Abstract

Spring brake orthosis (SBO) is a kind of hybrid orthosis system (HOS) which generates the swing phase of paraplegic gait by employing a spring at the knee joint to store energy during the knee extension through quadriceps stimulation, which is then released to produce knee flexion. The acceptance of any HOS and hence its degree of success depends largely on its performance in generating an acceptable gait trajectory. In this paper, the performances of continuous-time tracking control with PID and fuzzy logic control (FLC) as well as discrete-time cycle-to-cycle control are studied in generating the swing phase in an SBO equipped human leg. A leg model of an average sized (183 cm height) is developed for simulation purposes. The controller parameters are tuned using genetic algorithms (GAs) for carefully chosen objective functions. Simulations reveal the vital role of the trajectory for tracking control in FES applications, where the actuator (muscle) output is highly nonlinear and limited. The trajectory-less cycle-to-cycle control, on the other hand, is found to be more preferable because of its obvious capability of serving the actual purpose – producing full knee extension at the end of swing phase through a ballistic movement whose trajectory is defined purely by the physics of the leg-SBO combination. The unique trajectory is then used in the continuous-time feedback control and the result is found to be superior to that of discrete-time cycle-to-cycle control.

1 Introduction

Complete or partial loss of ability to walk or stand due to lower limb paralysis is a very common as well as drastic result of thoracic level spinal cord injury (SCI). The loss of lower limb function and inability to walk or stand significantly reduces the quality of life of disabled individuals and carries with them psychological and physiological effects. The spectrum of problems that may interfere with locomotory performance after and SCI includes hyperactivity of spinal reflex (muscle spasticity), alternation in the muscle activation patterns, including weaknesses and difficulty in coping with weight bearing, balance and hip joint.

The specific electrical stimulation of nervous system below the level of the spinal lesion can produce powerful muscle contractions and thus can be used to generate primitive movements. This is termed as ‘functional electrical stimulation’ (FES) and is used to obtain a functional, useful movement by evoking artificial contraction of the muscles deprived of nervous control. The aims of the restoration varies with the ambition of the researchers and range from assistance with wheelchair transfers to the ability to stand up and sit down, to take few steps, to walking for some distance. Most work has concentrated on the correction of foot drop in hemiplegia and on the restoration of standing and walking in paraplegia.

The main challenge in FES assisted movement arises from the fact that the artificially stimulated muscle fatigues very quickly because of the ‘reversed recruitment order’ of the artificially stimulated motor-neurons. The consequences are twofold: (a) limited duration of the FES assisted movement, especially standing and walking, (b) drastic changes in the actuator (muscle) properties lead to poor movement control. One of the major approaches to overcome these limitations is to reduce the use of active muscle, where possible, through the use of passive braces and is called hybrid orthosis systems (HOS).

The spring brake orthosis is a kind of HOS, which generates the swing phase of paraplegic gait [1]. During knee extension of swing phase, SBO uses quadriceps to partially store FES generated force as potential energy in a torsion spring attached to the knee joint. A brake is then employed to maintain the knee extension without any muscle contraction. Then knee flexion is achieved by releasing the brake and letting the spring to return to its resting position (approx 70° – 80°). The hip flexion is simultaneously produced as a result of consequent shift in the centre of mass (CoM) of the overall leg segment during this knee flexion and is maintained throughout the required duration by applying a brake/ratchet at the hip joint.

2 Methods

2.1 Model

A forward dynamic planner (sagittal) human leg consisting of segmental dynamics [2], passive properties at the joints [3], electrically stimulated muscle model of quadriceps [4] and SBO was modelled through a combination of visualNastran® (VN) software and
Simulink®. The SBO design parameters are taken from a previous study which employed Genetic algorithms (GAs) to find the best parameters.

2.2 Control of SBO

Since the SBO aided swing phase involves no control at the hip joint, its control in generating swing phase refers to the control of knee joint trajectory (mainly during knee extension) through quadriceps stimulation. Both PID and PD type Fuzzy logic controller (FLC) are tested in the closed-loop form. All the parameters of the controller are optimised using GAs for carefully chosen objective functions. Cycle-to-cycle control [5] is also investigated and optimised due to its increasing popularity and evident superiority over closed-loop control in FES control. Once again, a GA is employed to search for the best parameters for the cycle-to-cycle control strategy.

Attention is paid to derive the best trajectory for the closed-loop controllers. Two factors affected the choice of trajectory, (a) maximizing the energy efficiency following suggestion from [6], so as to increase energy efficiency as well as reduce muscle fatigue, (b) its degree of ability to drive the knee joint all the way to full knee extension. Since cycle-to-cycle control takes care of only the end-of-phase orientation of the concerned limb joint rather than taking it through a predefined trajectory, the joint trajectory thus traversed is of significant importance in terms of achieving full knee extension. Bearing this in mind, the knee joint trajectory traversed under an optimised cycle-to-cycle control strategy is used as reference trajectory in closed loop control strategy.

2.2.1 Controller Tuning with GAs

The controller parameters are initialised using Ziegler-Nichols Method (for PID) and heuristic method (for FLC). Several search operations are performed to find the best values for the controller parameters using GAs and MOGA [7].

3 Results

3.1 Closed-loop Control with Reference Trajectory Derived from Cycle-to-cycle Control

The optimised cycle-to-cycle control strategy with a successful end-of-phase knee extension results in a unique knee joints trajectory. This uniqueness is mainly characterized by the minimum time-integral of the active torque from the stimulated muscle. This unique trajectory is then used as the input reference for the closed-loop controllers of with the controller parameters tuned with GAs.

The success in introducing the new reference trajectory is very much obvious in Fig 1, which presents the resultant knee joint trajectory under FLC and PID control along with the reference trajectory. The result, besides asserting a high degree of suitability of the given trajectory, also reveals the variation in the degree of suitability amongst arbitrary trajectories for FES applications.

![Fig 1. PID and FL control of knee joint trajectory for SBO swing phase](image1)

Hind joint trajectory is found to be satisfactory (25°±4°) in all the cases, and that’s why it is not presented in all the results.

3.2 Comparison Between the Controllers

![Fig 2. Accumulation (integral) of active muscle torque during swing phase with different controllers](image2)

In FES applications, muscle fatigue is always an inevitable pitfall and hence always desirable to keep it as minimum as possible. Fig 2 is a brief representation of performances of the controllers investigated so far, in terms of fatigue immunity. The figure shows time-integral of the active quadriceps torque generated under each control strategy which is related to the energy consumption of the muscle and thus to the fatigue.
The two curves indicating least amount of time-integral of active torque correspond to the initial closed-loop control approach with modified passive oscillation as reference trajectory. Although they seem to produce potentially less fatigue, they are of no significance due to their inability to produce full knee extension. Among the other 3 curves cycle-to-cycle control seems to accumulate least active muscle torque. FLC appears to accumulate less active torque between the rest 2 curves of which both are closed-loop.

![Graph](image)

### Table 1: Knee Joint Trajectories

<table>
<thead>
<tr>
<th>Control</th>
<th>% Normal Excursion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle-to-cycle</td>
<td>83%</td>
</tr>
<tr>
<td>PID</td>
<td>86.57%</td>
</tr>
<tr>
<td>FLC</td>
<td>91.1%</td>
</tr>
</tbody>
</table>

**Fig 3.** (a) Knee joint trajectories with the same controllers of section 3.3 under fatigue condition (50% of normal quadriceps torque output), (b) Table showing percentage drop in the excursion of the knee under fatigue condition.

Although apparently the open-loop cycle-to-cycle control would produce least fatigue, the closed-loop controllers, due to their obvious nature are more robust against plant variations, e.g. due to fatigue. This is revealed in the result in Fig 3 (a) and (b), where Fig 3 (a) shows the trajectories with the same controllers, but active torque halved, simulating fatigue condition, while the table in Fig 3 (b) quantitatively presents the same result in terms of knee joint excursion as a percentage of the excursion in normal (fatigueless) condition. It is obvious that both the closed-loop controllers are more robust than the cycle-to-cycle controller with the FLC at the top.

## 4 Concluding Remarks

This work primarily concentrates on closed-loop tracking control of SBO assisted swing phase with a view to benefit for the advantages of feedback tracking control. One of the main attractions of cycle-to-cycle control lies in achieving the necessary end-of-phase orientation required for successful functional movement without the need of any trajectory. Being discrete-time in nature, it also suffers from the lack of real time online supervision of states. In principle, the current work combines the advantages of both the control strategies. A successful practical implementation of any FES control must include adaptation mechanism for the controller parameter(s), especially to cope with fatigue related changes. Such an optimised controller, as the one in this work, can serve as an initialised part of an adaptive controller through the addition of an online adaptation mechanism.

## Reference