

# Development of FES-cycling System with Network Capability for Multi-Center Clinical Studies

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## Abstract

The beneficial effects of cycling exercise via functional electrical stimulation (FES) have been demonstrated with the increase of muscle strength and endurance, increase of bone density, suppression of spasticity, improvement of cardiopulmonary function, and many other physiological and psychological effects for spinal cord injured (SCI) subjects. Several modified ergometers are commercially available in clinical rehabilitative treatment. However, those devices are relatively expensive and hardly affordable for the local SCI subjects. The aim of this research is to extend our FES-cycling prototype system for multicenter controlled studies. A telemeeting system has been built for online discussion and exchange of training protocols clinical centers via public Integrated Services of Digital Network (ISDN). This study is expected to provide the quantitative assessment criteria, more rational planning of patient-tailored therapeutic and rehabilitation procedures for SCI subjects participating in FES-cycling training.

**Keywords:** Functional electrical stimulation, Spinal cord injury, Telemeeting, Rehabilitation

## Introduction

The Functional electrical stimulation (FES) cycling ergometer has been shown effective in improving physiological fitness for SCI subjects. FES-cycling exercise, which stimulates lower extremities muscles to perform cycling movement for paraplegic spinal cord injury (SCI) subjects, has obtained obvious therapeutic effects for increasing physical capacities, including increase of muscle strength and endurance, improvement of cardiopulmonary function, and improvement of circulation, and many other effects [1,3,5,6]. Research on FES cycling system of quadriplegic subjects developed by Phillips et al. indicated that the resting blood pressure increased and the average systolic pressure decreased during exercise after one-month training [1]. Schutte et al. evaluated the factors of optimized cycling ergometer from the seated configuration, cycling load and stimulation sequence [2]. Their results indicated that an optimal mechanical design may

improve the cycling performance of paraplegic subjects. However, no clinical trial had been managed which might be due to high variability in different levels of injury and post-injury period among the subjects.

There have been many commercially available FES cycling ergometers for clinical uses. However, costs of each ergometer might be too high for local SCI subjects. In our previous study, we have developed a prototype FES-cycling device used for laboratory experiment [4]. In our prototype of FES cycling system, it possessed two major subsystems, the cycling ergometer and controllable electrical stimulator. The ergometry was an inclined typical cycling device, which has the same level between center of crank and seated position without any resistance on gear. The stimulator elicits constant current to activate the quadriceps and hamstrings muscle groups of both lower extremities. The continuous electrical stimulation would induce dynamic and repeated muscle contraction to sustain the cycling exercise [1,5,6]. Using FES cycling system, persons with SCI could acquire the opportunities to experience aerobic exercise, which is hard to undergo after spinal cord injury.

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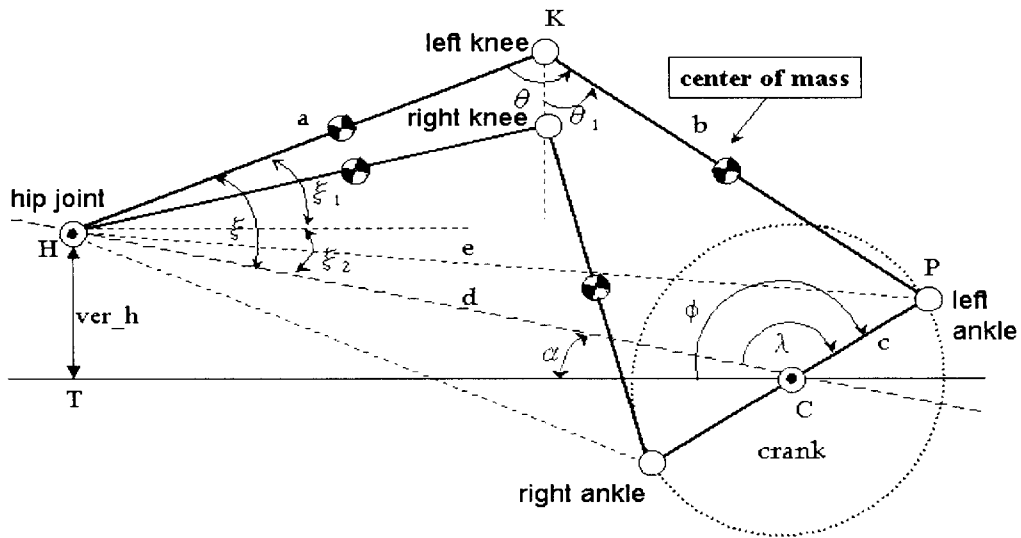


Figure 1. Five-bar linkage system of man-machine configuration

The aims of this study is to expand our prototype FES cycling system as an integrated cycling system which combined man-machine-environment consideration for multi-center controlled studies. To reduce the overhead of traveling among the clinical centers and to allow experience change during clinical trials, we have utilized the teleconference system to procure efficiently problem solving and communication for clinical users.

### Methods

In order to distribute the cycling device for clinical studies, we adopted a cycling ergometer from a local manufacturer (Tonic Fitness Technology Inc.) to achieve the goals. The new cycling ergometer has an adjustable seated position, which can be fit for subjects with different leg lengths. It also allows the adjustment of cycling resistance at different workloads. However, the altitude of seat position is not aligned with the center of crank, different from our prototype system. We need to determine the effect of this change as well as to examine the optimal seat position for varied leg lengths. Thus, the stimulation patterns have to be redesigned for the new cycling via the model developed in our previous study [4,5,6].

#### A. Five-bar linkage system and stimulus pattern

To model an adequate stimulus pattern, we simulated the ergometer cycling exercise as a five-bar linkage [4], as showed in Fig. 1. Supposed all elements of linkage system were rigid bodies and connected by hinge joints. The center of crank and hip joint was an unmovable rotational pivot with the same center. We also supposed rod a as left thigh, rod b as the left shin, and rod c as the left crank. The mass, length and distance between proximal part and center of mass were be shown as  $m$ ,  $l$ , and  $r$ , respectively. The  $\theta$  and  $\phi$  were the angle of knee joint and crank and  $\xi$  mean the angle of hip joint. By this model, we can infer the adequate sequence and timing of

stimulation. Thus, the stimulator could generate enough output to induce the cycling exercise of lower extremities.

Furthermore, an efficient stimulated pattern may play an important role to facilitate the smooth cycling exercise. It might be an intuition to design the stimulus pattern for paraplegic subjects according the muscle contraction sequence of able-bodies during cycling. However, it has not shown any significant evidences between myoelectrical signal sequence of able-bodies and stimulus pattern of paraplegic subjects. Our approach is to derive the stimulation patterns from the gravitation effect of the lower limbs which focuses on when the quadriceps and hamstring muscles should be activated at certain cycling angle. Another factor could affect cycling smoothness is the seat position. We use the same five-bar linkage to simulate the effect of seat position and to determine the optimal seat position.

With the appropriate design of stimulation pattern, another important issue is to control the stimulus output in order to maintain the desired cycling speed. Because the characteristics of stimulated muscles possess nonlinear and the different variability between each subject, it was hard to modeling an adequate dynamic cycling system and system identification. On account of these points, we used a model-free fuzzy logic controller to adopt our controlled scheme. By incorporating the rational stimulation patterns, the FLC can produce a smooth and prolonged cycling movement necessary for designing various training protocols [4,5,6].

#### B. Telemeeting system

In our study, collaborative studies were initiated at several clinical centers, including Taipei medical College, Taichung municipal rehabilitation hospital, and Kaoshiung Medical University, located around the Taiwan. A telemeeting system has been built for online discussion and exchange of training protocols clinical centers via public Integrated Services of Digital Network (ISDN). The schematic diagram of the telemeeting system is depicted in Fig. 2.

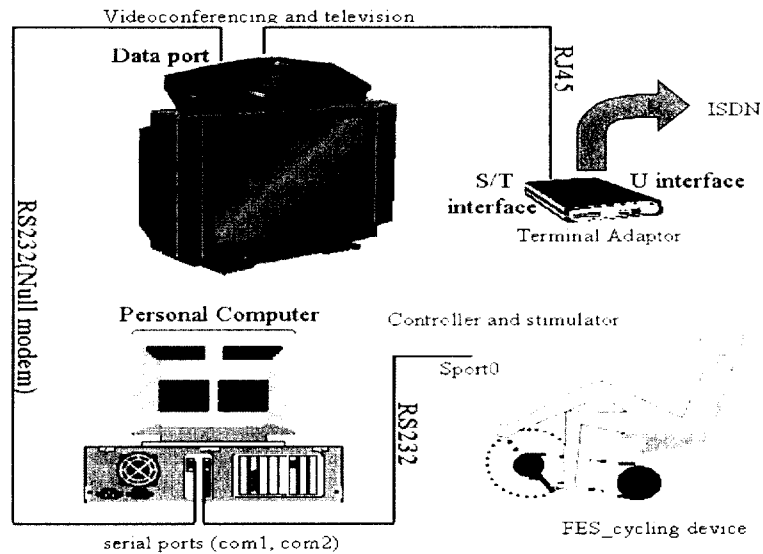


Figure 2. Schematic diagram of connection of telemeeting used for multi-channel FES-cycling controlled studies.

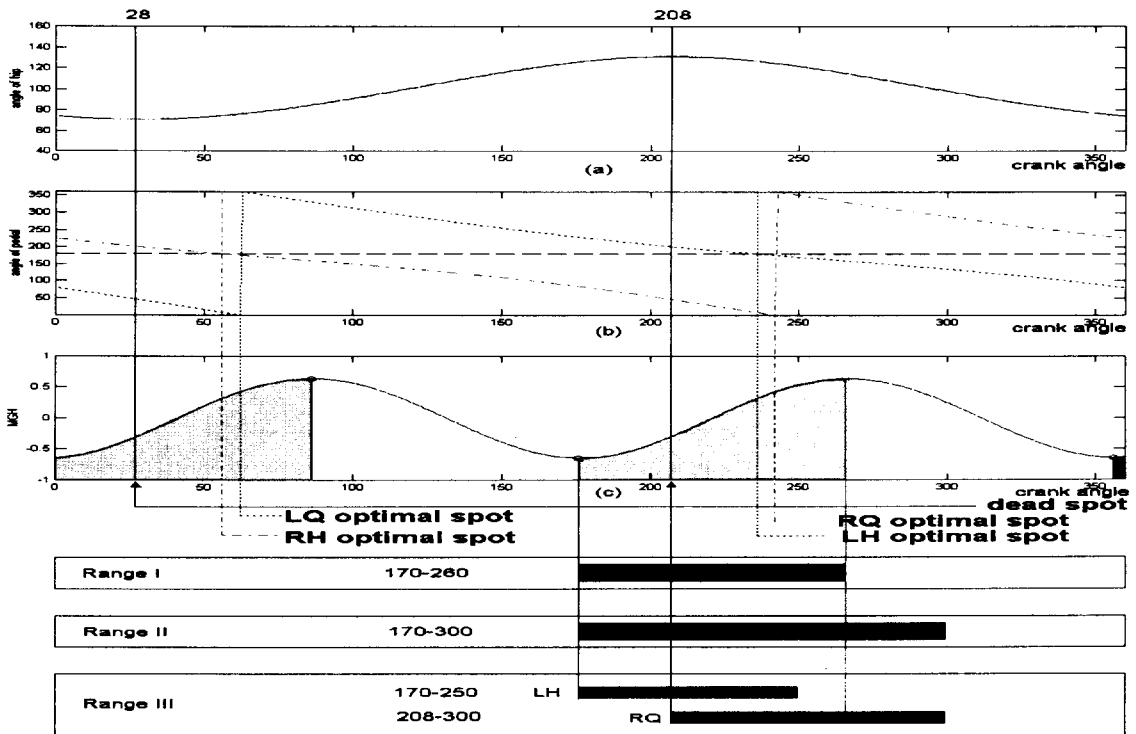


Figure 3. Design of stimulation pattern can be derived from (a) the trajectory of left hip joint, (b) angle between crank center and shin, and (c) the distribution of gravitational potential

Standalone teleconference devices have been set up in the clinical centers. The standalone device consists of video camera, microphone, ISDN terminal adapter, extraconnected television, and speakers [7,9]. The video image can be viewed via the local TV. The user in the remote site can adjust the camera locally for better view of the experiment in remote site. The video can be also recorded by using image grabbing card. The transmission baud rate are 128 K for the video image and 128 K for the sound (1S, 2B 128k). Except the video and audio communication, the users can also discuss the experiment via

white board communication mode [8,10].

## Results

### Design of Stimulation Patterns

From the five-bar linkage model, Fig. 3 shows the gravitational potential changes during 360 degree of cycling angles, measured from the anthropometrical data measured from a SCI subject of T3 level. Fig. 3(a) depicts the flexion and extension of hip angles during cycling movement. At about 0° or 180° between the angle of crank and pedal, stimulation of

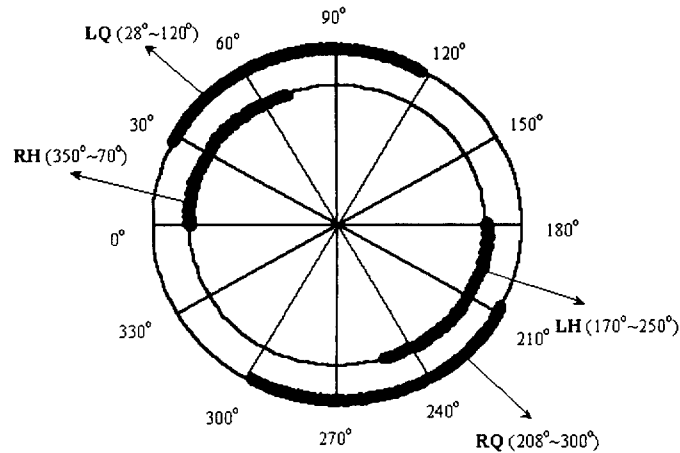


Figure 4. Diagram of stimulated patterns for right and left quadriceps (RQ and LQ) and hamstring (RH and LH).

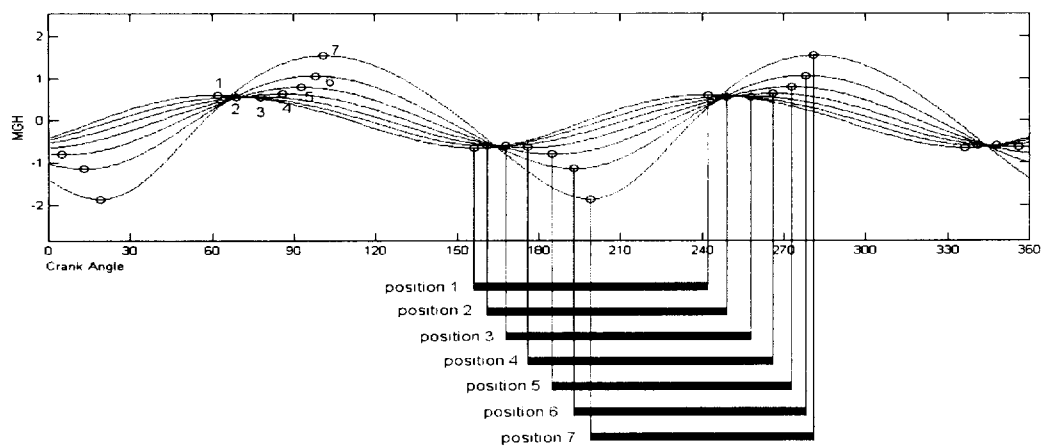


Figure 5. The changes of gravitational potential for seven seat positions.

quadriceps muscle, as the view of kinesiology, can generate the better power output, as indicated in Fig. 3(b). The area between peak and valley, the shaded area shown in Fig. 3(c), it required the contraction of muscle or rotational momentum to accomplish the exercise. It is expected that the stimulation should be applied at the area of increasing gravitational potential, as range I shown in Fig. 3. The shifted periods of stimulation can be adjusted according to the muscle strength of SCI subject as well as the varied of leg lengths. Since the quadriceps and the hamstring of contra-lateral side form a pair for force generation. Thus the range II can be divided into Range III, the individual stimulation ranges for quadriceps and hamstring muscle groups. We found that the contraction of hamstring muscle was shown in the lowest point of gravity potential. The strategies to stimulate the hamstrings muscle might begin at this point through the efficient area and expand over 20°~25° for better effects. The derived stimulation ranges for quadriceps and hamstrings of both legs can be represented in a polar plot, as shown in Fig. 4.

Another factor affecting the stimulation is the seat position as well as the altitude difference between seat and crank center. By employing the five-bar linkage model, we can observe the effects of changes in these factors. Fig. 5 shows the changes of

potential energy derived for the 7 seat positions in the cycling ergometer. These 7 positions correspond to leg length below 100 cm and 115 cm (or below 150 cm up to 185 cm in height). We can observe that mild shift in peak and valley positions as well as the magnitude of the gravitation potential. The SCI subject with long leg has higher gravitation potential to overcome and the angles for peak potential energy also shift backward.

We can observe the relationships between the range of knee angle and gravitation potential, as shown in Fig. 6. Fig. 6(a) shows that the range of knee angle increase following the elevation of seat to crank center. As seen from Fig. 6(b), minimum work appeared in about positions 2 and 3 in 120 degree of knee angle.

In order to understand the optimal seat position for almost subjects, referring to the average leg length in domestic data [11], we simulated the relationships between seat position and the range of knee angle for different leg length in the interval of per 2.5 centimeter, shown in Fig. 7. The simulation results indicated that the suggested positions, the shaded area in Fig. 7, in which the minimum positive power is needed during cycling. From this simulation, the optimal seat positions for varied leg lengths are listed in Table I.

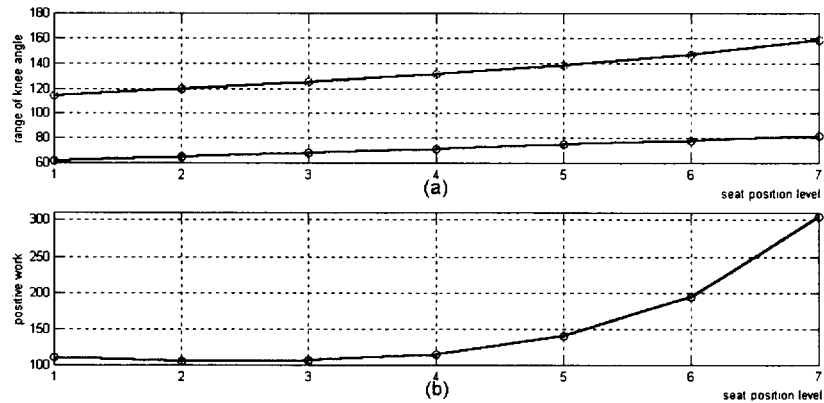


Figure 6. The relationships between (a) range of knee angle and (b) variance of gravitation.

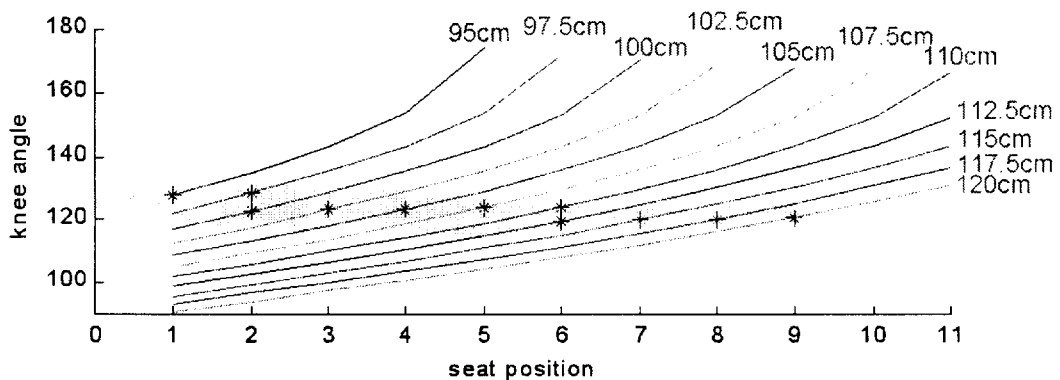


Figure 7. The relationships between seat position and maximum range of motion of knee joints in different leg lengths.

Table 1: The Suggested Seat Positions for Varied Leg Lengths

seat position	leg length (hip joint to sole )
1	~ 100 cm
2	95 cm ~ 102.5 cm
3	97.5 cm ~ 105 cm
4	102.5 cm ~ 107.5 cm
5	105 cm ~ 112.5 cm
6	107.5 cm ~ 115 cm
7	112.5 cm ~ 117.5 cm
8	115 cm ~

### Control Strategy

To supply electrical stimulation, both quadriceps and hamstrings muscle groups have been applied gel-back surface electrodes. The muscles were stimulated by pulse frequency of 20 Hz with 300 microseconds pulse duration during cycling experiments.

Two approaches of control strategies have been tested. One is to update the stimulation current once in a cycle and another is update the current every 50 ms, i.e. 20 Hz (same as the stimulation frequency). The higher updating could fast adjust the stimulation current within a cycle. However, it could also cause too fast in the change of stimulation current. Fig. 8 shows typical results of the constant speed cycling. Since the muscle power of the SCI subject is relatively weak, he only

could cycle at a rather short time. However, the SCI can cycle at the desired speed with the stimulation current controlled by our FLC scheme. Usually, higher cycling speed accompanied low variation which is due to higher rotational inertia for overcoming the deadspots.

Another factor could affect the control strategy is the cycling smoothness. Instantaneous cycling speed which is derived from the crank angles during each cycle, as shown in Fig. 9(a). Under a stable cycling status, we found that the cycling speed decreased more violent at about 45° and 210° of crank angle, as depicted in Fig. 9(b). Several factors could result in the decrease in the cycling speed at these particular cycling angles. It might be due to the mechanical dead spots of ergometer at which the stimulated muscle has minimal amount of torque output. On contrast, these two cycling angles require higher kinetic energy to overcome the gravitational potential. If there is not enough moment to overcome these two points, the cycling would come to a halt. It is interesting to note that the instantaneous speed at 50 degrees is significantly lower than that of corresponding angles at another half cycle, i.e. 230 degrees. This variation could result from an asymmetry in muscle power of two legs.

### Network Capacity of Multi-center Clinical Study

With establishment of teleconference system, exchange of training protocols becomes rather simple between clinical



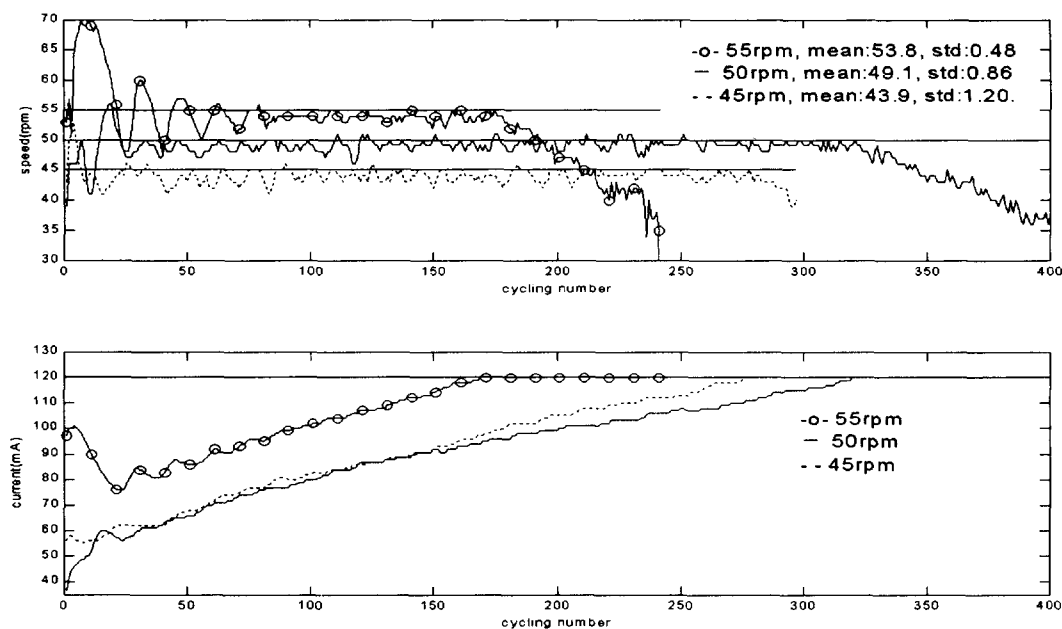


Figure 8. (a) The cycling speed (b) is controlled with fuzzy logic control of the stimulation current.

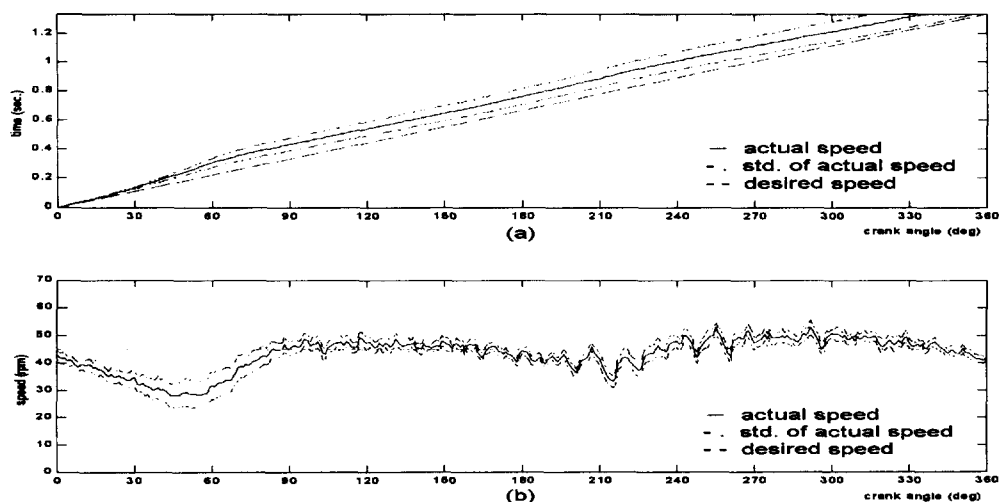


Figure 9. The instantaneous cycling speed can be derived from crank angle, significant lower cycling at around 50 degree which might due to asymmetrical muscle power of both legs.

training centers. Especially at the beginning of the clinical trials, the usage of stimulator as well as the mechanical problems of cycling ergometer are often raised by the clinical practitioners. With ISDN communication, research data can be transmitted from one clinical center to the other. In addition to text, pictures during cycling are rather useful between the system designer and clinical practitioners. To assess the effectiveness of this training device, we have designed special topics, including musculoskeletal system and psychosocial influence, spasticity, cardiopulmonary function and hybrid exercise protocols in four clinical centers. Although there are no quantifying data to show exact benefit of networking for the FES-cycling clinical trials. The most obvious cost reduction is the decreased necessity for travel. The traveling cost reduction

include the expenditures for consultants traveling and patients to distant consultants and transfer to other facilities. In addition to traveling cost reduction, enhanced decision making and problem solving between the research group discussion provided by telmeeting do facilitate the research progress of this project.

## Discussion and Conclusion

According to the model of five-bar linkage system, we can design the stimulation pattern for SCI individuals to perform the expected exercise and accomplish the goals of clinical training. The experimental leg cycling ergometer with an adjustable seat position and load was initially constructed. However, the training effects may be restricted after the physical capability was improved.

Since the new cycling ergometer was adopted from device used for able-bodies. There are certain limitations due to electro-mechanical structure. For example, the new cycling device would consume more energy than our prototype. Furthermore, the vertical level between hip joint and seat was higher than our prototype system. These factors would require higher power output for the SCI subjects. This indicated that the SCI subjects need longer muscle strengthening prior to performing FES-cycling training.

With our stimulation patterns and control strategy, the system possessed the controlled abilities for constant and varied speed of 35–65 revolution per minute under the resistance. However, the experimental cycling ergometer was modified from the regular ergometer that considered just for able-bodies and might be a barrier for spinal cord injury subjects. Although the environmental modification had been made, the more adaptive assistants are still need for better performance and effects.

By using the telemeeting, we might on-line solve the mechanical problems and modify the stimulation parameters. It could save time and man power efficiently. Following the increasing frequency of clinical trials, the telemeeting will play a more important role in discussion and communication between research group and clinical centers. Our ongoing study is to develop an in-home using device with data communication protocol. With in-home use FES-cycling device, that the SCI subjects can train at home and sent the data to clinical center for monitoring the progress of training and for adjusting the system parameters.

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# 發展應用於多醫學中心功能性電刺激踩車系統

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## 摘 要

功能性電刺激踩車已證實對於脊髓損傷者具有增加肌力與其耐受性、改善心肺功能與下肢循環及痙攣等其他生理及心理上的優點。目前上有許多商品化之復健中心用之踩車系統。然而，其所需之費用也相對地較為昂貴無法為國內脊髓損傷患者廣泛利用。本研究的目的在使我們所研發之功能性電刺激踩車系統能推展至臨床使用，並且利用整體服務數位網路 (ISDN) 之視訊會議系統與臨床醫學中心進行線上討論及交換訓練方式及經驗。期望能提供脊髓損傷者功能電刺激踩車訓練量化及合理訓練模式完成復健之過程改善生活品質之目的。

**關鍵詞：**功能性電刺激、脊髓損傷、視訊會議、復健醫學

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