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Sensory Supported FES Control in Gait Training of Incomplete Spinal Cord Injury Persons

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Abstract: Sensory supported electrical stimulation of the peroneal nerve during treadmill walking is proposed as a gait-training modality in incomplete spinal cord injury (SCI) patients. A multisensor device provides information on the tilt of the shank during gait. The information provided significantly improves the triggering instant of the electrical stimulation. Simultaneously, swing-phase estimation serves as a reference to determine the required motor augmentation support. Both approaches, as well as triggering using intensity control of the functional electrical stimulation were applied on a healthy person and on an incomplete C4–5 SCI patient. **Key Words:** Electrical stimulation—Sensors—Therapy—Incomplete—Spinal cord injury—Treadmill.

In recent decades, more incomplete than complete spinal cord injury (SCI) patients are arriving at spinal units. One of the primary goals of the rehabilitative program for the incompletely paralyzed subjects is to restore their walking patterns. The gait pattern can be restored in paralyzed persons by surface or implanted multi- or single-channel functional electrical stimulation (FES), by delivering electrical stimuli to the efferent and/or afferent nerves. The swing phase obtained by eliciting a synergistic flexion response through electrical stimulation of the common peroneal nerve has been extensively used by our group (1). The gait-training modalities eliciting reflex responses result in complex and imitation-natural movements which in consequence provoke afferent signals in joints, tendons, and muscles which are important for re-education of walking. Treadmill-walking produces hip extension at the end of the stance phase which induces reflex hip flexion, and thus initiates the swing phase of walking (2). The treadmill training can be combined with electrical stimulation of the partially paralyzed extremities and may be used in combination with body-weight support (BWS) (3). The BWS helps the patient to concentrate on walking without having problems with maintaining stability. In early gait-training, either the physiotherapist or patient was manually triggering the electrical stimulation (1). When the triggering was performed by the physiotherapist, the patient was able to focus on the gait performance, while the physiotherapist's task remains as the estimation of walking quality. Therefore, the instant of triggering was based on physiotherapist's experience and may vary from step to step. Consequently, the patient's walking performance depended on physiotherapist's skills. In order to overcome this undesired dependency, FES-triggering should be automatic, i.e., linked with a selected gait event or gait phase. Several attempts to use sensory information for direct control of FES to achieve the desired joint motion have already been proposed (4). Here, we suggest the use of tilt information from the shank in combination with an algorithm for swing evaluation (5). The swing-evaluation algorithm estimates the quality of the performed swing phase on the basis of the detected gait cycle and assessed acceleration time-course. While tilt information is succesfully used for stimulation triggering, the output of the swing-evaluation algorithm is applied to control of the stimulation intensity. Afterwards, the swing-phase quality may be classified into three levels and provided to the patient during treadmill walking as audio-cognitive feedback. The proposed method also

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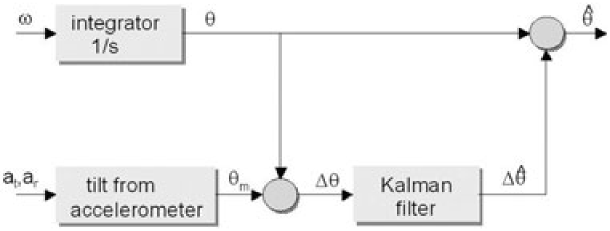

FIG. 1. An indirect Kalman filter was implemented for reliable shank angle (θ) determination. The shank angle reached its peak, in clinical terms the maximal knee flexion, in the preswing phase. This was the moment before the toe-off when the lower extremity went into the swing phase. During the swing phase the knee joint was moving toward extension. Therefore, the peak in the shank angle time-course ($\theta_{trigger}$) was used to trigger the FES.

allows the patient to fully cooperate in the rehabilitation process and to take voluntary actions to improve his/her walking pattern.

In this article the use of the sensory information to trigger the surface peroneal nerve stimulation combined with treadmill-walking as a modality for gait-training in incomplete SCI persons (6) is presented.

MATERIALS AND METHODS

One of the most effective and frequently used methods for gait restoration in incomplete SCI persons is still the application of electrical stimuli to the peroneal nerve. Functional electrical stimulation of the peroneal nerve provokes a flexion reflex, i.e., simultaneous hip flexion, knee flexion, and ankle dorsiflexion. Such action is needed to proceed into the swing phase and successfully complete the gait cycle. It is most likely that FES was triggered by the patient himself pressing the push-button at the appropriate moment. The alternative was the heel-mounted push-button that leads to automatic FES triggering. We proposed goniometer-based triggering (6) and it has proved successful despite sliding of the goniometer, misplacement before treadmill training, and the need for frequent calibration. Some of the time-consuming procedures encountered may be overcome by applying sensors already in use (6) for these purposes. The chosen variable for FES triggering, the shank angle, could be determined by a two-axis accelerometer with low-pass filter, but difficulties turned up during the design of an efficient low-pass filter due to the time delay in the high-order filter. Therefore, we used a gyroscope that was built into the multisensor device for the purposes of swing-phase detection and estimation (5). Using both sensor types and applying a recursive Kalman filter, we were able to determine the shank angle irrespective of sensor misplacement or strong heel strike, which had been frequent sources of error.

In Fig. 1, the gyroscope measurement of the shank angular velocity was the main source of information. Unfortunately, the signal contained non-negligible bias that caused an integration error. Therefore, the output was corrected on-line by a Kalman estimator-filter that contained a gyroscope error model and used additional measurements from the accelerometer-based tilt sensor. The output of such a filter system was a bias-free integration of shank angular velocity that resulted in shank angle.

The analysis of the gait cycle shows that the shank angle reaches its peak, in clinical terms the maximal knee flexion, in the preswing phase. This is the moment before the toe-off when the lower extremity goes into the swing phase. During the swing phase the knee joint moves toward extension. Therefore, the peak in the shank-angle time-course ($\theta_{trigger}$) was used to trigger the FES. Additional conditions were implemented to avoid ambiguity. The first condition in

$$(\hat{\theta} \leq \theta_{trigger}) \wedge (SWP \neq true) \wedge (\dot{\hat{\theta}} < 0)$$

is evaluated as a trigger function, the second disabled additional triggering (Not **SW**ing **P**hase) in the swing phase, and the last condition restricted the triggering to the time before limb advancement. An adjustable time delay was also introduced to assure the appropriate instant of triggering for patients with various motor disabilities.

Motor augmentation intensity adjustment was based on a swing-phase evaluation algorithm (5). The swing phase was evaluated during treadmill walking and two independent counters were implemented. Each was counting "good" and "poor" swing phases, respectively. The physiotherapist decided the number of gait cycles needed for motor augmentation inten-

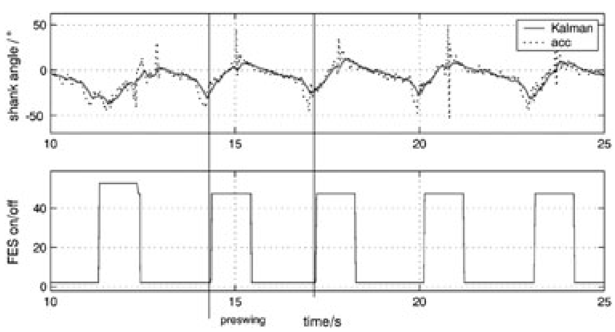

FIG. 2. The instant of FES triggering was based on estimated shank angle (from accelerometer-based and Kalman filter-based estimation). The necessary time-delay was set manually. Data assessed in incomplete SCI person.

FIG. 3. An incomplete SCI patient's (ASIA C) walking when controlled peroneal electrical stimulation was applied.

sity adjustment. In the case of a certain number of consecutive "good" swings, the intensity was decreased but it was increased in the opposite case (5).

RESULTS

In this research one healthy and one incomplete SCI person participated (Table 1). The role of the measurements in the healthy subject was to verify the assessed reference shank-angle trajectory because this was the major sensory information for development of stimulation triggering. On the basis of measurements we found out that although the shank tilt was uniformly determined in the terminal stance and preswing phase, we still needed a variable preset time delay to compensate for the variations caused by disparity of injury level and consequently the different timing of motor augmentation support. Finally, FES was applied to the incomplete SCI patient during treadmill walking.

The surface electrodes were placed over the peroneal nerve with the aim of evoking the flexion reflex. An electrical stimulation frequency of 20 Hz, pulse duration of 0.2 ms, and intensity of 35 mA was applied with the intention of improving swing-phase performance. The instant of triggering of the electrical stimulation was uniformly determined by the estimated shank angle as presented in Fig. 2. When the subject entered the preswing phase, the shank angle reached the predefined trigger value. Considering the predefined time-delay, the train of electrical stimulation pulses was delivered to the peroneal nerve. Before the gait-training session the duration of the train of stimuli, depending on patient's deficits and demands, was also set up.

TABLE 1. *Persons participating in sensory supported FES control validation*

Person	Healthy	Incomplete SCI
Injury level	None	C4–C5
Height (cm)/ weight (kg)	172/74	174/84
Age (year)	29	30
Mobility	Perfect (>ASIA E)	ASIA C

Our patient had difficulties performing a swing phase and was unable to make his lower extremity progress into the swing phase without functional electrical stimulation. The applied peroneal nerve stimulation significantly increased hip and knee flexion and ankle dorsiflexion during the swing phase of walking. Consequently, the leg progressed into the swing phase efficiently as shown in Fig. 3. Even more, the patient was able to maintain stability and to walk on the treadmill without arm support.

DISCUSSION

For several decades FES for lower extremities has been a research issue. Most of the conclusions state that permanent use of FES cannot be very efficient due to muscular fatigue and patients' rejection of cumbersome devices. We can claim that therapeutic FES has proven successful, especially in combination with other rehabilitation techniques, such as treadmill walking. We have shown efficient cooperation of the patient which is demonstrated by the successful combination of the patient's voluntary action and the use of FES during treadmill walking (6). The method proposed in this article also suggests the use of a small, portable multifunctional sensory system to control FES for therapeutic purposes after incomplete spinal cord injury.

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