A PROBABILISTIC APPROACH TO FEEDFORWARD FES CONTROL IN THE RAT HINDLIMB

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INTRODUCTION

Functional electrical stimulation (FES) is a promising technique to restore behavior to the paralyzed limbs of spinal cord injury patients by artificially stimulating peripheral nerves and/or muscles. However, it is very challenging to design a FES system that continuously modulates behavior using many muscles. So far, FES systems have primarily been successful in restoring either pre-programmed behaviors or relatively simple behaviors with only a few muscles [1]. In this work, we have begun to systematically examine the performance of feedforward FES control of isometric endpoint forces. The results from this research can be used to further improve integrated feedforward-feedback FES control strategies.

We focus our control task on isometric forces because they are an essential component of any complete behavior where the limb interacts with the external environment, e.g. grasping a cup, eating with a fork, etc. The characterization of feedforward isometric force control has been difficult in humans because of internal movements, the comfort of the patient, etc. To overcome these limitations, we developed a test platform using a rat hindlimb model. With this platform, we can co-stimulate over 10 muscles and accurately measure isometric endpoint forces of the hindlimb.

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Here, we develop a probabilistic model to optimize commands for desired isometric forces by accounting for the variability of individual recruitment curves. Traditionally, FES control strategies assume a deterministic model to describe the relationship between muscle stimulation commands and force outputs. In other words, these deterministic models assume the isometric muscle force for a given stimulus is known with certainty. However, the recruitment properties of muscles are often variable depending on muscle fatigue, electrode displacement, and many other factors. Deterministic models are unable to account for this variability and will often lead to inaccurate predictions of isometric force. Our probabilistic model attempts to address this limitation and improve the certainty, and thus accuracy, of feedforward isometric force control.

We compared the certainty of isometric forces predicted assuming our probabilistic model and a deterministic model. We showed that by using a probabilistic model, the certainty of the optimized forces are much higher than when using a deterministic model. This suggests that our probabilistic approach can be used to improve feedforward FES control strategies, especially in real, paralyzed limbs where variability in muscle force properties are expected.

METHODS

In previous work, we developed a FES test platform to control isometric endpoint forces using the rat hindlimb [2]. All procedures were approved by the Northwestern University animal care and use committee. Adult Sprague Dawley rats were anesthetized. Metal posts were be implanted in the pelvis and secured to a stereotaxic frame. A threaded attachment was implanted in the tibia near the ankle and used to connect the hindlimb to a 6 dof force transducer. Monopolar stimulating electrodes were placed in approximately 10 muscles spanning proximal joints. We determined the recruitment curves by stimulating the muscles (0.5s train, 75Hz, biphasic pulses) while the ankle was rigidly attached to the force transducer using a 16-channel stimulator [3]. The average steady-state forces (final 200msec of force plateau) generated at the ankle were recorded for increasing pulse-amplitudes while holding the pulse-width constant at 0.1msec. Forces were measured in the sagittal plane. We collected two sets of recruitment curves separated in time by approximately 1-2 hours.
Figure 1: Sample recruitment curves parameterized using our probabilistic method. Top: Vastus medialis. Bottom: Caudal femoralis. Force magnitude was measured in N and stimulus amplitude in mA. Red lines are distribution of possible parameterized recruitment curves given the data (blue points).

We fit parameterized functions (sigmoids) to the recruitment data to predict the output isometric force magnitude given a stimulus. For the probabilistic model, we used a sampling method to form a distribution of possible recruitment curves given the force magnitude data (Fig. 1). Uncertainty in the structure of the recruitment curves resulted when the data was variable within a single trial and over time across the two (or more) sets of recruitment curve data. For the deterministic model, we parameterized recruitment curves using maximum likelihood estimation of force magnitude.

We used both models to optimize muscle commands to achieve desired force targets within the feasible force space of the rat hindlimb. We used the same cost function for both models that penalized the sum of the squared activation and expectation of desired forces. For our probabilistic model, the expectation of the desired forces resulted in a penalty on the variability of the force while the deterministic model neglected this variability.

RESULTS AND DISCUSSION

The goal of this research was to develop a probabilistic method to improve the performance of feedforward FES control strategies. We compared the certainty of optimal forces for targets throughout the feasible force space of the hindlimb using our probabilistic model and a deterministic model. The certainty of the forces produced using our probabilistic model (Fig. 2A) was much higher than the certainty of the forces produced using the deterministic model (Fig. 2B). This means that we can be confident that we will produce accurate desired forces throughout the workspace when we account for the variability associated with recruitment curves.

CONCLUSIONS

The results suggest that a probabilistic framework can be used effectively to minimize the reliance on feedback control in more complex FES systems.

Figure 2: Certainty maps of isometric forces in the sagittal plane of the rat hindlimb. A: Probabilistic model. B: Deterministic model. Green outline is the feasible force space of the limb. Certainty was measured in N.

REFERENCES


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