# Online Feedback Control of Functional Electrical Stimulation Using Dorsal Root Ganglia Recordings


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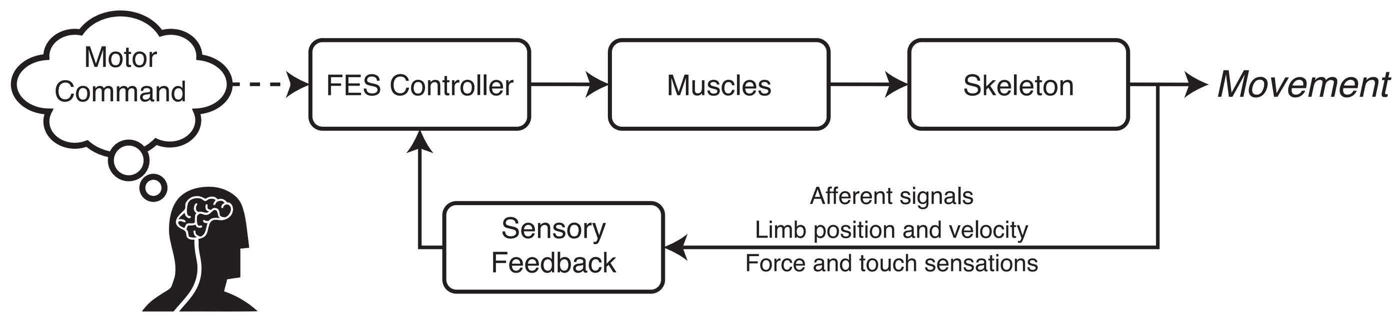
## Introduction

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




### Disadvantages of current FES systems

**Open loop** systems rely entirely on pre-programmed stimulation patterns.

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

### Feedback is essential for stable control

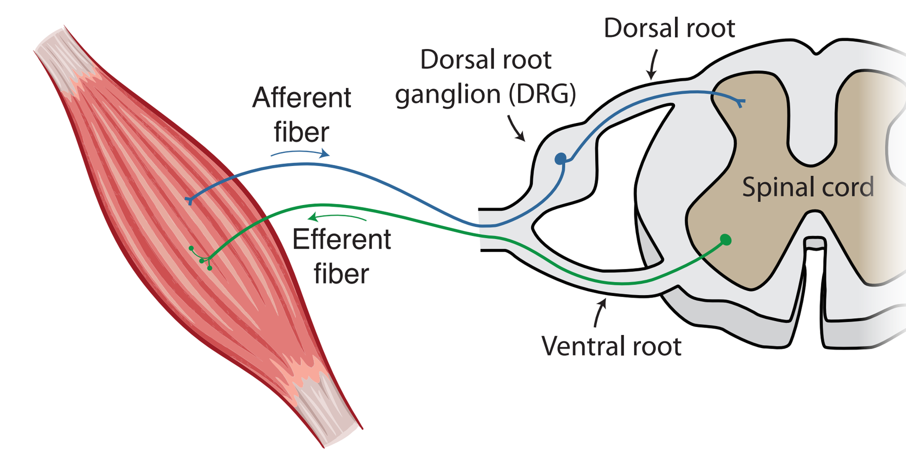
Continuous full-limb feedback allows for

- corrections to external perturbations
- dynamic adjustments for muscle fatigue
- compensation for nonlinearities in the muscles

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

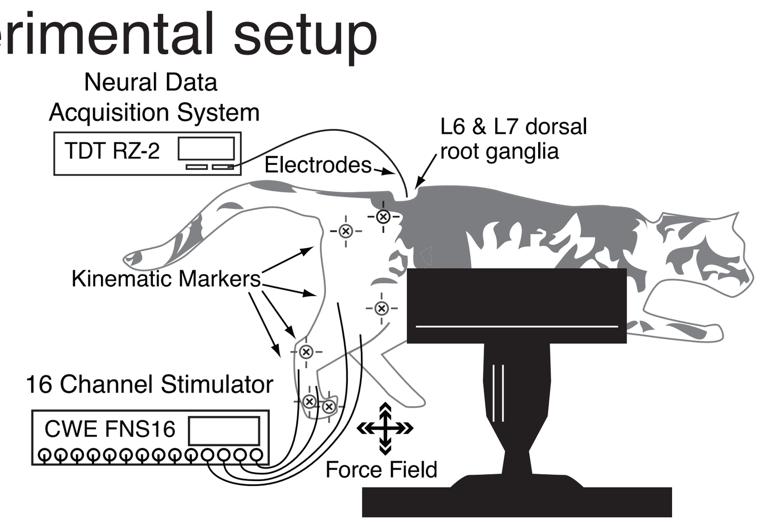
Limb state information is naturally represented in the firing rates of primary afferent neurons. The dorsal root ganglia (DRG) contain the cell bodies for afferent fibers where they enter the spinal cord.

- The DRG contain purely sensory afferents
- 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

### Experimental setup



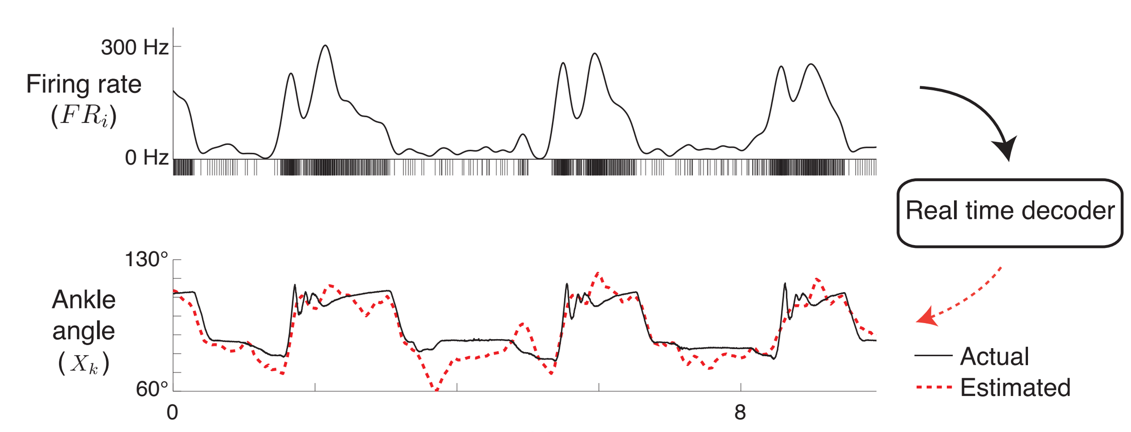

- 90 microelectrodes were inserted into the left L6 and L7 DRG
- Neural spiking data was recorded with a realtime signal processing system. Spikes were thresholded and sorted in real time and converted to smoothed firing rates with a 150 ms wide triangular kernel.
- Kinematic data was recorded with a 6 camera motion capture system
- A haptic robot was used to create a virtual floor, rendering ground reaction forces during the stance phase of the step cycle
- Nine patch and intramuscular stimulating electrodes were placed in the primary muscles that span the hip, knee and ankle joints for FES

### Real time decoding of limb position

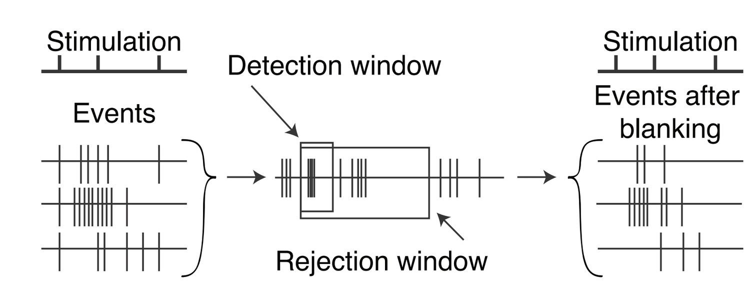
- The joint angles ($X_k$) were estimated by modeling them as a linear function of the observed firing rates ($FR_i$) in real time over 128 units such that:

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

- The model was generated online with the actual kinematics while a robot manipulator passively moved the limb
- Based on the measured limb segment lengths and the estimated joint angles, the limb endpoint was also estimated




### 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

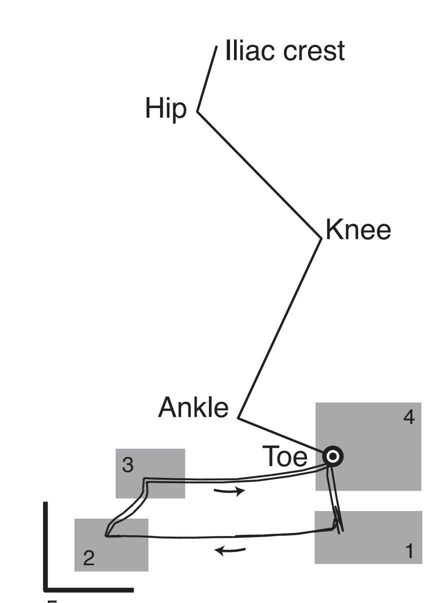
### Finite state stimulation controller

Neural firing rates were streamed in real time to a finite state controller

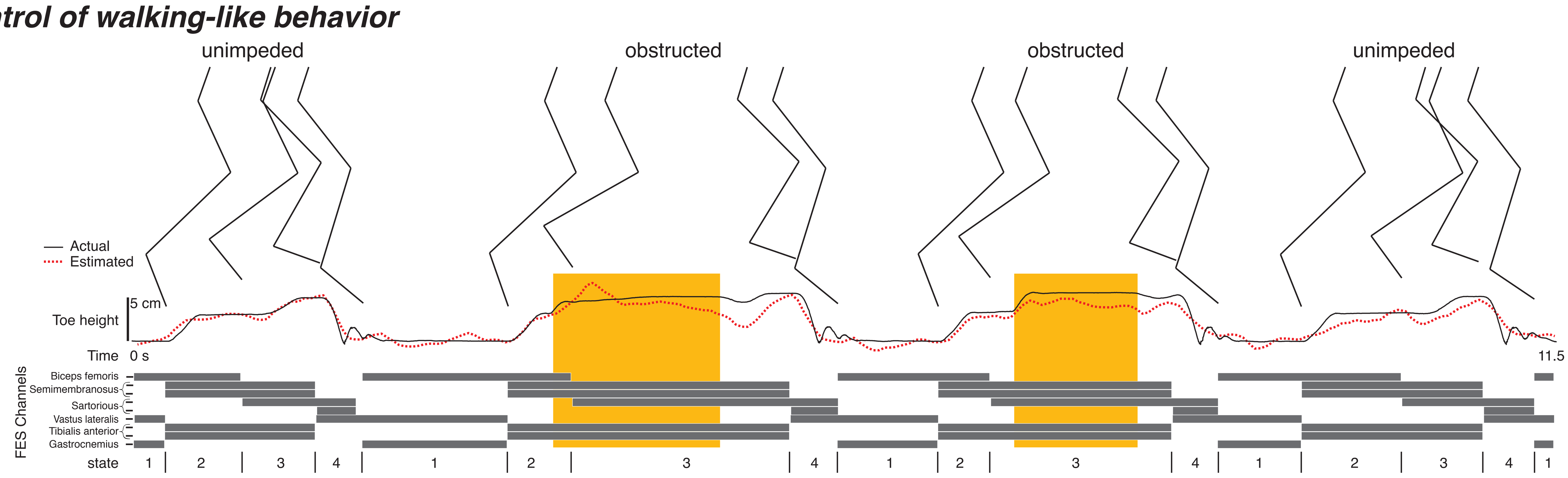
- Four states were associated with phases of the gait cycle: toe strike, toe lift, swing initiation, and end swing
- Transitions were based upon limb endpoint, estimated every 50 ms
- The controller generated charge-balanced stimulation commands with independent variable amplitudes at constant 200 µs pulse width and 30 Hz

## Results

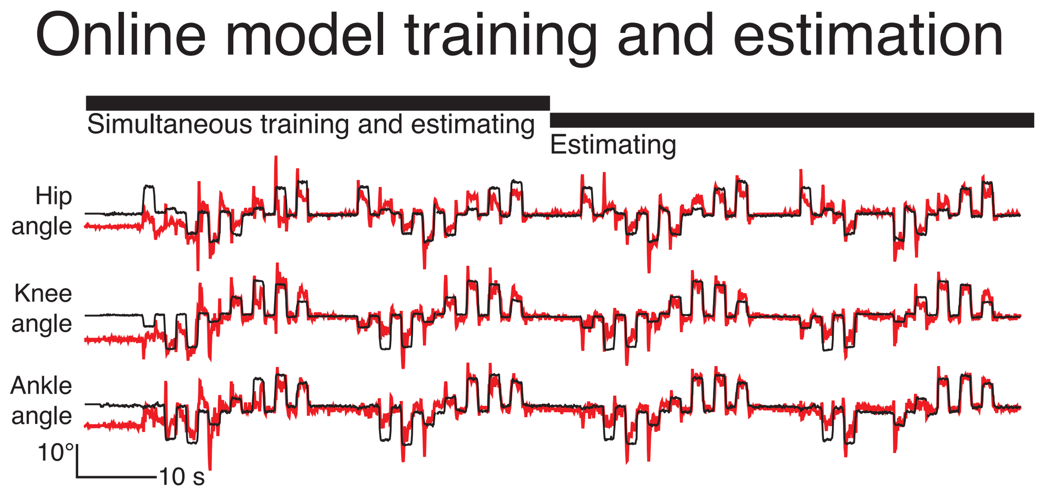
### *Closed loop control of walking-like behavior*




The state transition zones are shown above with an unimpeded endpoint path superimposed. To the right, four complete stepping cycles are displayed. The leg was manually obstructed during the orange blocks.



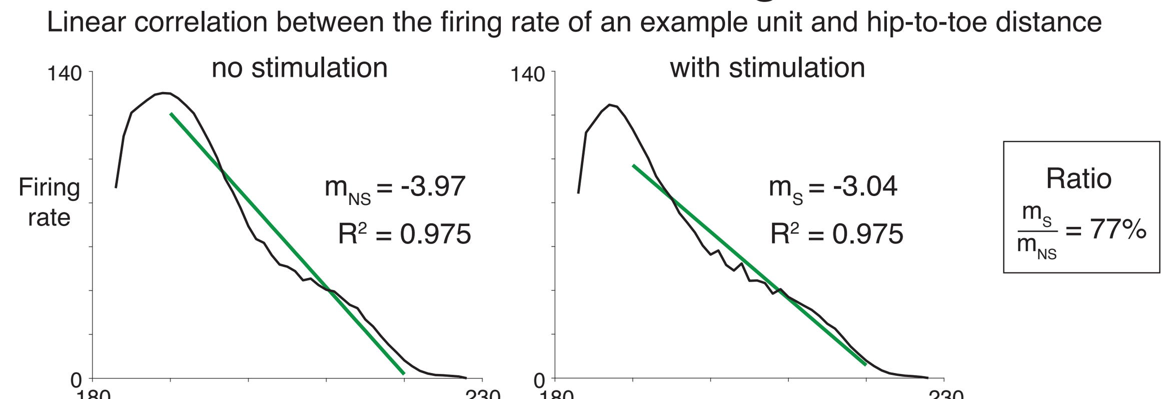

### Online model training and estimation




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.

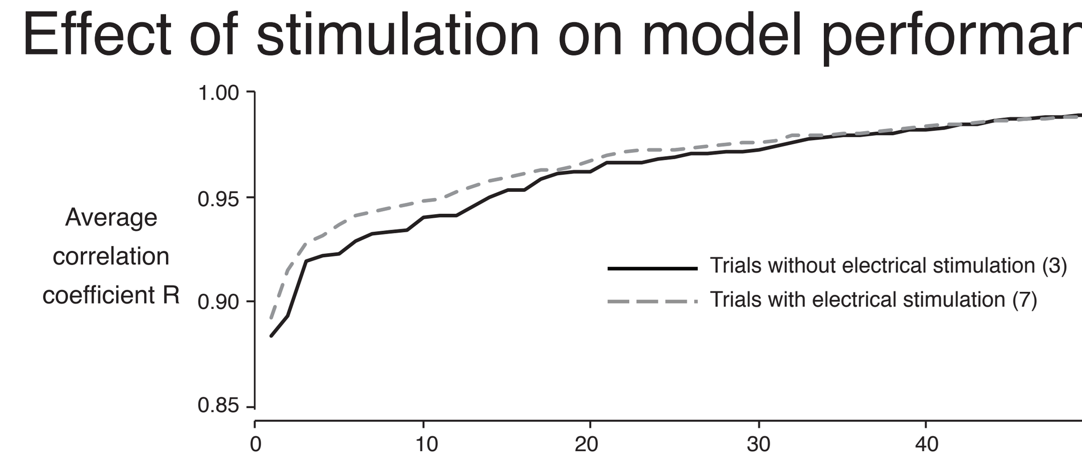
### Effect of stimulation on unit gain

Linear correlation between the firing rate of an example unit and hip-to-toe distance




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 unit responses.

### Effect of stimulation on model performance




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
- Stimulation did not significantly impact unit responses
- 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
- Alternate FES electrode interfaces such as peripheral nerve or intra-spinal stimulation may improve muscle recruitment and function
- Develop a reliable chronic DRG interface: a non-penetrating electrode design may increase recording longevity and clinical acceptability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