Energy-Efficient FES Cycling with Quadriceps Stimulation
B.S.KSM KADER IBRAHIM, S.C.GHAROONI, M.O.TOKHI, R.MASSOUD,
Department of Automatic Control &System Engineering, The University of Sheffield. United Kingdom

Abstract

This paper discusses the use of energy storage device to assist FES-cycling for paraplegics and at the same time to eliminate the dead points of the pedal cycle. Implementation of an energy storage device has many desirable influences on FES-cycling. In this study, simple elastic cables are used as energy storage device. Elastic cables can store elastic potential energy due to either compression or stretching. They can be used to improve the performance of FES-cycling especially when only one muscle group is stimulated. In this method excess energy of quadriceps muscle is saved and released at appropriate time of cycling. This subsequently reduces the number of stimulation channels required.

1 Introduction

Spinal cord injury (SCI) is defined as damage to the spinal cord that in turn results in loss of function resulting in reduced mobility. Functional electrical stimulation (FES) is the best way to restore movement of the working limb muscles. FES-cycling can help paraplegics to exercise effectively by stimulating their paralysed leg muscles. Since it is safe and easy and also results in improvement in the cardiovascular function and muscle forces [3,4].

To obtain steady FES-cycling most researchers have stimulated at least two muscle groups (quadriceps and hamstring). The more muscles involved in the stimulation process the more electrodes are required to be correctly positioned and thus the more time consuming. Actually the most challenging problem faced by paraplegics during the preparation for FES-cycling is placing the surface stimulation electrodes in their proper positions[5]. A novel approach involving the stimulation of only the quadriceps to obtain steady FES-cycling stimulating knee has been proposed by Massoud (2007).

Hunt et al (2004) have reported that auxiliary motors can enhance FES-cycling performance, the overall power can be greatly increased, loss of power due to muscle fatigue can be compensated for and leg cycling motion can be maintained. However the associated power supply is relatively large in size and bulky.

Gharooni et. al (2000) used a spring brake orthosis (SBO) as gait restoration system in which stored spring elastic energy and potential energy of limb segments are utilised to aid gait. This energy is released as kinetic energy at the optimal time to provide the desired limb motion. Rasmussen et al. (2005) tried to eliminate the dead centres of the pedal cycle by providing the bicycle frame with a spring in their ergonomic bicycle. In this research elastic cables are used as energy storage device.

Implementation of the elastic cables has many desirable influences on FES-cycling especially to overcome the problem of repositioning a large number of electrodes. An energy storage device can assist FES-cycling, and could possibility replace conventional auxiliary electric motors so as to increase cycling performance with only depends on the stimulated muscles effort. Energy storage device do not need any external energy supplement and the construction is simple.

2 Method

2.1 Energy Storage Device

Elastic cable can be used to improve the performance of FES-cycling especially when only one muscle group is stimulated. In this method excess energy of quadriceps muscle is saved and released in the appropriate time of cycling. The two elastic cables are stretched and compressed as the crank revolves as shown in Figure 1. With the correct positioning this may allow the legs to store and release elastic energy that can subsequently help the paraplegic to perform the cycling and at the same time to overcome the dead centre of the pedal cycle.

The shape of elastic cables can be deformed quite a bit before they reach their elastic limit. Because they
stretch, they can store energy that can be used to do work in the future. This type of stored energy is elastic potential energy. As elastic potential energy is released, it is converted into kinetic energy, or energy of motion.

The length of an elastic cable which does not have any forces acting upon it is known as the natural length of the elastic cable. If an elastic cable has been stretched, then the extension is how much longer the elastic cable is as a result of being stretched. Modulus of elasticity of an elastic cable is a measure of how stretchy it is.

Hooke's law states that the tension in an elastic cable, $T$, is found using the following formula:

$$ T = \frac{\lambda x}{l} $$  \hspace{1cm} (1)

where $\lambda$ is the modulus of elasticity, $x$ is the extension and $l$ is the natural length of the elastic cable.

Elastic potential energy stored in an elastic cable is given by

$$ E = \frac{\lambda x^2}{2l} $$  \hspace{1cm} (2)

2.2 Elastic cable to overcome the dead points

The main difficulty in cycling is the dead points, which are defined as the two pedal positions at which the net moment referred to crank rotation centre is zero [2]. A pedalling cycle of 360° has two so-called dead points, which on an ordinary bicycle fall when the pedal arms are close to vertical. These two points (dead spots) of crank angle, $\theta$ occur at 0° and 180° as shown in Figure 2. The moment arms in these points will be zero.

In these positions it is difficult for the human body to produce much crank torque because the tangential pedal force direction is perpendicular to the preferred force direction of the legs. Much effort has been invested into mechanisms that reduce or eliminate these dead points. Rasmussen et al. [6] demonstrated an intricate mechanism bicycle for paraplegics that helps overcome the dead point by making sure that it does not occur simultaneously for the two legs.

Basically to overcome the dead points in normal conditions, the corresponding leg must push to move the crank in the cycling direction while the other leg is flexing to give a sufficient driving torque to overcome the situation. After passing the dead point the cycling speed begins to increase, and the corresponding leg starts to flex to overcome this increase and to negate the influence of its earlier extension. These important tasks of the knee flexors during the cycling process make them absolutely essential in cycling and researchers have used them as important elements in investigating FES-cycling for paraplegics.

The knee flexors are not stimulated in this study, and the only way to reduce the crank cadence after the dead point is to apply another moment in the opposite direction. This can be achieved by arranging elastic cables as shown in Figure 3.
3 Results

The amount of elastic potential energy stored in an elastic cable is related to the amount of stretch of the device. There are two different positions of the elastic cable to be considered. The first position is when the cable stretches to the maximum point or energy storing stage as shown in Figure 4. The second position is when cable releases the stored energy which occurs 90° away from the first position as shown in Figure 5. From this cyclical legs motion it is seen that the two elastics are stretched and compressed which allow the legs to store and release elastic energy. At quarter of cycle the maximum position of the pedal is reached so the maximum energy is stored in the elastic cable. This energy is released in the next cycle. Instead of using hamstring for flexion this energy can be used to pull the pedal backward. This causes the knee to flex without stimulating the hamstring muscle. The presence of elastic cables helps the paraplegic to perform cycling exercise with only one muscle (quadriceps) and also helps to overcome the dead points by providing moments in the opposite direction. The only challenge is the quadriceps muscle needs to be stimulated more than with standard FES cycling because its action has to extend the knee and also to stretch the elastic cable; this double action would imply a greater fatigue of quadriceps during the task. However this double action needs only at the initial stage of cycling or charging phase of elastic cable.

4 Conclusion

The paper has highlighted how energy storage device can be used to assist paraplegia to perform FES-cycling. In this study elastic cables are used to store and release energy at appropriate time of cycling. The implementation of elastic cables shows that the cycling motion can be performed by only stimulating one muscle group. It can also eliminate the dead points of the pedal cycle. Future work will investigate the development of appropriate control strategy to achieve optimal stimulated current and pulse width with combination of energy storage device (elastic cables) for smooth cycling motion.

5 Literature


