FUNCTIONAL ELECTRICAL STIMULATION USING PERCUTANEOUS INTRAMUSCULAR ELECTRODES IN PARAPLEGIA

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Abstract – *Clinical results of functional electrical stimulation using percutaneous intramuscular electrodes in paraplegia were reported. Several types of hybrid orthosis, including FRO, AKJ, Walkabout, and RGO were utilized to increase the stability and to decrease the fatigue due to electrical stimulation. Maximum duration of continuous walking with hybrid FES was 300m in complete paraplegia and 600m in incomplete paraparesis patients. The failure rate of electrodes in lower extremities was 6.7%. The hybrid FES was useful for restoration of ambulation without serious complications in paraplegia.*
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Keywords: functional electrical stimulation, hybrid FES, paraplegia, ambulation

1. Introduction

Functional electrical stimulation (FES) has been utilized to restore independence in performing daily functions in paraplegia. We have used percutaneous intramuscular FES since 1990[1-3]. The purpose of this study was to report of the clinical results of FES using percutaneous intramuscular electrodes in paraplegia.

2. Subjects

The subjects included 15 patients (13 males and 2 females) . The patients was consisted of 9 with complete paraplegia, 8 incomplete paraparesis. All patients could not stand and walk by themselves, and have used wheelchair in daily living. The average patient age was 34.3 years (range, 4-68 years). The subjects suffered from spinal cord injury at the level of T4-12. The average follow-up time was 2 years and 5 months (range, 7 months to 7 years).

3. Methods

The FES system developed by the Nippon Electric Company was used for therapeutic electrical stimulation (TES) in this study[4-6]. This system consisted of a stimulation data creating system (SDC) and a 30-channel stimulator. The SDC was used to compose and store the stimulation parameters that set the threshold voltages for each muscle and controlled the pulse shape and individual pulse sequence (Fig.1). The portable stimulator measured 8.9 X 14.5 X 3.1cm and weighed 330g and was usually worn on a belt (Fig 2). The pulse amplitude was modulated from 0 to -15V. Rectangular pulse trains were used with 200 microseconds pulse width and a pulse interval of 50ms. A customized pattern of stimulation was composed for each subject based on the observed muscle function. For restoration of reciprocal gait, we have used original stimulators (Akita stimulator I and II). Akita stimulator I which had 16 channels, including two channels for swinging the leg by stimulating the iliopsoas muscle and two for continuous stimulation, and Akita stimulator II which had 32 channels and the function of high-frequency stimulation varied from 20Hz to 100Hz, was developed (Fig. 3, 4).

Fig 1. Stimulation data creating system

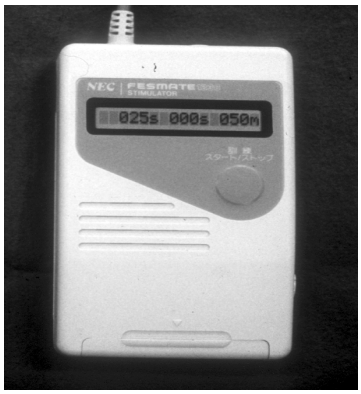
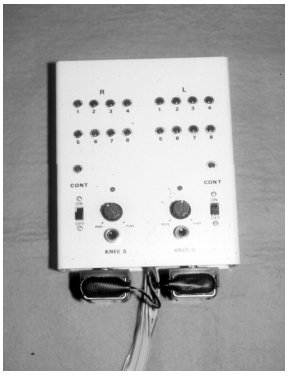


Fig 2. Portable stimulator (FESMATE, NEC)



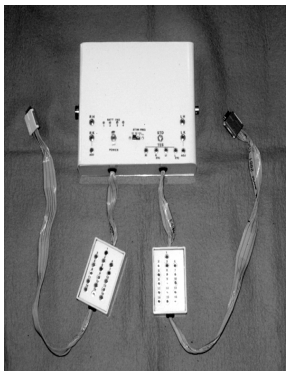


Fig 3. Akita stimulator I **Fig 4. Akita stimulator II**

The indwelling electrode[5)] was formed as a helically wound Teflon-coated 19 strand stainless steel (Nippon Seisen Co. Ltd.) (Fig 5). The tip of an electrode was deinsulated. Electrodes were implanted percutaneously into the motor point of the muscles.

Prior to implantation, the sensitivity and location of motor point were determined using surface electrode stimulation. Implantation of the electrodes was performed under sterile conditions. We chose a common body-entry point for electrodes located at both anterior proximal thighs.

The hybrid-orthosis, ankle-foot-orthosis (AFO), Akita Knee Joint (AKJ)[7)], Walkabout, and Reciprocal gait orthosis (RGO)[8)], were provided for stabilization in complete paraplegic patients (Fig. 6-9).

Electrical exercise commenced two weeks after implantation to allow time for tissues to heal. This reduced the problem associated with electrode movement. Stimulation of the muscles was conducted for 5 minutes three times daily at the beginning. After 5 weeks, the stimulation was applied for 30 minutes, five times daily. After exercising like this for more than three months, standing and walking training started.

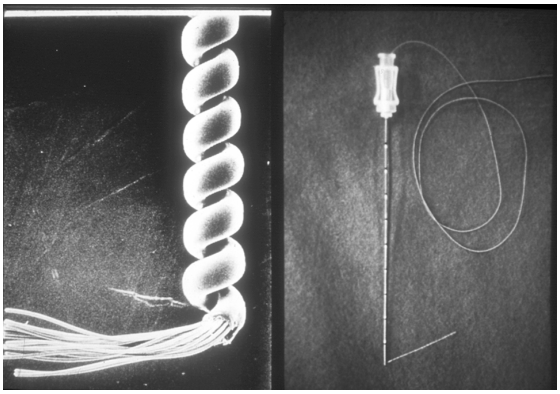


Fig 5. Percutuneous intramuscular electrode (Nippon Seisen, Japan)

Fig 6. Hybrid FES using AFO

Fig 7. Hybrid FES using AKJ

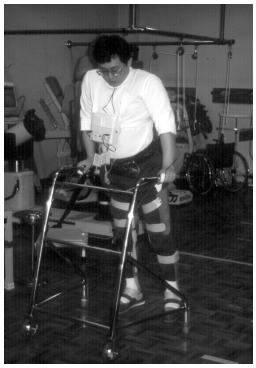


Fig 8. Hybrid FES using Walkabout

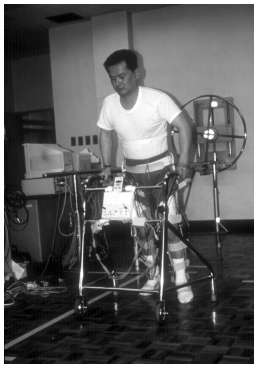


Fig 9. Hybrid FES using RGO

3. RESULTS

In incomplete paraparesis patients, maximum duration of standing by electrical stimulation only was for 60 minutes and maximum distance of walking was for 600m. In complete paraplegic patients, maximum durations of standing were for 25 minutes with AFO, for 150 minutes with Walkabout, for 60minutes with RGO, and for 30 minutes with AKJ and maximum distances of walking were for 30m with AFO, for 300m with Walkabout, for 70m with RGO, and for 40m with AKJ, respectively. The maximal gait speed was 0.6 m/sec in TES only, 0.5m/sec in pure FES, 0.1 m/sec with AFO, 0.43m/sec with Walkabout, 0.22 m/sec with RGO, 0.1 m/sec with AKJ, respectively. The failure rate of electrodes in lower extremities was 6.7%.

4. Discussion

Surface electrodes require daily placement and removal. In addition, some patients feel discomfort when excessive stimulation is given by surface electrodes. It is difficult to stimulate the deep muscles, such as the iliopsoas muscle, by surface electrodes. For these reasons, we have used intramuscular electrodes to restore the paralyzed limbs. Handa[5)] reported that the rate of breakage was 1.3 per cent in 457 electrodes using the same electrodes as ours. A helically coiled structure of the

electrode has demonstrated resistance to breakage even when the electrode was implanted into bulky leg muscles[4)5)6)]. These results suggested that the ultrafine intramuscular electrode was practical and available for long term use in paraplegic patients.

In restoring locomotion in paraplegics, it is necessary to control the hip, knee, and ankle joints and to maintain muscle activity to sustain the upright posture during standing and walking. Muscle fatigue is a major problem for restoration by FES. Hybrid FES has following advantages: 1) controlling all the muscles which are related to locomotion and antigravity posture[11)] 2) introducing withdrawal reflex for making locomotive motion[2)] 3) decreasing loads to the antigravity muscles with an orthosis[15)] 4) introducing a closed-loop control system with sensors[11)].

We have selected several types of hybrid-orthosis depends on the reaction of muscles to the electrical stimulation. The hybrid-FES with AFO was superior to the other in cosmesis, donning-doffing, standing-up, and using wheelchair. The Walkabout and RGO were superior in stability, reducing muscle fatigue, energy consumption, and maintenance of standing. The AKJ was intermediate of these hybrid-FES.

Our results suggest that hybrid-FES using percutaneous intramuscular electrodes was useful for restoration of standing and walking without serious complications in paraplegia. In addition, the afferent effects of TES was sometimes remarkable in incomplete paraparesis patients.

References

1. Shimada Y, sato K, Abe E, Kagaya H, Ebata K, Oba M, Sato M (1996) Clinical experience of functional electrical stimulation in complete paraplegia, Spinal cord 34: 615-619.
2. Shimada Y, Sato K, Kagaya H, Konishi N, Miyamoto S, Matsunaga T (1996) Clinical use of percutaneous intramuscular electrodes for functional electrical stimulation. Arch Phys Med rehabil 77: 1014-1018.
3. Shimada Y, Sato K, Kagaya H, Ebata K, Kodama H, Konishi N (1995) Closed-loop control for functional electrical stimulation with percutaneous electrode in paraplegics. In: Proceedings of 5th Vienna International Workshop on FES: 1995 Aug 17-19; Vienna. Austria: Austrian Society for Artificial Organs Biomaterials and Medical Replacement Devices, 259-262.
4. Handa Y, Ohkubo K, Hoshimiya N (1989) A portable multichannel FES system for restoration of motor function of the paralyzed extremities. Automedica 11: 221-231.
5. Handa Y, Hoshimiya N, Iguchi Y, Oda T (1989) Development of percutaneous intramuscular electrode for multichannel FES system. IEEE Trans Biomed Eng 36: 705-710.
6. Hoshimiya N, Handa Y (1989) Master-slave type multichannel functional electrical stimulation (FES) system for the control of the paralyzed upper extrmities Automedica 11: 209-220
7. Kagaya H, Shimada Y, Sato K, Sato M, Iizuka K (1996) An electrical knee lock stystem for functional electrical stimulation. Arch Phys Med rehabil 77:870-873.
8. Solomonow M, Baratta R, Beaudette P, Shoji H, D'Ambrosia R (1989) Gait performance of paraplegics ambulating with the reciprocating gait orthosis powered by electrical muscle stimulation. Proc 11th Intern Conf IEEE/EMBS 1013.
9. Marsolais EB, Kobetic R (1987) Functional electrical stimulation for walking in paraplegia. J Bone Joint Surg 69-A: 728-733.
10. Ichie M (1990) Restoration of locomotion by FES. Proc Rehabil Intern Seminar 1-12.
11. Andrews BJ, Baxendale RH, Barnett R, Yamazaki T, Paul JP, Freeman PA (1988) Hybrid FES orthosis incorporating closed and sensory feedback. J Biomed Eng 10: 189-195.