# FES-CONTROLLED LOCOMOTION IN THE PARAPLEGIC PATIENT

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## INTRODUCTION

Mechanical strength of a percutaneous intramuscular electrode for functional electrical stimulation (FES) is greatly improved [1]. Therefore, long term FES systems are achieved for the control of locomotion in paraplegic patients. The use of such percutaneous intramuscular electrodes enables realization of a more sophisticated and better control of locomotion. To obtain a sophisticated movements of lower extremities for locomotion, the pattern of muscle activation is essential. We examined the temporal and spatial sequence of muscle contraction during locomotion in normal subjects and created the stimulation pattern [2-4]. It was found that locomotive movements of paraplegics could be basically controlled using this method.

This paper describes the method for control of standidng-up and locomotion of a paraplegic patient by a multichannel percutaneous FES system.

## METHOD

### 1.EMG analysis

To create the stimulation pattern for locomotion, muscle activity of different muscle groups in lower extremities were recorded in two normal subjects (23 years old female and 27 years old male) while standing up and walking. The muscles included in recording are in Table 1. Bipolar intramuscular electrodes made of a Teflon coated stainless steel wire (75 microns) were percutaneously implanted into each of the muscle belly centers. Angular changes of hip, knee and ankle joints were recorded using electro-goniometers. Taking-off from a chair during standing-up process was determined using touch sensor attached to the hip.

Activities in all of selected muscles are shown in Table 1, and corresponding signals from goniometers and touch sensor were simultaneously detected and fed into a 28 channel data recorder (TEAC SR-90) The EMG signals were rectified and averaged. For comparison, the amplitude of averaged EMG signal in a specific muscle was normalized to the maximal muscle activity.

| | |
|---|---|
| Rectus abdominis | Gluteus maximus |
| Iliopsaoas | Gluteus medius |
| Tensor facia latae | Gluteus minimus |
| Gracilis | Biceps femoris |
| Adductor magnus | Semimembranosus |
| Adductor longus | Sartorius |
| Qadriceps femoris | Tibialis anterior |
| Rectus femoris | Peroneus longus |
| Vastus lateralis | Tibialis posterior |
| Vastus medialis | Gastrocnemius lateralis |
| Soleus | Gastrocnemius medialis |

Table 1. Muscles for EMG recordings

### 2.Generation of the stimulation data

The standard stimulation patterns were basically determined by analyzing spatio-temporal sequence of EMG activity during standing-up and walking as described elsewhere [2-4]. These patterns were stored into the memory of a stimulation data creating system (SDC system) consisting of a portable type personal computer (NEC PC-98LT). Stimulation data for control of lower extremities of each patient were automatically created by inputting the maximum and threshold voltages of individual muscles from a keyboard of the SDC system and were sent to the RAM of a portable FES system through a serial communication channel.

### 3.Configuration of an FES locomotion system

An FES system for locomotion consists of control switches attached to a walker, the portable FES system and percutaneous electrodes.

## RESULTS

### 1.EMG analysis

An example of normalized muscle activities and changes of joint angles during standing up are shown in Figure 1. At the initiation of the standing-up, flexion of the hip and dorsiflexion of the ankle joint were sequentially occurred Taking -off the hip from the chair was induced by the knee extension, where activities of the quadriceps an iliopsoas were markedly increased. At the mid phase of the standing-up, flexion of the hip and dorsiflexion of the ankle attained to maximum, and then extension of these joints was observed. When the standing-up process ends, maintenance of upright posture was achieved by knee locking, the activities of most of recorded muscles markedly decreased.

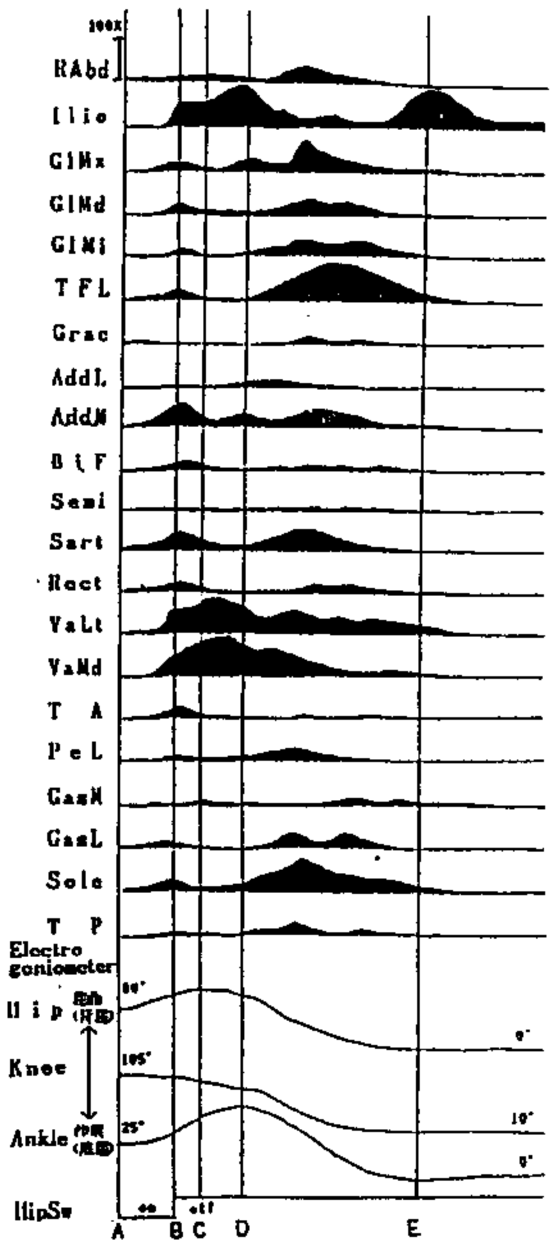


Figure 1. EMG of standing up: A) Start; B) Taking-off of the hip; C) Peak of flexion of the hip joint; D) Peak of dorsal flexion of the ankle joint; E) Completion of standing up

In case ow walking, although each prime mover of the swing and stance phases showed some activity, their normalized amplitude were much smaller than that of standing-up movements. The assumed that the reason is optimized use of legs as pendulum induced by inertial forces while walking with normal gait speed. Consequently small contractile forces are needed for normal gait speed realization.

**2.Standard stimulation pattern**

Standard stimulation patterns for standing-up was generated from trapezoidal approximation of the averaged EMG. However, most of the EMG activities of muscles examined disappeared when fully erected position was attained. A few muscles participated in standing inducing locking mechanisms of the knee joint. In paraplegic patient, it appears dangerous to use such knee locking as observe in normal humans. Therefore, we used the EMG pattern, just before completion of the standing-up motion as the stimulation data for the maintenance of vertical position (Fig 2).

Although EMG data were basically used, the FES pattern for control of locomotion was mainly simplified at present state of development.

**3.Control of standing-up and ambulation**

**Case 1.** The FES candidate was a T7 paraplegic patient who suffered spinal cord injury 4 years before to the beginning of the program. The FES strengthening program was applied for more than three months. Percutaneous intramuscular electrodes were implanted in muscled important for the restoration of lower extremity functions. Usually, bulky muscles have several motor points. Therefore, two or three electrodes were implanted into each of these muscles to enable enough contractile force and good controllability. As total number of electrodes was 60, four sets of 16 channel portable FES stimulator were connected and used for control. Control switches for standing-up and walking by FES were attached to both grips of a walker. After several trials, the patient learned to coordinate his upper limbs and upper trunk with the FES-induced motion of lower extremities. Finally, the smooth standing-up movement was achieved easily (Figure 3). FES control of ambulation was also realized by the developed system. However, the amplitude of the swing was very small and steps were relatively short. This was mainly due to lack of stimulation of iliopsoas m., a dominant hip flexor. Additionally, it was found that coordinated coactivation of lower trunk muscle was necessary to provide body balance during ambulation.

**Case 2.** The patient was 68 years old man whose thoracic cord was damaged by anterior spinal artery syndrome at the lower level two years prior the treatment. Since his lower limbs were paretic and some weak joint motions, such as hip flexion and knee extension were observed, we implanted percutaneous electrodes to the iliopsoas m., quadriceps femoris m., hamstrings m. and the peroneal nerve bilaterally to improve functions of the paretic limbs. Although joint motions were markedly improved, the patient still needed the long leg brace (LLB) or standing even after 6 months of electrical stimulation.

Therefore, we started to control his locomotive activities by stimulating hip flexor muscles bilaterally with the use of LLB. In this hybrid system, the patient could ambulate alternating swing of legs. Walking speed and distance were higher and longer than those by 4-point gait without the FES. Although we have not examined the energy consumption, the patient commented that the gait by this hybrid FES system was much easier.

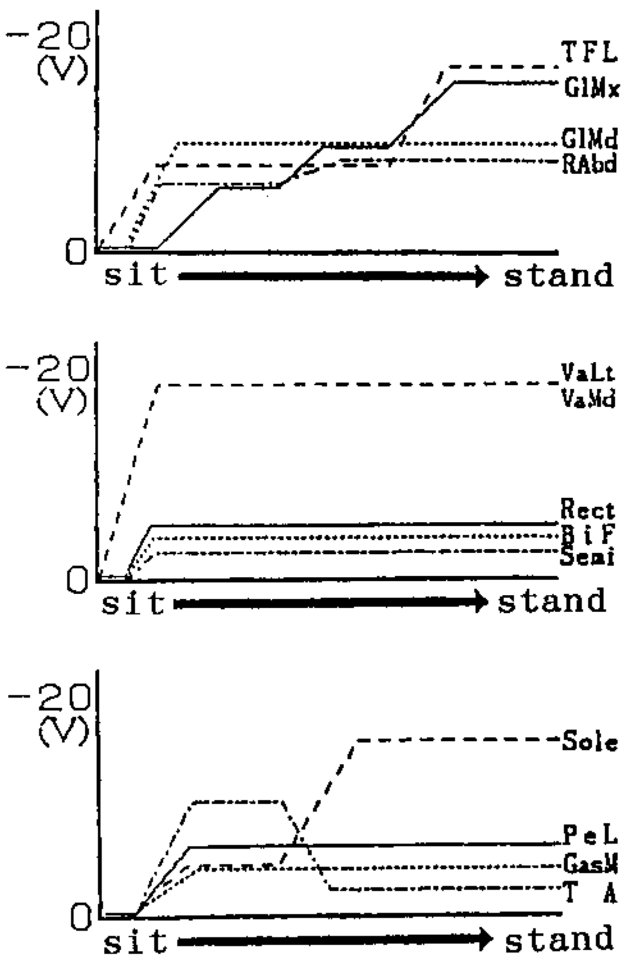


Figure 2. Stimulation pattern of the standing up

Figure 3. Control of standing in T7 Paraplegic Patient

## DISCUSSION

For practical usage of lower limb FES in paraplegic patient several criteria have been provided [5]. The FES should provide enough locomotor functions for locomotion, protection from injuries, ease of application, to lower the energy consumption and the like. FES controlled standing-up and ambulation without the use of orthosis for the lower limbs didn't satisfied these criteria at the present stage of development. Different from the upper extremity, the lower limb function are mainly performed by non-contractile mechanisms with minimum participation of reflexive muscle contraction. Such mechanisms should be taken into account. Therefore, further investigations are necessary for restoring practically available locomotion behaviour generated solely by an FES system. The hybrid FES system may be more practical until control methods of paralyzed limbs by the FES are better developed

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