (Handa et al. 1989a). Furthermore, the development of large capacity, high speed microcomputers enables to process the muscle stimulation data using a multi-channel system and to create stimulation patterns which control a number of muscles according to the input command (Handa et al. 1989, 1992; Hoshimiya et al. 1989: Hoshimiya and Hanada 1989).

Researchers (Peckham et al. 1980a, b, 1988; Nathan 1984) reported that they restored the movement of upper limbs by FES, but the control of shoulder motion was not their target. In this background, the authors aimed at controlling the shoulder motion by FES (Kameyama et al. 1990, 1991, 1992). In our previous papers (Kameyama et al. 1990, 1991), we presented dynamic EMG measurements of the muscles relating to shoulder motion in healthy human subjects while making kinesiological analysis of the shoulder motion. The obtained data was statistically processed, and three standard stimulation patterns to move the shoulder joint have been made recently (Kameyama et al. 1999).

In this paper, we reported on the restoration of paralyzed shoulder motion, by applying FES to six patients with stroke and cervical cord injury.

Subjects and Methods

Application of stimulation patterns to the patient

The subjects were three hemiplegics with stroke and three quadriplegics with cervical spinal cord injury (Table 1). The patients were all affected by spasticity but their relevant muscles were not atrophied in the upper extremity. Case 1 (male, age of 44, hemiplegic) had suffered from stroke for four years. The motor function of his left upper extremity including the shoulder was totally impaired. Spasticity existed and voluntary movements were scarcely observed in his left upper extremity. FES was applied to almost all of the joints in his upper extremity including the elbow, wrist, hand and shoulder.

The occupation of Case 2 (male, age of 48) was painting signboards, and we made efforts to allow him to return to his job. Even before electrical stimulation training, he could produce an associated movement of shoulder and elbow (Brun-

Table 1. *Six patients undergoing application of FES for restoration of shoulder movement*

Case	Age (Years)	Disease	Time from injury to implantation (Years)	State of shoulder
1	44	Intracerebral hemorrhage	4	Paralysis
2	48	Cerebral infarction	2	Paresis
3	64	Cerebral infarction	1.5	Paresis
4	43	Spinal cord injury (C5)	2	Paresis
5	61	Spinal cord injury (C4)	6	Paralysis
6	37	Spinal cord injury (C4)	3.5	Paresis

strom III level) (Reynolds and Brunnstrom 1958; Brunnstrom 1970). After about 7 months of electrical stimulation training of the muscles, the patient could maintain his shoulder joint at 90° flexion for 1 to 2 seconds, (Brunstrom IV level), but this duration was not sufficient to cope with his job. He needed to produce 90° shoulder flexion and adequate elbow and wrist extension in his left upper extremity since he had to support his upper trunk against the board with his left arm while drawing. Control of the hand was also needed to grasp various objects. To produce these movements, FES was applied not only in the muscles of the shoulder but also in the elbow, wrist and hand.

We created three basic stimulation patterns which give the following movements (under submission).

i) 90° flexion from the neutral position of the shoulder joint to 90° horizontal abduction

ii) 90° flexion from the neutral position to 20° horizontal adduction

iii) 90° abduction from the neutral position to 90° horizontal adduction

In applying these stimulation patterns, we used a portable FES apparatus developed by the authors (FESMATE 1000, NEC San-ei, Co., Ltd., Tokyo) (Handa et al. 1989a, b, 1992; Hoshimiya et al. 1989).

Percutaneous intramuscular electrodes developed by Handa et al. (Handa et al. 1989a) were used as stimulation electrodes. Using a 21 gauge needle, the electrode was implanted into a motor point of the paralyzed muscle to be controlled. A reference electrode was implanted into the subcutaneous tissue just above the lateral brachial intermuscular septum at the middle portion of the upper arm. One week after the implantation, stimulation data to control shoulder movements in the individual patients was created by tuning stimulation parameters for each muscle (Handa et al. 1989b, 1992; Hoshimiya et al. 1989). Then electrical training of the muscles was started. When the muscles showed satisfactory increases in contractile force and fatigue resistance one to eight months after the electrode implantation (Vodovnik 1981; Vodovnik et al. 1982; Thomas et al. 1992), a regular FES program to restore shoulder motion was started.

Measurements of the FES-controlled shoulder movements (Quick Motion Analyzer G Series [Quick MAG], Oyo Keisoku Kenkyujo, Tokyo) in the frontal, sagittal and horizontal planes were made from a position 5 meters behind, 5 meters laterally left and 2 meters above the head of the subject, and the obtained data was analyzed by a two-dimensional motion analysis software (Quick MAG). The markers in the frontal plane was put on the T1 spinassus process of thoracic vetebra, acromion, and olecranon. The markers in the sagittal plane were put on the top of the ear, acromion, and lateral epicondyl. The markers in the horizontal plane were put on the top of the head, acromion, and lateral epicondyl.

Results

Based on the stimulation data created for each patient, FES was applied to

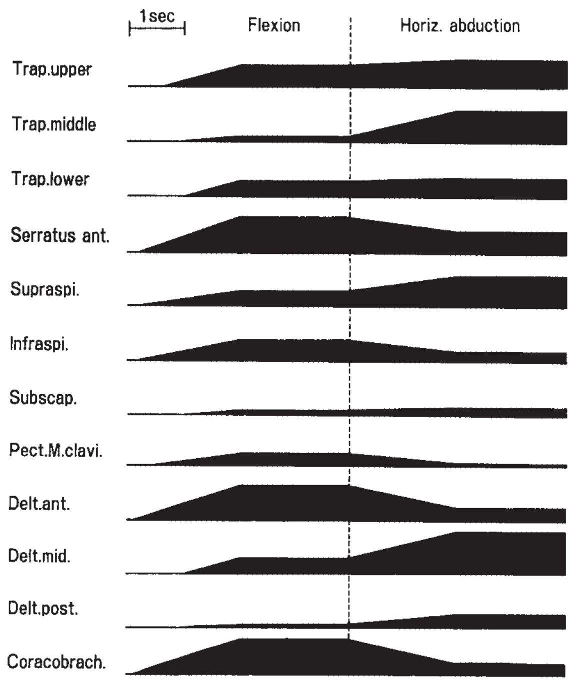


Fig. 1A. Stimulating pattern for functional restoration of 90° flexion and 90° horizontal abduction.

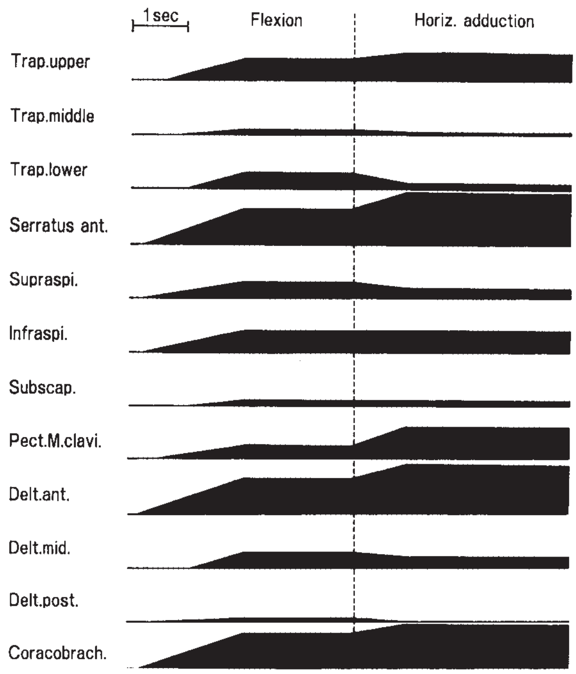


Fig. 1B. Stimulating pattern for functional restoration of 90° flexion and 20° horizontal adduction.

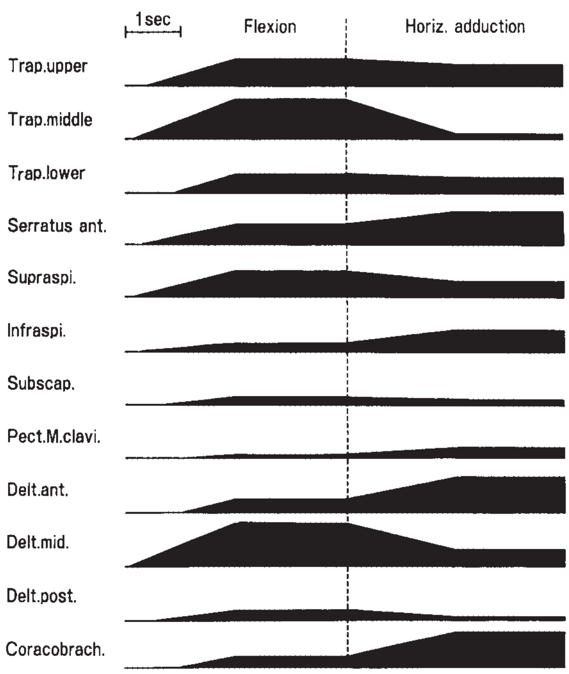


Fig. 1C. Stimulating pattern for functional restoration of 90° abduction and 90° horizontal adduction.

Fig. 1. Standard stimulation patterns created for restoration of shoulder movement.

the subjects using the portable FES apparatus. The intended shoulder movements were satisfactorily restored by FES in five of the six patients. In a C4 quadriplegic patient (Case 5), flexion to horizontal adduction of the shoulder joint could not be restored because of pain during stimulation at the clavicular head of

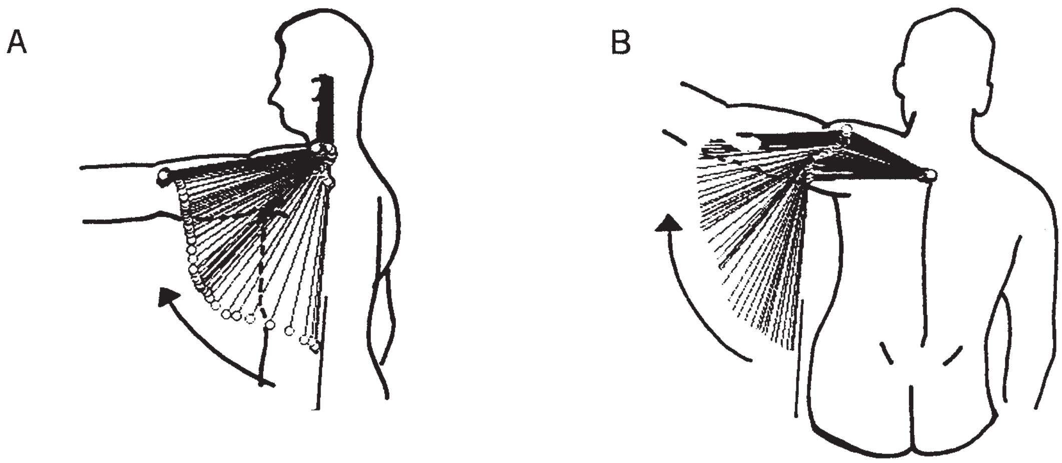
Fig. 2. Shoulder joint could be controlled and the arm lifted up. The subject is a 44-year old male, hemiplegic for 4 years.

the pectoralis major and anterior part of the deltoid, although abduction of the shoulder joint was sufficiently controlled by FES.

In our study, the electrodes were maintained for about three years with only very slight infection on the skin in one patient. An antibiotic healed the affection. The electrodes stayed in place and electrode breaks did not occur. The skin was sterilized with Isodine every time the patients took a bath. Two of the patients complained discomfort caused by the electrodes. One of them was the skin infection case mentioned above.

Fig. 2 shows FES control of the shoulder movement in Case 1. Shoulder abduction with elbow flexion was restored. Fig. 3 shows stick diagrams representing motion of the upper limb in Case 1. The stimulation data for 90° flexion and 90° abduction from the neutral position of the shoulder produced about 80° flexion and about 90° abduction, respectively (Figs. 3A and B). Figs. 3C, 3D and 3E show the top views of sequential shoulder movements induced by three kinds of stimulation data created from the standard patterns represented in Figs. 1A, 1B and 1C, respectively. At the initial position before FES control, the shoulder joint showed slight abduction and flexion because of spasticity of the shoulder muscles. The stimulation data for 90° horizontal abduction from the position of 90° flexion (initial position: 0° horizontal abduction) produced about 60° horizontal abduction of the upper arm (Fig. 3C). The data for 20° horizontal adduction from the position of 90° flexion (initial position: 0° horizontal adduction) produced 30° horizontal adduction (in this case, as shown in Fig. 3D, the upper arm at the initial position was abducted about 20° from 0° horizontal adduction). The data for 90° horizontal adduction from the position of 90° abduction produced 60° horizontal adduction (in this case, the upper arm at the initial position was abducted about 60° from 0° horizontal adduction) (Fig. 3E).

FES control of the shoulder was applied to Case 2 in order to restore the function of the affected left upper extremity and allow him to return to his



Figs. 3A and 3B. Stick diagram representing the function of the shoulder joint by stimulating pattern of 90° flexion and 90° abduction.

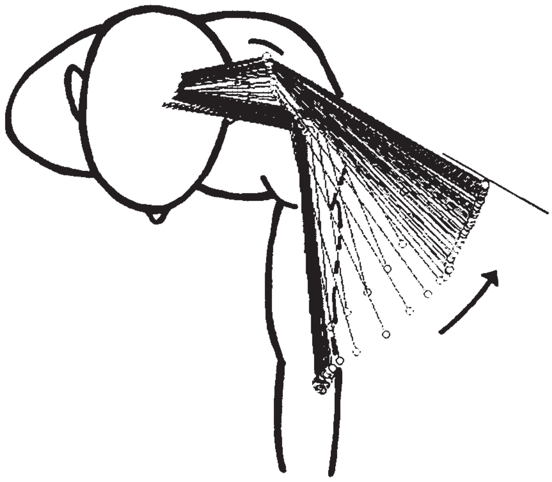


Fig. 3C. Stick diagram representing the function of the shoulder joint by stimulation pattern from 90° flexion to 90° horizontal abduction.

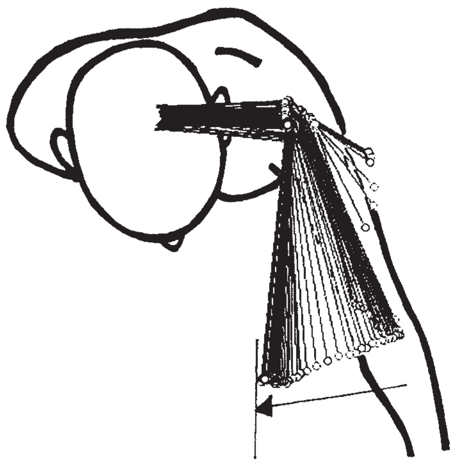


Fig. 3D. Stick diagram representing the function of the shoulder joint by stimulation pattern from 90° flexion to 20° horizontal adduction.

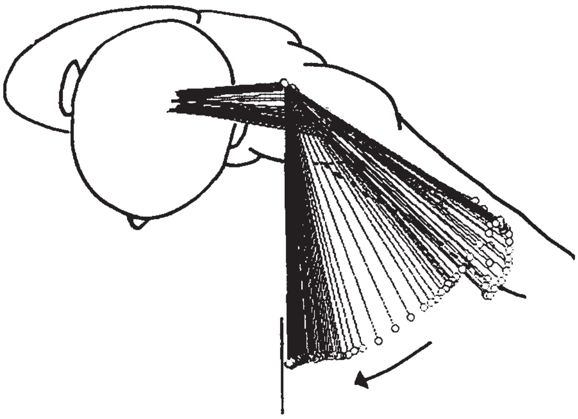


Fig. 3E. Stick diagram representing the function of the shoulder joint by stimulation pattern from 90° abduction to 90° horizontal adduction.

Fig. 3. Stick diagrams representing shoulder movement by FES.

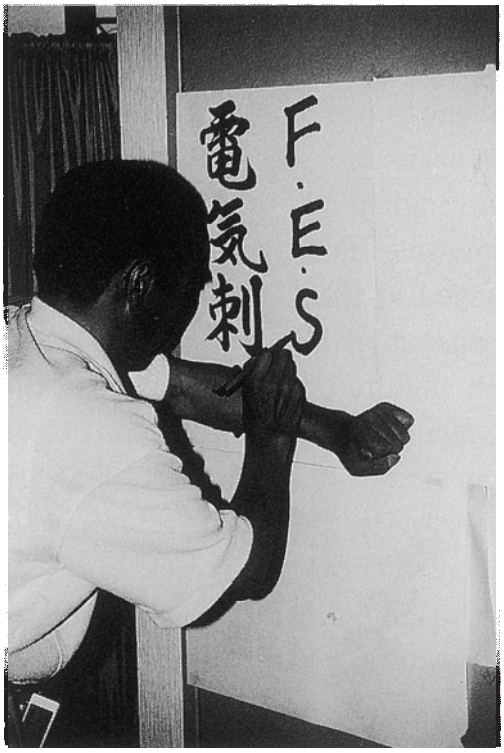


Fig. 4. Clinical application-restoration of shoulder movement by FES-In order to paint and write letters on an advertising board, the paralyzed upper limb is supported by FES. The subject is a 48-year old male who has had hemiplegic for 2 years.

occupation of painting signboards (Fig. 4). As shown in Fig. 4, he could successfully draw on the advertising board by stabilizing his trunk against a wall with his FES controlled left arm. He could also control a ruler with his FES-controlled upper extremity. With two months of electrical stimulation training, the patient was able to maintain this work for about 20 minutes. After a break for 1 to 2 minutes, the patient could start working again for about 5 minutes. Further training is expected to prolong the working duration.

Discussion

Researchers have done EMG analyses on some of the muscles which control shoulder motion, but there are few reports on the restoration of shoulder motion by applying the functional electrical stimulation patterns created from the obtained EMG data. In our EMG analysis we used 24 points on the muscles which cotrol shoulder motion and created stimulation patterns. In the clinical application, we satisfactorily controlled shoulder motion of the patients by FES and restored their shoulder function. One of the patients returned to his job since his shoulder motion was restored.

Shoulder joints have to support the upper extremities, and this causes a problem of muscular fatigue. Before controlling shoulder motion by FES, more than three months of electrical stimulation training of the muscles are requuired for the patients to make it possible to support their upper extremities and to move their shoulders.

In this study, Case 1 and Case 2 showed a noticeable restoration in shoulder movement, since intermittently occurring spasticity prevented them from muscle atrophy. We treated the patients with FES and spasticity did not interfere with FES. In the case of C4 quadriplegic patients with complete paralysis in their upper extremities, we sometimes failed to control their shoulders, since the lower motor neurons were damaged at the C5 and/or C6 segmental of the spinal cord. When the lower motor neurons of C4 quadriparetic patients were not damaged, FES worked efficiently on the muscles which participate in shoulder movements, restoring functional movement of the upper extremity. There is a possibility that FES may have a therapeutic effect (Vodovnik et al. 1981, 1982; Thomas et al. 1992) (i.e., reduction of spasticity, increases in muscle strength and volume etc.), and that voluntary movements of the muscle may be improved. We must, however, study muscular fatigue and selective stimulation of nerve fibers.

Further studies are required to apply FES which selectively control the standard shoulder motions needed for activities of daily livings, to examine other possible stimulation patterns, and to associate the control of the shoulder with that of the elbow, wrist, and finger joints. It is also important to create the three dimmensional stimulation patterns which produce the intended muscle movement.

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