Estimation of muscle activity from chronic single unit ventral root recordings

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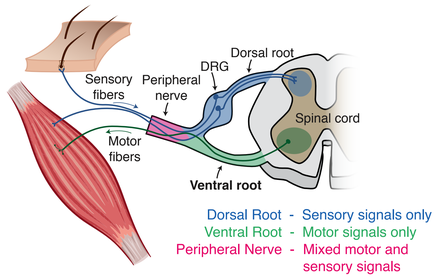
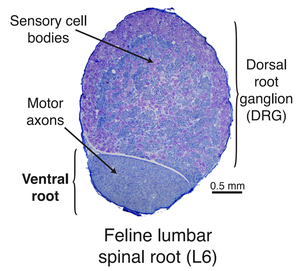
Introduction



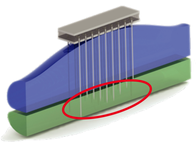


Feline lumbar spinal root (L6)

- 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

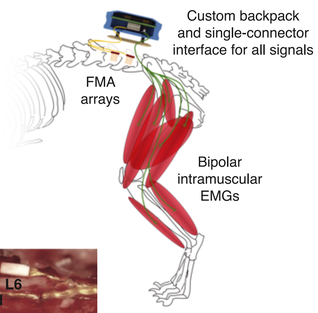
***Objective**: Identify and record from motor units in ventral roots and evaluate their ability to estimate muscle activity*

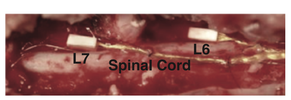
Methods

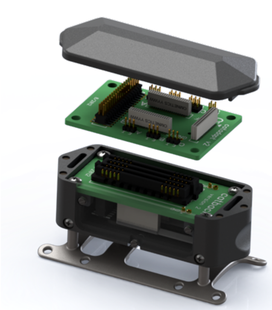


Sterile surgery

- Chronically implanted 32-channel floating microelectrode arrays (FMAs, MicroProbes, Inc.) with varying electrode shank lengths (2.0-3.7mm) in left L6 and L7 spinal nerves of ten 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
- All signals were routed through custom circuit boards with a single-connector interface (SEARAY, Samtec) mounted within a protective backpack assembly







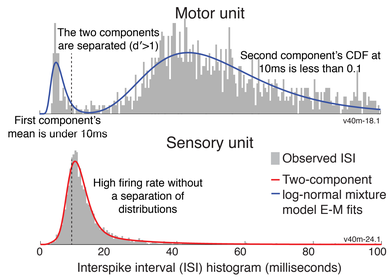
Experimental procedures

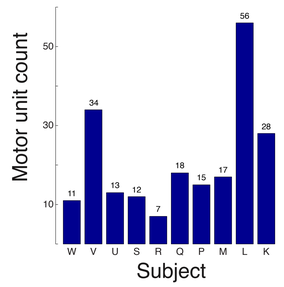
- Neural signals were sampled at 40kHz with a multi-channel neural recording system (DigiAmp, Plexon, Inc) and hand sorted offline, with muscle signals sampled at 20kHz or 40kHz
- Awake (treadmill walking at speeds of 0.4-1.2 m/s) and anesthetized (passive movements, under dexmedetomidine) recording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

Identifying Motor Units

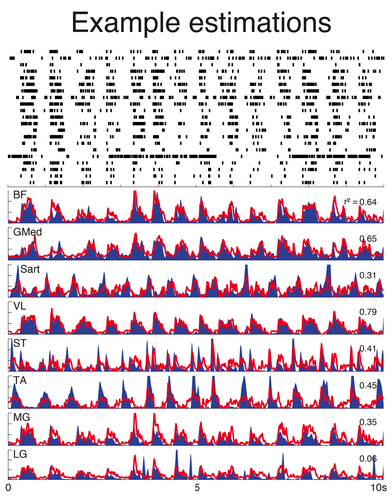
Units were excluded from analysis if they were:

- actively firing during passive movements under anesthesia (sensory units will still respond under anesthesia),
- on the same electrode as a unit that was active under anesthesia,
- or if they violated 'motor unit-like' firing behavior with a two-component log-normal fit of the inter-spike interval (ISI):





Estimating EMG Activation



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)

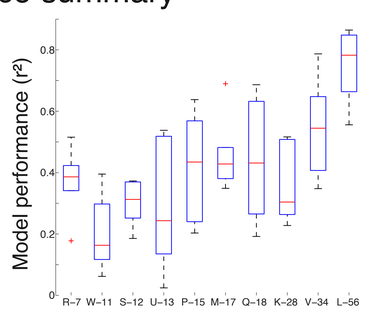
- EMG Signals were band-pass filtered (50-500Hz), rectified, and smoothed with a low-pass filter (10Hz)
- Spikes from units identified as motor units were converted to firing rates (FR) by convolving the spike times with a causal alpha kernel $\alpha^2 t \exp(-\alpha t)$ with a time constant of 50ms (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

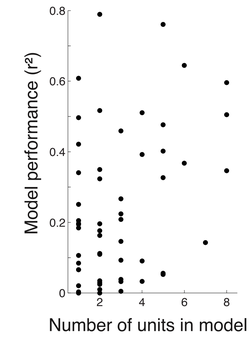
- Four of the subjects have at least three functionally distinct muscles with testing performance $r^2 > 0.5$
- The number of units is a significant factor ($p < 0.01$) in the model's r^2 performance, whereas the subject (as a categorical variable) is not significant
- When only considering the highest performing muscle, the number of units is not significant, suggesting only a small number of good units are required for each muscle.



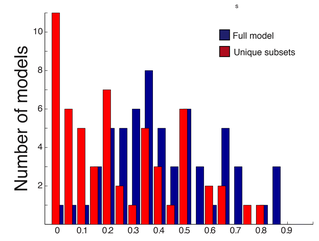
Testing performance over the top six muscles, summarized by quartiles, arranged in order of increasing number of motor units

Physiological Subsetting

- Each motor unit axon only innervates one muscle, but the multiple linear regression framework uses all units in its estimation of each muscle
- A more physiologically informed 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

Acknowledgements

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