Genetic Optimization of Spring Brake Orthosis Parameters: Spring Properties

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Abstract

Spring Brake Orthosis (SBO) [1] generates the swing phase of 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 spring characteristics in this case would be the only optimizable parameters determining the resultant knee flexion trajectory. In this work, subject specific optimum spring parameters (spring constant, spring rest angle) for SBO purposes are obtained using Genetic Algorithms (GAs). Both linear and nonlinear types of spring are tested. The Mean Square Error (MSE) between the reference and actual trajectory is defined as the cost function. It turns out that linear spring could perform better than nonlinear spring in SBO.

1. INTRODUCTION

Functional electrical stimulation (FES) induces muscle contraction through electrical stimulation of the constituent motor neurons [2]. Nowadays, it appears to be a promising means of restoring limited useful movements in paralyzed people, who have lost mobility due to spinal cord injury (SCI), while having their muscles and nerves of the extremities distal to the injured region capable of generating force. But the FES stimulated muscle fatigues very quickly because of the reversed recruitment order of artificially stimulated motoneurons [3]. The consequences are twofold: (*i*) limiting the duration of the FES assisted movement, especially standing and walking, (*ii*) drastic changes in the plant (muscle) properties which pose challenge in the control task.

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 [4]. This is classified as ‘hybrid orthosis’ and combines FES with a lower limb orthotic brace.

Spring Brake Orthosis (SBO) Concept: The quadriceps muscles, when artificially stimulated, could produce much more torque than is required just to extend the knee. During knee extension of swing phase, SBO exploits this feature of the quadriceps through partially storing FES generated quadriceps 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, thus reducing fatigue. Then knee flexion is achieved by releasing the brake and letting the spring to return to its resting position (approx 70^0 – 80^0). 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. This results in a hybrid orthosis combing electrical stimulation of quadriceps muscle, spring and brake at the knee joint and brake/ratchet at the hip joint, with the activation of each of them at appropriate instant and for appropriate period.

Genetic Algorithm (GA) Optimization: Genetic algorithms, first proposed by Holland in 1975 [5], constitute a class of computational models that mimic natural evolution to solve problems in a wide variety of domains. It is formed by a set of individual elements (the population) and a set of biological inspired operators that can change these individuals. According to evolutionary theory only the individuals that are the more suited in the population are likely to survive and to generate off-springs, thus transmitting their biological heredity to new generations [6].

2. METHODS

2.2. The SBO equipped leg model:

A human leg consisting the following components was modelled through a combination of visualNastran® (VN) software and Simulink®

(***i***) ***Leg Segments and Joints***: The body segments *viz.* trunk, thigh, shank and foot were developed in VN software. The thigh and shank were developed as simple cylinders and the foot as rectangular box. Anthropometric data (mass, dimension, position of CoM, radius of gyration etc.) were obtained using [7].

The hip and knee joints were realized as hinge joints with single degree of freedom (DOF) within the same software environment while the ankle joint were simplified as rigid joint with no DOF.

(***ii***) ***The SBO***: The spring and the brake were implemented within the VN software environment. Both linear and nonlinear torsion springs modelled as below were tested at the knee joint:

$M_{\text{spring}} = -k\theta$ linear spring

$M_{\text{spring}} = -k\theta^2$ nonlinear spring

where M_{spring} is the spring torque, k is the spring constant and θ is the angular displacement from its rest angle

(***iii***) ***Dynamic Equilibrium at Joints****:* For normal leg, the dynamic equilibrium at each joint can be expressed as:

$M_i = M_g + M_s + M_d + M_a$

where M_i, M_g, M_s, M_d and M_a represent the torque due to moment of inertia of the rotating segment, gravity, joint stiffness, joint viscosity and muscle activation respectively. As there will be no muscle activity during the period considered, M_a becomes zero. The mathematical model to describe the passive lower limb joint moments developed by [8] has been used in the leg model to account for the passive hip and knee joint torques. This generic model is based upon the Kelvin model for viscoelasticity and able to describe both elastic and viscous properties of each joint of lower extremity throughout the range of motion and as a function of all relevant joint angles. M_i and M_g were realised within the VN software environment, which required positioning the segmental CoM according to the anthropometric data [7].

2.3. The GA Optimization Process:

GA was employed to search for the optimum spring parameters. While the model (segmental dynamics) is mainly run in VN software, the two spring parameters, *i.e*. spring constant k and rest angle θ_r, that are to be optimized were arranged to be adjustable from the Simulink environment and the resultant trajectory fed back to the Simulink. This in turn enabled inputting the parameters of interest from Matlab where the optimizing program is running. Similarly the resultant trajectory made available within the Matlab environment for MSE calculation purposes was required by the optimization process. In this regard, reference trajectory for all lower limb joints for normal human gait was obtained from [7]. In SBO operation the spring starts operating from slightly (15% of the gait cycle) before the actual swing phase, till the maximum knee flexion, which encompasses approximately 50% of the swing phase and 30% of the whole gait cycle. Accordingly, the reference trajectory for the knee for that period of time (approx. 0.31 seconds) was used to define the objective function, which is the MSE between the reference and actual knee trajectory. Figure 1 shows the normal gait joint orientations during this period.

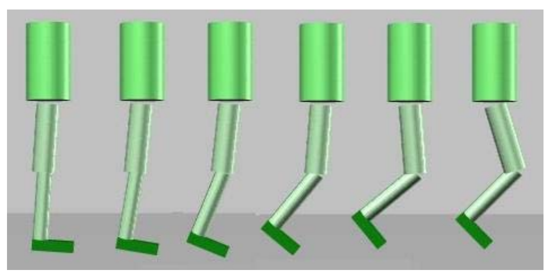

Figure 1 Joint orientation in natural gait during the period corresponding to the SBO Spring Operation

The GA optimization procedure was initialized with the following parameters:

Number of individuals	40
Number of generations	100
Generation gap	0.8
Crossover rate	0.8
Precision	20 Bit
Mutation rate	0.001

3. RESULTS

Figure 2 shows the decay of the MSE and the convergence of the knee trajectory with generation. It can be seen that for the linear spring case, the MSE doesn't show any significant improvement after the 22nd generation, while it's the 76th in case of the linear spring. This result also reveals that linear spring is more suitable than the nonlinear spring for this purpose.

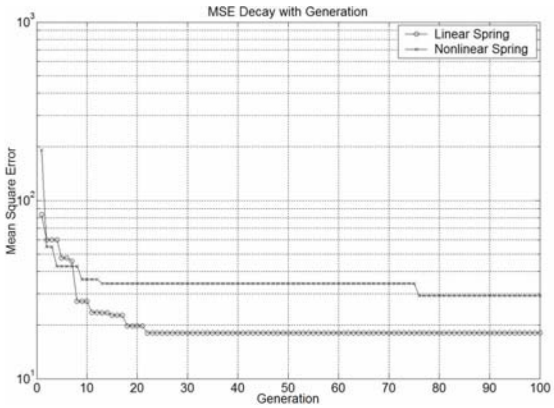

Figure 2 Generation vs. Mean Square Error nonlinear spring

The optimum values of the spring parameters obtained were as follow:

Spring type	*k* (Nm/deg.)	Rest angle (deg.)
Linear	0.14969	63.55
Nonlinear	0.11837	68.96

Table 1 Optimum spring parameters obtained with GA

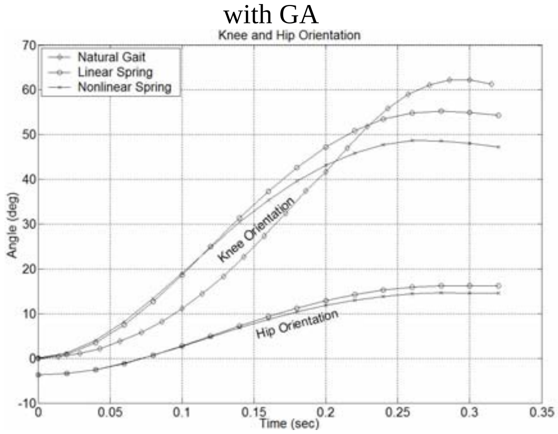

Figure 3 Resultant knee and hip trajectory and natural knee trajectory

Figure 3 shows the resultant hip and knee trajectory along with the reference knee trajectory. The best fit linear spring was found to produce more knee flexion and consequently more hip flexion than that with the nonlinear spring.

4. DISCUSSION AND CONCLUSION

The work has utilized the global search technique of GA to optimize the spring in SBO for an individual subject. Similar approach could be a part of designing SBO for an individual subject for optimal performance and before further experimentation.

Obviously in such artificial gait, producing the required maximum joint flexion/extension angles at appropriate instant of the gait cycle is more important than the overall trajectory. As such, the optimization could come up with more useful result by weighting the errors during the time of required maximum knee flexion more than the remaining part. One way of achieving this would be to define the time weighted MSE as the objective function.

It is noteworthy that such optimization procedure is subject-specific. One of the potential utility of such optimization could be to explore the means of changing walking speed through applying reference trajectories of different gait speeds of interest and finding the optimum parameters for each of them, and perhaps exploring any mathematical relation that may exist relating the speed and optimum values.

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