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Stable control of functional electrical stimulation with online feedback from dorsal root ganglion recordings

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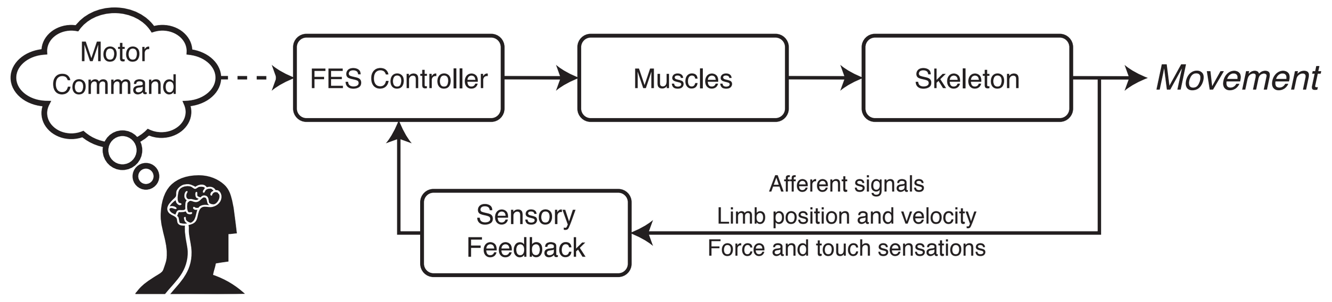
Introduction

Project objective: Closed loop control of locomotion with functional electrical stimulation (FES)



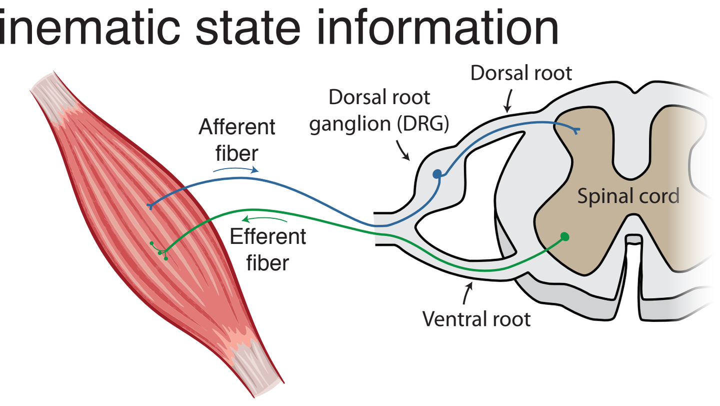
Disadvantages of existing FES implementations

Current **open loop** systems rely entirely on pre-programmed stimulation patterns. Without feedback, they are unable to correct for external perturbations and muscle fatigue.

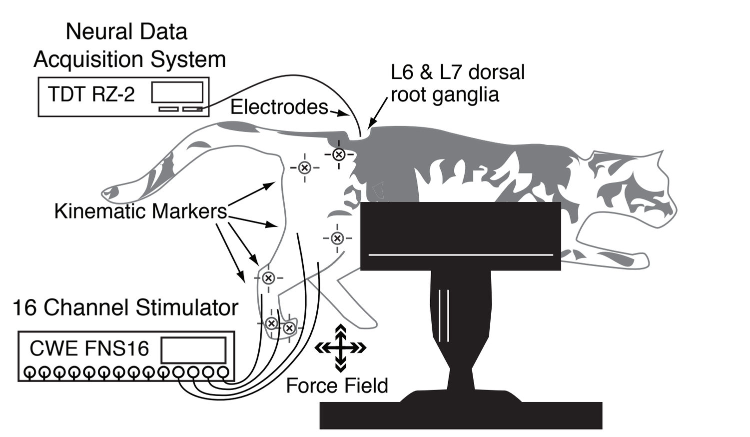
Current **closed loop** systems incorporate some feedback information, but generally only from one joint or sensor. External sensors may be bulky and fragile.

Dorsal root ganglia provide access to full-limb kinematic state information

- The dorsal root ganglia (DRG) contain only sensory afferents and their cell bodies
- Neural recordings from one or two lumbar DRG can reflect the state of the entire hind limb
- High signal-to-noise ratio from multi-electrode arrays allow large numbers of isolated neurons to be simultaneously recorded for concurrent tracking of muscle spindles (limb proprioception), cutaneous (touch) and Golgi tendon organs (force) afferents



Methods



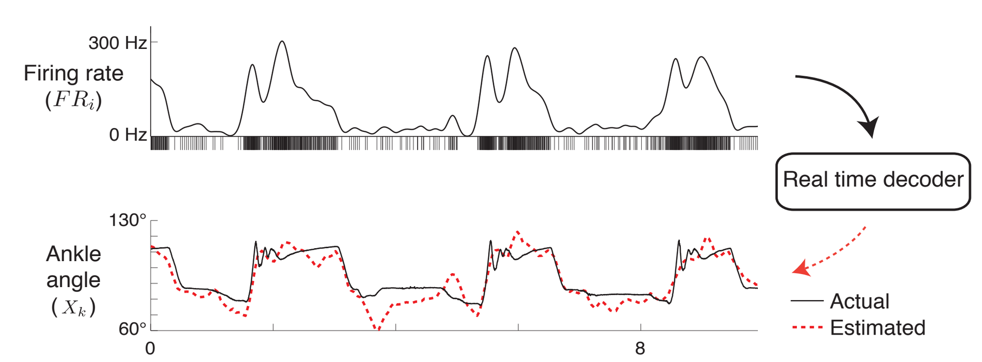
- 90 microelectrodes (split MultiPort arrays, Blackrock Microsystems) were inserted into the left L6 and L7 DRG of two cats
- Neural spiking data was recorded, thresholded and sorted with a realtime signal processing system (TDT RZ-2)
- Spikes were converted into firing rates in 50 ms bins and smoothed with a 150 ms wide triangular kernel (Weber et al, 2007)
- A 6 camera motion capture system recorded kinematics (Phasespace
- A haptic robot rendered a virtual floor, creating ground reaction forces during the stance phase of the step cycle
- Patch and intramuscular stimulating electrodes were placed in the primary muscles that span the hip, knee and ankle joints for FES

Online decoding of limb position

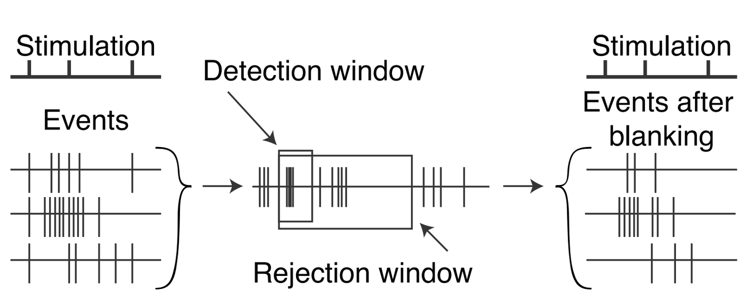
- Endpoint position or joint angles (X_k) were estimated by modeling them as a linear function of the observed firing rates of over 120 units (FR_i) in real time such that:

$$X_k = \beta_{k0} + \sum_i^N \beta_{ki} FR_i + \varepsilon_k$$

- The model was generated online with the actual kinematics

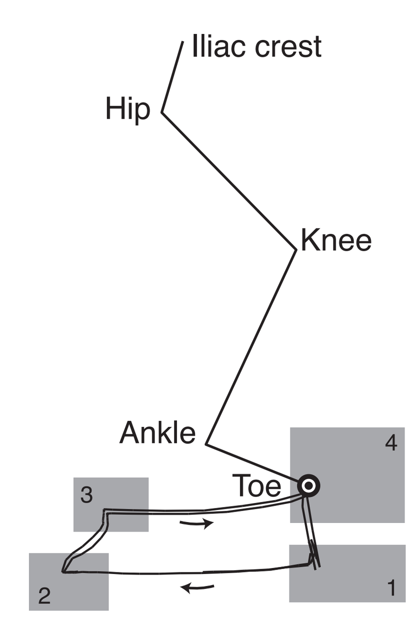


Stimulus artifact rejection



If more than 60% of the channels had spikes within a 400 µs detection window, then all spikes inside the 2 ms rejection window were ignored

Finite state stimulation controller

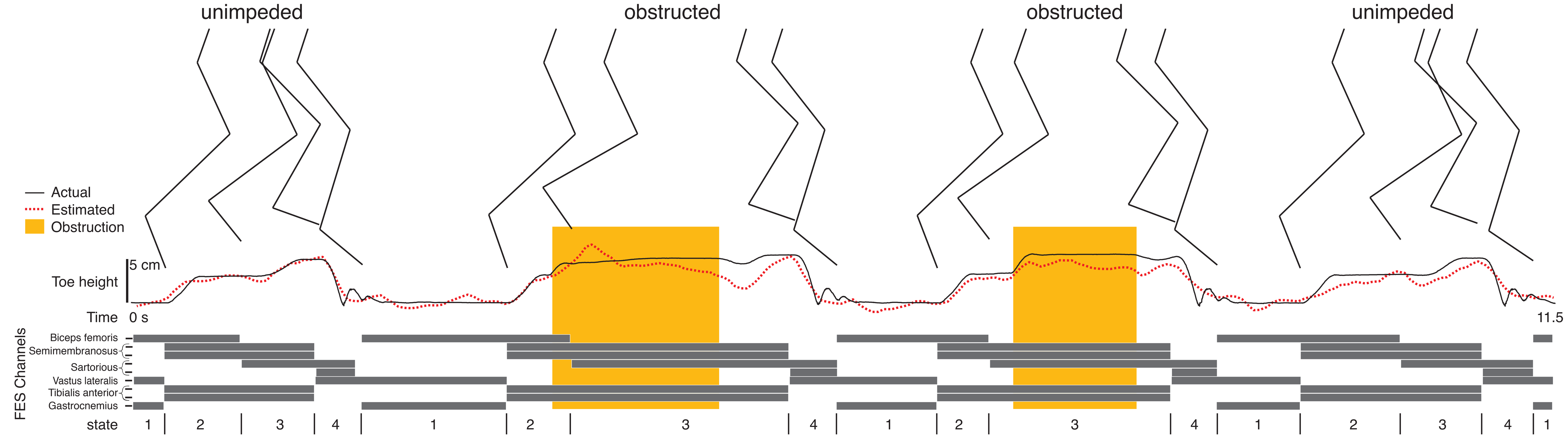


Position estimates were streamed in real time to a finite state controller running in LabView

- Four states were associated with phases of the gait cycle: toe strike, toe lift, swing initiation, and end swing
- State transition times were determined from the decoded toe position, updated every 50 ms
- The controller generated charge-balanced stimulation commands with independent variable amplitudes at constant 200 µs pulse width and 30 Hz

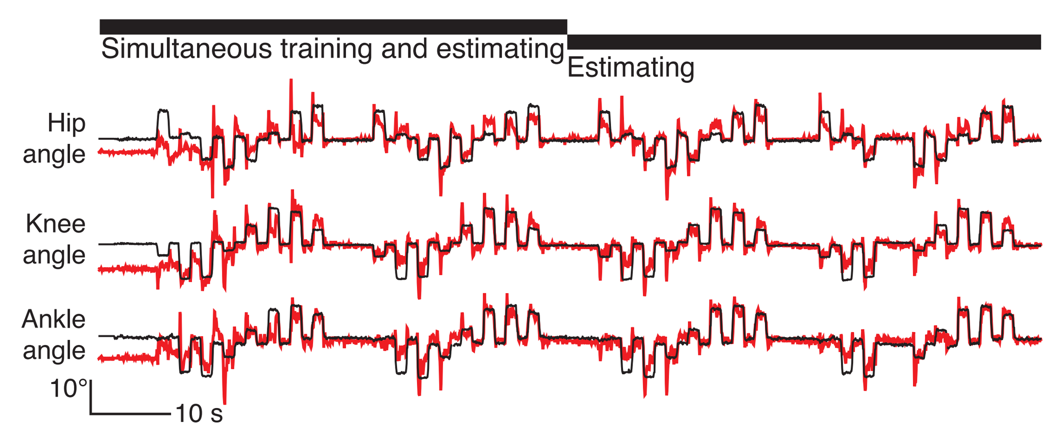
Results

Closed loop control of FES-enabled stepping



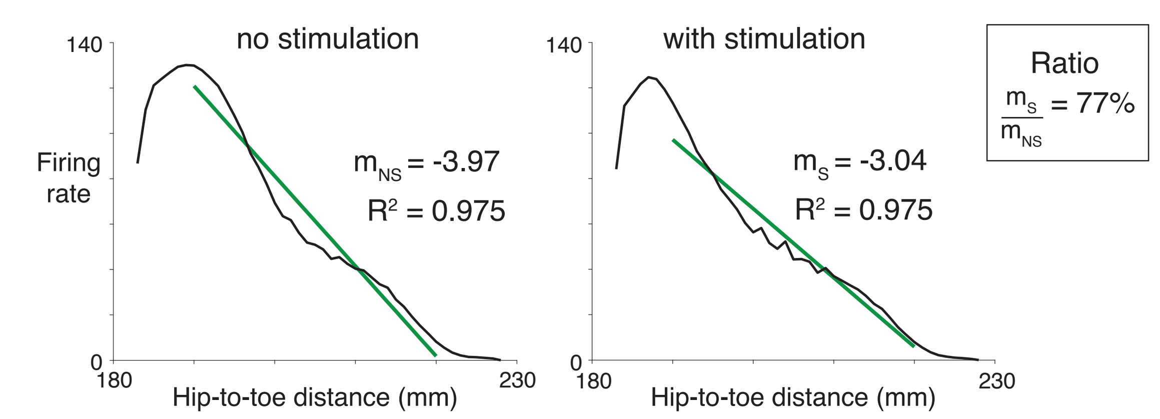
- One minute stepping trials were performed, in which the leg was under continuous closed-loop FES control, with 1-2 minutes between each trial
- Fatigue was observed starting near the mid-point of each trial, leading to a decrease in both step height and speed of motion
- Robust step trajectories were achieved despite declines in muscle force due to fatigue
- Swing phase perturbations were used to obstruct motion of the leg during stimulation (two perturbed and two unperturbed step cycles are shown above)
- The neural decoder reliably tracked the limb position throughout the perturbation and enabled robust perturbation compensation

Online model training and estimation



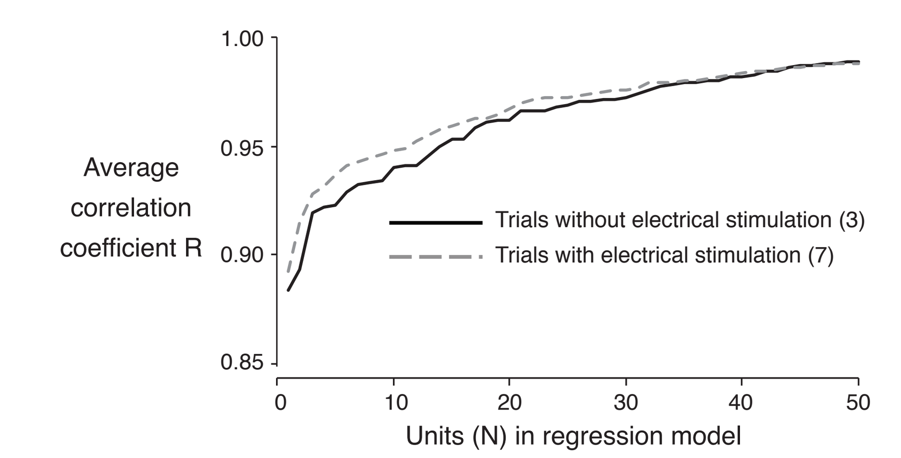
Example of real-time estimation of joint angles during passive movement. During the training phase, the actual joint angles and the neural firing rates were used to continuously update the model. Simultaneously, the decoder used the most recent model to estimate the joint position (red). After the training phase, the final model was used to estimate the kinematics.

Effect of stimulation on neural coding



Across 31 units (2 experiments) whose fit of firing rate to kinematics had an R^2 value greater than 0.9, the average ratio of unit gain with stimulation to unit gain without stimulation was 90.1 ± 28.4%. Stimulation did not have a significant effect on neural coding properties.

Effect of stimulation on estimation



The regression model was compared for passive fixed-space movements with stimulation (7 trials) and without stimulation (3 trials) in 2 experiments. Decoding of limb endpoint position was minimally affected by stimulation.

Discussion

Conclusions

- We demonstrated that ensemble neural recordings in hindlimb DRG may be used to provide limb position feedback for a simple closed-loop FES controller for walking-like behavior in two cats
- Stimulation did not significantly impact unit responses or online decoding
- The state controller was able to adjust automatically to changes in the limb position and perturbations

Future directions

- Improve real time decoding performance: Bayesian classifiers or fuzzy neural networks may improve decoder accuracy while remaining computationally tractable
- Improve FES controller design: a continuous PID controller would enable reference trajectory tracking and may prove to be more robust
- Improve stimulation interface with alternate electrode interfaces such as peripheral nerve or intra-spinal stimulation
- Develop a reliable chronic DRG interface: a non-penetrating electrode design may increase recording longevity and clinical acceptability

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