A Proportional Derivative FES Controller for Planar Arm Movement

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Abstract

In most clinical applications of Functional Electrical Stimulation, the timing and amplitude of electrical stimuli have been controlled by open loop pattern generators. The control of upper extremity reaching movements, however, will require feedback control. Here we present a Proportional Derivative (PD) controller for six arm muscles, using two joint angle sensors. Controllers were optimized and evaluated on a computational arm model that includes realistic musculoskeletal dynamics. Optimization was performed by minimizing a weighted sum of position errors and muscle forces. Generalizability of the controllers was quantified by performing movements for which the controller was not optimized, and robustness was quantified by removing single muscles from the model.

After optimization with a properly weighted cost function, PD controllers performed fast and accurate reaching movements. Oscillatory behavior of muscles was sometimes seen after improper tuning. Performance improved as the number of independently optimized gains increased. Robustness and generalizability were deemed satisfactory for practical applications, even when all muscle-sensor combinations were given identical proportional and derivative gains. Considering the ease of tuning only two parameters, this controller architecture is recommended for initial clinical tests.

1 Introduction

Functional Electrical Stimulation (FES) involves the electrical activation of peripheral nerves and muscles for the restoration of motor function. To date, FES technology has been applied to simple motions in both lower extremity (LE) and upper extremity (UE) systems. However, there remains a need for controllers capable of accomplishing more complex and goal-directed motions, such as reaching. The development of a control algorithm for UE FES systems that facilitates complex dynamic movements will expand the types of motion available to those with neurological impairments.

Implementing controllers for more complex movements will first require an analysis of their effectiveness in accurate models, while at present the majority of FES control literature assumes oversimplified models of human body dynamics [1]. To address these shortcomings, in this study we use a more realistic muscle model containing force-length and force-velocity properties, as well as activation dynamics.

We selected PD control as our feedback controller due to its similarity to Equilibrium Point control, which has been shown to approximate human movement well [2]. The purposes of this study were (i) the design of a PD controller stimulating six arm muscles to perform goal-directed reaching movements in the horizontal plane for a 2-segment arm model with realistic muscle properties and (ii) the evaluation of its performance in a computational model of musculoskeletal dynamics.

2 Methods

2.1 Biomechanical Model

Controller performance was evaluated using a biomechanical model for arm movement. The model had 2 segments (upper arm, forearm), 2 hinge joints (shoulder, elbow) and was driven by 6 muscles, which were modelled using a Hill-based approach.

2.2 Controller

The Proportional Derivative (PD) controller generates a response whose magnitude is proportional to the errors in joint angles and their time-derivatives. Forward dynamic simulations were used to perform planar reaching tasks.

The PD controller determined stimulation value u for each muscle according to:

$$\mathbf{u} = \mathbf{G}(\mathbf{s} - \mathbf{s_0}) \qquad (1)$$

where **u** is the vector of six muscle stimulation values (which were clipped to 0 or 1 if the calculated value exceeded these bounds), **G** is the 6 [muscles] x 4 [sensors] gain matrix, and **s** is a matrix of sensor values. The set of sensors consisted of joint angles and angular velocities for both shoulder and elbow.

Optimal controller gains G were found by minimizing a cost function consisting of an error term (f_{error}, representing the distance to the goal) and an effort term (f_{effort}, representing the amount of muscle force). The effort term was weighted by a factor W. The cost function is given by:

$$f(\mathbf{G}) = f_{error} + (W * f_{effort}) \qquad (2)$$

where f_{error} and f_{effort} are given by (3) and (4), respectively:

$$f_{error} = \sqrt{\frac{1}{2TN_m} \sum_{i=1}^{N_m} \sum_{j=1}^{2} \int_0^T (\varphi_{ij}(t) - \varphi_j^{\text{target}})^2 \, dt} \qquad (3)$$

$$f_{\text{effort}} = \sqrt{\frac{1}{6TN_m} \sum_{i=1}^{N_m} \sum_{j=1}^{6} \int_0^T \left(F_{ij}(t)\right)^2 dt} \qquad (4)$$

where φ_{ij} is the angle in radians of joint j at time i; $\varphi_j^{\text{target}}$ is the target joint angle in radians; F_{ij} is the muscle force of muscle j at time i in Newtons; N_m is the number of movement tasks; and T is duration of the simulated movement. T was chosen to be 2 s.

Cost function optimization was performed using the simulated annealing algorithm, which employs a random search to locate the global minimum specified objective function of the system.

2.3 Simulation Experiments

2.3.1 Effect of cost function weighting on controller performance: To determine the capabilities of the 2- and 24-parameter PD controllers, the effect of the weighting factor W within the cost function, which determined the significance of f_{effort}, was investigated. The value of W was varied by orders of 10, with values ranging from 1 x 10^{-7} to 1.5. A set of 12 reaching tasks was simulated in each iteration of the optimization algorithm, with both joint angles starting and ending at 20 or 80 degrees.

2.3.2 Effect of controller architecture: In this investigation, the number of parameters in the PD controller was varied, and the performance of each controller was determined. Controllers specified by 24, 16 and 2 parameters were investigated.

2.3.3 Generality test of controllers: To test the ability of the controllers to perform tasks for which they had not been optimized, each of the three optimized controllers was applied to two reaching movements that had not been included in the 12-task set.

2.3.4 Robustness test of controllers: To investigate the robustness of the controllers, each of the 6 muscles included in our model was individually removed, and the 3 optimized controllers were applied to this system, to generate the same set of 12 reaching tasks for which the controller had been optimized.

3 Results

3.1 Effect of cost function weighting on controller performance

The weight factor W of the cost function influenced the behavior of the resulting optimized controller. As weight W increased, movements were performed with less muscle force and higher error, as shown by lower f_{effort} and higher f_{error} (Fig. 1).

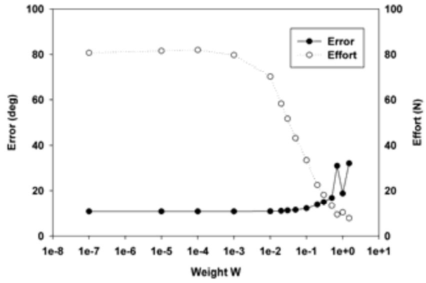

Figure 1. Error and Effort as functions of cost function weighting factor W for 24-parameter PD controller.

If the W value was too low, steady-state oscillations were sometimes seen.

3.2 Effect of controller architecture

Controller performance, indicated by the optimized cost function value, improved with increasing number of controller parameters, with the 24-parameter controller exhibiting the best performance and the 2-parameter controller, the worst (Table 1). Fig. 2 shows joint angles and muscle forces for a single reaching task performed by the optimized 24-parameter controller.

Table 1. Comparison of 3 PD controllers

Controller (# param.)	**Cost Function**	**Error (°)**	**Effort (N)**
24	13.69	11.54	42.99
16	13.94	11.57	47.38
2	14.51	11.93	51.66

(a)
(b)

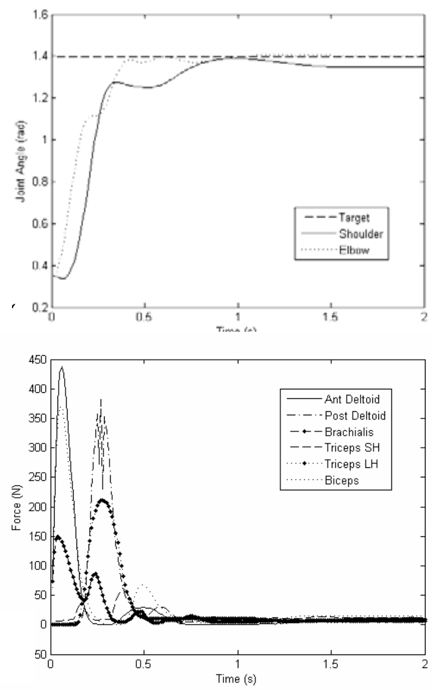

Figure 2. Optimized (W = 0.05) 24-parameter controller outputs for the (20° shoulder, 20° elbow) to (80°, 80°) reaching task. (a) Shoulder and elbow joint angles. (b) Muscle forces.

3.3 Generality test for controllers

In the generality test, in which the optimized parameters from the 12 reaching task set were applied to two different single reaching tasks for which the controller was not optimized, for each reaching task, cost function value improved (decreased) slightly as the number of parameters in the controller was increased. All 3 controllers performed these tasks with good accuracy and low muscular effort.

3.4 Robustness test for controllers

In the robustness test, removing a muscle from the model nearly always resulted in controller error and effort values that were larger than those of the same controller with all muscles intact. Although movements were less accurate with this altered model, they were still able to be executed with all 3 controllers.

4 Discussion and Conclusions

We designed a PD controller for a 2-segment, 6-muscle UE model with realistic muscle properties. This controller was found to be successful, provided that sufficient controller optimization is performed. Arm movement generated by this controller is similar to that of real human motion [3]: smooth and sigmoid-shaped joint angle curves; joint moments that show acceleration followed by deceleration; and the completion of movements on the same time scale (approx. 300 ms) as those completed by humans.

For the three versions of the PD controller we tested (using 2, 16 or 24 parameters), performance and robustness were similar. For this reason, we believe that the use of the 2-parameter version of the PD controller, which required the least time to optimize, is justified for future testing in humans [4].

References

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