Abstract

In the paper we present the sensory part of the FES gait re-education system for incomplete spinal cord injured persons. The proposed system is equipped with four accelerometers, gyro and two goniometers placed at the shank of the paretic leg. The data assessed present input into mathematical algorithms applied for swing quality estimation. The estimation is based on the swing phase detection and signal correlation and is used to determine the cognitive feedback signal. The feedback signal is designed as a three level output and provided as an auditory signal.

The preliminary measurements were performed on incomplete spinal cord injured person with C6 lesion during walking on the treadmill. FES was triggered by a physiotherapist.

The results have shown that multisensor use was successful in gait quality estimation. Therefore, the use of FES, multisensor and cognitive feedback could be efficient rehabilitative approach in early stage of rehabilitation.

1. Introduction

In the recent years our research studies have been focused on incomplete spinal cord injured (SCI) patients. In our earlier studies we realized the necessity of functional electrical stimulation (FES) gait training in the early period after spinal cord injury [1]. The candidates were all patients with upper motor neuron lesion, in more clinical terms the patients with thoracic or cervical lesion to the spinal cord. Only a few of incomplete SCI patients were found candidates for permanent FES, most of them used FES only after being released from the rehabilitation centre. In these patients peroneal nerve stimulation was found useful to provoke flexion response resulting in the swing phase of walking.

Several systems employing peroneal nerve stimulation used sensory information to trigger FES during walking. The sensory information was usually provided by use of simple artificial sensors [3]. Data collected by a pair of miniature accelerometers were used to distinguish between the stance and swing phase. Automatic detection algorithms were used to identify the appropriate phase of walking and to control FES. On the basis of the results obtained, development of a small implantable sensor-stimulator device was proposed. No sensor failure or minimal misadjustment was considered.

The aim of a FES rehabilitative system for re-education of walking is not only to deliver electrical stimulation to the paralyzed muscles, but also to assess the sensory information from the paralyzed limb. The sensory information is fed back to the patient and not to the stimulator control unit. The FES rehabilitation systems for re-education of walking are intended to be used with incomplete SCI persons soon after the accident or onset of disease [2]. These systems are to be used within the rehabilitation centers and applied by therapists. Surface electrical stimulation is therefore appropriate. We are developing two separate systems for swing and stance phase. The adequate approach must be selected according to the patient’s gait deficits. In this paper we are proposing a swing phase quality estimation.

Gait re-education system for swing phase detection and swing quality estimation is based on multisensor use, simple feedback signal, which is fed back to the patient, and FES. The feedback signal can be delivered to the patient with vibrotactile or electrical stimulation or with a small earphone. It represents the successfulness or unsuccessfulness of performing the swing phase. The patient has the possibility to simultaneously control the amplitude of FES by a control lever [4] in the handle of the crutch in order to improve swinging of the paralyzed lower extremity.

2. Methods

We used the modified sensory system [5], employing two goniometers (Penny & Gilles), single-axial gyroscope (Murata ENC 03JA) and two pairs of single-axial accelerometers (ACCESS, Switzerland). Multisensor system had several functional tasks. Gyroscope signal was used for swing phase detection, while other sensors took part in swing quality estimation.

Preliminary measurements are aimed to determine the term swing quality. In incomplete SCI, where usually only one side is affected, we want to achieve symmetry during swing phase. Therefore, the reeducation must be focused on making the swing phase of the affected similar to the non-affected swing phase. The multisensor system was placed on the shank of the non-affected extremity to
assess the ankle joint acceleration during walking on the treadmill. The time-course of the assessed acceleration in one gait cycle was used as a reference for affected extremity during the other gait cycles.

When a lower extremity comes into the swing phase, there occurs a significant change in the angular velocity of the shank. This change is detected as the start of the swing phase. The end of the swing phase is detected with the same presumption. During the swing phase the ankle joint acceleration and knee joint angle time-courses are recorded.

\[ \varphi_{\text{meas}, \text{ref}}(t, \tau) = \frac{1}{n} \sum_{k=1}^{n} \text{acc}_{\text{meas}}(t) \text{acc}_{\text{ref}}(t + \tau) \]

Then the correlation coefficient is calculated:

\[ \rho_{\text{meas}, \text{ref}} = \frac{\mathbb{E}[(\text{acc}_{\text{meas}}(t) - m_{\text{meas}}(t))(\text{acc}_{\text{ref}}(t + \tau) - m_{\text{ref}}(t + \tau))]}{\sqrt{\mathbb{E}[(\text{acc}_{\text{meas}}(t) - m_{\text{meas}}(t))^2](\text{acc}_{\text{ref}}(t + \tau) - m_{\text{ref}}(t + \tau))^2]} \]

where \( m \) represents the mean of the signal.

When the calculated coefficient is close to 0, there is no correlation between the signals and closer to 1 it gets more signal resemblance we have. As a matter of fact the correlation coefficient presents the desired swing match (0 – poor, 1 – perfect).

On the basis of the correlation coefficient we have defined the cognitive feedback. The feedback signal was divided into three discrete steps. In a case of insufficient knee flexion or low correlation coefficient the swing was deemed as poor. When the coefficient reached 0.2, then a swing phase was considered sufficient and above 0.6 good. These criteria can be set for any individual patient. The coefficient limits are set according to the patient’s deficits and our requirements. In the presented paper we used auditory cognitive feedback. Personal computer (PC) provided a sound of three different frequencies.

3. Results

In the preliminary measurements three healthy subjects and two incomplete SCI patients were involved. The data of the patient with C6 lesion while walking on a treadmill are presented in this paper. The treadmill speed was set to 0.7 m/s and later decreased to 0.5 m/s. During walking we used the described measurement system [5] and sensory feedback algorithm, running on PC, using MathWorks software.

The first measurements were made without any FES. In the following measurements the physiotherapist was triggering the surface peroneal nerve stimulator. We present only the measurement results with FES, since those are relevant for swing quality estimation. Figure 1 and 2 present the gyro signal, which was used to detect the swing phase. The absolute value of the ankle joint acceleration \( |a_0| \) during the swing phase was the main criterion for quality estimation. The joint angles in ankle and knee are also presented in Figs. 1 and 2.
Figure 3. Time-course of gyroscope, absolute value of ankle joint acceleration and ankle and knee joint angles during FES assisted walking of C6 patient walking on the treadmill. The output of swing detection algorithm and the appertaining value of the correlation coefficient while using FES is also presented.

Figure 3 presents the FES sequence, swing phase detection with all sensor signals and finally the correlation coefficient value – swing phase quality.

Figure 4. The incomplete C6 SCI patient during walking on treadmill. The left lower extremity is in initial swing phase.

There is a significant difference between healthy person’s and incomplete SCI patient’s walking. But we used the same algorithm for swing phase estimation as presented in figure 3 and got good results. Instead of prerecorded ankle joint acceleration of a healthy extremity we used the non-affected extremity of the incomplete SCI patient as a reference signal. The lower chart in figure 3 presents the correlation coefficients. Some double signals can be noticed in the record. This was a consequence of misdetection of the swing phase end, as the patient was not used to FES. It is believed that with more training this can improve.

4. Conclusions
On the basis of the results we can describe the swing quality estimation algorithm as a successful attempt of multisensor use. Most of the swings, recorded in incomplete SCI patient’s walking, were more or less satisfactory, since patient’s walking was almost symmetric. There were some swing phases misdetections, fortunately without significant influence on feedback at the end of the swing phase.

The presented preliminary measurements have shown the multisensor use in gait reeducation. The proposed algorithm can help physiotherapists in early stage of rehabilitation of SCI patients. In the preliminary experiments the physiotherapist triggered the FES according to the auditory feedback. Further development will make possible the FES triggering by the patient and assess more walking data in order to achieve simple gait analysis.

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References