Estimation of Muscle Activity from Chronic Single Unit Ventral Root Recordings

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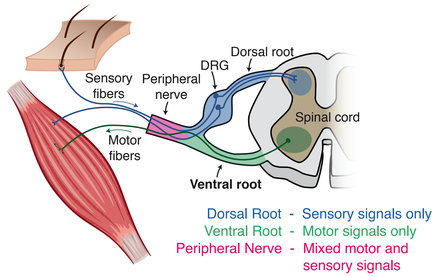
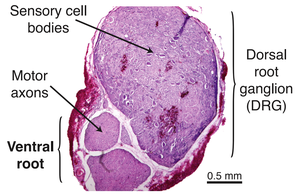
Introduction



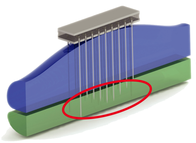


Feline lumbar spinal root (L7)

- Spinal roots are a promising target for a peripheral neural interface
- Motor (ventral) and sensory (dorsal) signals are spatially segregated and could be independently targeted for recording and stimulation
- Neural activity in the axons of the ventral root leads directly to muscle contraction and could be used as a source for motor control signals that are directly linked to normal musculoskeletal action
- The spinal column provides more mechanical protection and electrical isolation from muscle activity than is possible in the distal nerves

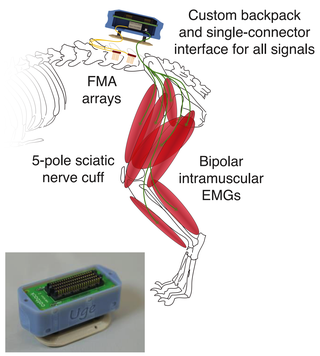
***Objective**: Identify and record from motor units in ventral roots and evaluate their ability to estimate muscle activity*

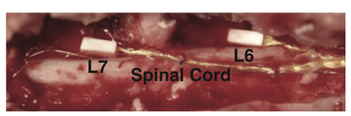
Methods



Sterile surgery

- Chronically implanted 32-channel floating microelectrode arrays (FMAs, MicroProbes, Inc.) with varying electrode shank lengths in the left L6 and L7 spinal nerves of nine adult male cats
- Targeted the ventral roots intra-operatively by incrementally inserting the array pneumatically until sensory activity was only observed on the shallowest electrodes
- Instrumented up to ten muscles with bipolar intramuscular electromyography (EMG) electrodes and the sciatic nerve with a 5-pole spiral nerve cuff (Ardiem Medical)
- All signals were routed through custom circuit boards with a single-connector interface (SEARAY, Samtec) mounted within a protective backpack assembly





Experimental procedures

- Neural signals were sampled at 40kHz with a multi-channel neural recording system (DigiAmp, Plexon, Inc) and hand sorted offline, with muscle and nerve signals sampled at 20kHz
- Kinematics were captured with OptiTrak (NaturalPoint, Inc) or Cineplex (Plexon, Inc)
- Awake (treadmill walking at speeds of 0.4-1.2 m/s) and anesthetized (passive movements, under dexdomitor) recording sessions were conducted at least weekly for each cat

Identifying Motor Units

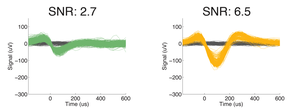
Units were excluded from analysis if they were:

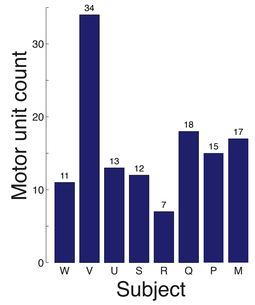
- recorded during passive movements under anesthesia,
- on the same electrode as a unit that was active under anesthesia,
- or if they violated 'motor unit-like' firing behavior:

The inter-spike intervals were fit by a two-component logarithmic Gaussian mixture model. A unit is motor neuron-like only if either:

a) less than 10% of the distribution is under 20ms
or b) the two distributions are well-separated (d' > 1) and match doublet (component mean is under 10ms) and primary firing rate statistics (less than 10% of component distribution is under 20ms).

Example motor unit recordings





Estimating EMG Activation

Example estimations

Ten seconds of aligned motor unit (top raster, each row is a unit) and smoothed EMG activity, with the predictions overlaid in red (cat V)

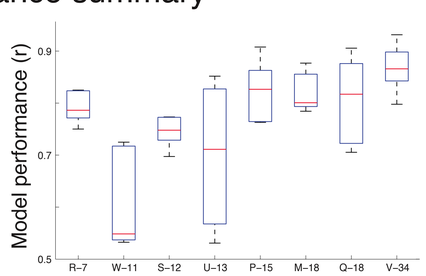
- EMG Signals were band-pass filtered (80-500Hz), rectified, and smoothed with a low-pass filter (10Hz)
- Spikes from units identified as motor units were converted to firing rates (FR) by convolving the spike times with a causal alpha kernel $\alpha^2 t \exp(-\alpha t)$ with a time constant of 50ms (from 0-100ms)
- A fitted multiple linear regression models estimated EMG activation from smoothed motor unit firing rates
- Each muscle was considered to be independent, such that:

$$EMG_i = b_{i_0} + \sum_j b_{i_j} FR_j$$

- Models were trained on 50s of treadmill walking data and tested against a later 50s from the same day, with speeds of 0.4-1.2 m/s

Performance summary

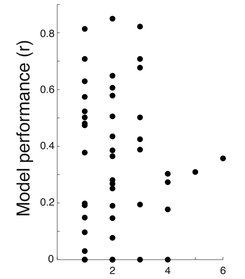
- The number of units in the model significantly affected ($p < 0.01$) its ability to accurately estimate EMG activity
- The number of units, however, is not a significant factor in the performance of the muscle with the highest performance, suggesting that only a small number of units are required for each muscle.



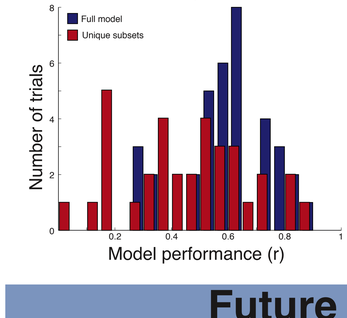
Each subject's testing performance over all muscles summarized by quartiles, arranged in order of increasing number of motor units

Physiological Subsetting

- Each motor unit axon only innervates one muscle, but the simple multiple linear regression framework uses all units in its estimation of each muscle
- A more physiological approach is to choose a unique subset of motor units to use for each muscle (without replacement)
- Units were selected greedily from the largest significant coefficients of the aggregate models to estimate just one muscle each



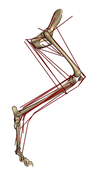
Performance compared to full model



- Some muscles retain very good performance with fewer than three motor unit inputs
- Unlike the aggregate models, there is no significant relationship between number of units and model performance

Future Directions

- Use the known physiology of the motor neuron to refine the regression model, incorporating nonlinearities such as doublets
- We've previously shown that in 29% of our motor unit recordings, we can identify the muscle a motor unit targets through spike-triggered averaging of the evoked muscle potential. Using this information in the subsetted model may improve performance



- Use the estimated muscle activation to drive input into a musculoskeletal model to predict forces and kinematics

Summary

- Identified and recorded from motor units in ventral roots
- Estimated EMG activity of all muscles with good performance across most of the subjects
- Some muscles were accurately estimated from a very small subset of the recorded units

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