Abstract

Objective- To evaluate the standing-up motion with hybrid FES in complete paraplegic patients. Methods- Three complete paraplegic patients volunteered for this study. Stimulation patterns were obtained from the trapezoidal-approximating data of the integrated EMG from the standing-up motion in healthy volunteers, and entered into the portable computer. The paraplegic patients wearing the ankle-foot-orthosis were asked to stand up from a wheelchair using parallel bars by FES. The automatic coordination system was used to measure the joint-angle motions. Results- The paraplegic patients could stand up in a motion time of 2.4 ± 0.3 sec (Mean ± SD). The curved lines of both the hip- and knee-joint angles were smooth. The maximum duration of stable standing by open-loop FES was 12 ± 7 min. Conclusion- FES enabled the completely paraplegic patients to stand up smoothly by themselves and hold standing under stability. FES assisted stand-up can improve the quality of daily life in paraplegic patients.

1. Introduction

There are some FES systems to restore standing-up motion in paraplegic patients; surface, percutaneous and implantable electrode system [1-3]. In the percutaneous or implantable electrode system, stimulation pattern is complex and difficult to customize if there are many channels to stimulate. For the appropriate stimulation, Handa and colleagues advanced a method to obtain stimulation patterns from the trapezoidal-approximating data of the integrated EMG from the standing-up motion in healthy volunteers [4].

We have been investigated the FES assisted standing-up motion by percutaneous electrode system [5]. For the energy-efficient restoration, we measured the integrated EMG of standing-up motion in healthy subjects who wore the ankle-foot-orthosis (AFO). From these results, the new stimulation patterns were obtained for the hybrid-FES assisted standing-up [6]. The purpose of this study was to evaluate the FES assisted standing-up motion in complete paraplegic patients by the new stimulation patterns.

2. Methods

Three male complete paraplegic patients volunteered for this study. The causes of paralysis were all spinal cord injuries due to motor vehicle accidents. The injury levels were all mid-thoracic level. Duration from onset was from 2 years 11 months to 5 years 5 months. ASIA impairment scale were all A.

All subjects had already started therapeutic electrical stimulation programs. Implantation of the percutaneous intramuscular electrodes was performed under general anesthesia. Electrically stimulated nerves and muscles were the rectus femoris, vastus lateralis, vastus medialis, long head of biceps femoris, and the gluteus maximus. If the electrically stimulated hip flexor torque and knee extensor torque were not enough to stand up, the femoral nerves were also stimulated.

Stimulation frequency was 20Hz. Rectangular monophasic pulse waveforms were used. Pulse width was 0.2msec, and the pulse amplitude was modulated from 0 to -15 volts. The FESMATE system, developed by the Sendai FES projects, was used for the restoration. Stimulation patterns were transformed from the trapezoidal-
approximating data of the integrated EMG data to stimulation programs, and entered into the portable FESMATE computer through the system controller (Fig 1). The subjects who wore AFOs sat with their feet 25cm apart on a force plate. The force plate was used to measure vertical force at a rate of 60Hz for 4 seconds. Also, Quick-MAG system was used to measure the joint-angle motions of both the hip and the knee. When the Hybrid-FES standing was performed, subjects were asked to stand-up from a wheelchair using parallel bars, and the motion was measured automatically by Force plate and Quick-MAG. For the evaluations, the motion time was determined from the initial hip angle motion (over 0.5 degree during 0.17 seconds motion) to the final hip angle motion (under 0.5 degree during 0.17 seconds motion). Duration of the stable standing was also measured. The changes of the joint-angle motions of both the hip and the knee and the ground-reaction force data in the vertical direction were also analyzed.

3. Results

All subjects could stand up using the hybrid-FES. The paraplegic patients could stand up in a motion time of 2.4 ± 0.3 seconds. The maximum duration of stable standing by open-loop FES was 12 ± 7 min. Standing for a long time caused muscle fatigue, and knee buckling prevented maintaining the standing position. Fig 2 represents the changes of the joint angles and the ground reaction forces in the vertical direction during the standing-up motion. In case 1 and 3, both the hip and knee joints continued to extend during the motion. In case 2, before the buttocks came off the chair, the knee joint remained flexed, and after the buttocks came off began to extend. The curved lines of both the hip and knee joint angles were almost smooth. The peak value of the ground reaction force in the vertical direction were 52%BW in case 1, 67%BW in case 2, and 51%BW in case 3.

4. Discussion

There are many benefits for paraplegic patients from the restoration of the standing-up motion by FES [2]. Standing may help to prevent joint contractures and decubitus caused by chronic sitting posture. The upright posture may improve the position of the internal organs. Electrical stimulation improves circulation in the lower extremities. And increased functional abilities while standing enhance personal self-esteem. In this study, we could restore the smooth standing-up motion by the hybrid-FES with an anterior floor reaction type ankle-foot-orthosis. Hybrid-FES has more advantages than pure-FES. The brace alone will prevent knee collapse and thereby greatly reduce the need for electrical stimulation, which induces muscle fatigue. It can increase the joint torque by fixation of one joint of the two joint muscles, and stabilize the standing-up motion by decreasing the number of joints needed to control. This system can be applied easily to the closed-control system because the feedback sensors can be attached to the orthoses. In the next stage of development, we will apply this system to the closed-control system.

![Fig 1. Preparation of the stimulation data](image1)

![Fig 2. Changes of the joint angles and the ground-reaction forces during standing-up motion](image2)
5. Summary and Conclusions

Three complete paraplegic patients wearing the AFO could stand up with FES by the new stimulation pattern. The mean stand-up motion time was 2.4 sec. The joint angle data showed the smooth motion. Hybrid-FES enabled the completely paraplegic patients to stand-up smoothly by themselves and hold standing under stability.

References