Abstract

Pedaling exercise on a bicycle ergometer is possible for spinal cord injured (SCI) and stroke patients who are preparing to maintain or recover functional movement abilities. The aims of this study are to develop tailor-made stimulation paradigms that can be applied to varied groups of subjects including complete and incomplete SCI, and stroke subjects for FES-cycling training. Compared to paralyzed limbs in complete SCI subjects, asymmetrical movement patterns caused by muscle weakness or spasticity have often been found in incomplete SCI and stroke subjects. Thus, additional quantitative indices are needed to represent the asymmetrical movement in cycling ergometer from kinematical and muscle activity aspects. To measure the cycling smoothness, roughness index (RI), derived from curvature of instantaneous cycling speed, is used to measure kinematical information. The symmetry index (SI) measures the similarity of muscle activities recorded form affected and unaffected limbs. RI represents the kinematical output of pedaling due to the stimulation or voluntary movement in stroke subjects. However, the muscle power in the unaffected side of stroke subject might dominate the entire pedaling cycle. These two parameters provide additional guidelines for tuning the stimulation schemes for incomplete SCI and stroke subjects.

1. INTRODUCTION

Researchers have indicated that cycling exercises are safe, functional, and accessible to SCI and hemiplegic patients with a wide range of motor impairments [5][7]. However, there is still lack of universal stimulation paradigm for different groups of subjects in bipedal cycling under varied physiological and physical conditions. Thus, one of critical factors in applying functional electrical stimulation (FES) device for clinical studies is the appropriate design of stimulation patterns for various training paradigms. Thus, approaches are highly desirable to tune the stimulation patterns and training scheme when the subjects at varied levels of weakness and then gain more and more strength in the stimulated limb [2].

The aims of this study are to develop tailormade stimulation paradigms that can be applied to varied groups of potential users of this FES-cycling device which include complete and incomplete SCI, and stroke subjects. Compared to paralyzed limbs in complete SCI subjects, asymmetrical movement patterns caused by muscle weakness or spasticity have often been found in incomplete SCI and stroke subjects. Thus, additional quantitative indices from kinematical and kinesiological data are desired.

2. METHODS

For stationary cycling device, the FES-cycling study emphasizes the training of muscles strength and the enhancement of cardiopulmonary function. A standard ergometer with an electromagnetic load was modified to include a comfortable seat with back support and an arm rest for better trunk stability during pedaling. A pair of ankle-foot orthoses were added to maintain the position of the lower legs, as well as to reduce the instability of knee joints during pedaling. An optical encoder with a resolution of 1440 pulses/ cycle was utilized to detect the crank position for kinematics analysis.

As to stimulation patterns for complete SCI subjects, the contraction of the quadriceps produces strength to increase knee angle in the upper cycle; the contraction of the hamstring produces strength to decrease knee angle in the lower cycle. Stimulation pattern design was generally based on the muscle activation...
sequence as well as biomechanical linkage model of lower limbs derived from neurologically intact subject’s cycling movement. FES-cycling studies [1]. For complete SCI subjects, our study therefore focused on designing a special control strategy to prolong cycling time and overcome the ineluctable physiological limitations for paralyzed muscles. In our previous studies, we have developed a closed-loop FES-cycling system based on fuzzy logic control (FLC) that enabled subjects with paraplegia to produce a smooth and prolonged cycling movement according to a designed training protocol [1, 5].

However, there are residual muscle forces in incomplete SCI. Thus, additional care might be needed to detect the difference in the functionality of both limbs which are usually different in strength and might have spasticity in their limbs. For hemiparetic patients with asymmetrical lower limb functions, it is rather difficult to perform continuous and smooth reciprocal movements in the lower extremities. Other research noted a poor correlation between the EMG-based stimulation sequence and the practical stimulation pattern [6]. Although the practicability of designing an individualized stimulation pattern has been proposed, no systematic approach has been presented. The evaluation of cycling smoothness for the assessment of designed stimulation patterns has been investigated. Using kinematical information of the crank position, the cycling unsmoothness (denoted as roughness index, RI) can be derived from the curvature of the instantaneous cycling speed [4].

For stroke patients, we need to provide additional kinesiological data from EMG for quantitative analyses of asymmetrical movements between affected and unaffected limbs in a cycling ergometer. The active EMG electrodes (Motion Control, Salt Lake city, Utah) were positioned over the distal half of the muscle belly, which were aligned longitudinally along the muscle fibers. The EMG signal of quadriceps muscle, the major propeller for pedaling, was amplified and then sampled at 2 kHz for further processing. The symmetry index (SI) was designed to measure the similarity between muscle activities recorded from affected and unaffected limbs of stroke subjects [4][7].

### 3. RESULTS

For complete SCI subjects, we have performed clinical trials for the FES-cycling device in several medical centers in Taiwan, and the clinical data have proven that the fuzzy logic control can keep the cycling exercise on stable speed over thirty minutes [2][3].

Figure 1 shows a typical example of instantaneous cycling speed derived from crank angle. We can observe the unsmoothness in the pedaling between 180 and 300 degrees of the cycling. By increasing the stimulation intensity of the desired muscles, smoother kinematical output with improving rough index from RI=35.18 to RI=8.72 can be seen in Fig. 1.

![Roughness index (RI) of cycling period.](image)

**Figure 1.** Roughness index (RI) of cycling period. RI derived from the polynomial curve fitting of instantaneous cycling speed of an incomplete SCI subject. (a) before and (b) after tuning the stimulation intensity of two limbs.

Asymmetrical EMG linear envelope (LE) of a hemiplegic stroke subject after aligning the quadriceps EMG of two legs is shown in Figure 2. From this kinesiological observation, we can easily observe the asymmetry in muscle power of both sides. Stimulation pattern can be designed based on symmetry index (SI=0.06 in this case) on the EMG output. Then, cycling results from electrical stimulation can be further verified from RI index.
4. DISCUSSION AND CONCLUSIONS

For complete SCI subject, our stimulation scheme focused on the control aspect. A model-free FLC is employed in our FES-cycling control scheme, thereby avoiding exact modeling of a complicated musculoskeletal-ergometer system [1][5]. The cycling smoothness of pedaling was evaluated from kinematical data, RI which is related to the symmetry of the muscle power. This indicator is quite useful for tuning the stimulation patterns of incomplete SCI subjects. However, RIs did not appear significant difference for subjects with hemiplegic legs under light loading. This is because the sound side of stroke subject might dominate the pedalling movement for the entire cycle. Thus, heavier load is needed for this verification purpose. In addition, the similarity in EMG profile (SI) during pedalling further verified the kinesiological data output. By integrating the surface EMG of the quadriceps of both legs, as well as crank positions, we can have reliable quantitative indices for designing stimulation schemes.

In conclusion, the cycling performances, which assessed by cycling smoothness (RI) and muscle activities (SI), appeared significantly represent the symmetry of power output of two legs during FES-cycling. The assessment index of cycling smoothness, RI, and symmetry (SI) did apply significantly rapid and valid evaluation for pedaling exercise. It is appropriate index to identify the kinesiological parameters and provide the intervention goals during clinical application. The indexes also can be applied to design the therapeutic intervention of functional electrical stimulation.

References

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