Chronic ventral root recordings as a source for neuroprosthetic control

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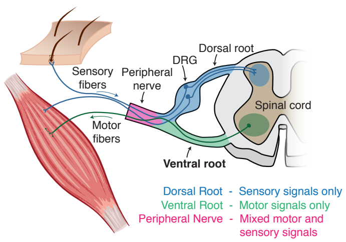
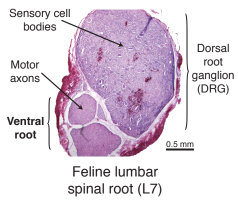
Introduction





Feline lumbar spinal root (L7)

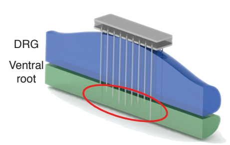
- Spinal roots are a promising target for a peripheral neural interface to control prosthetic limbs
- Protected within the spinal column, they often remain intact after nerve injury or limb amputation and are more mechanically stable than distal nerves
- Motor (ventral) and sensory (dorsal) signals are spatially segregated and can be independently targeted for recording and stimulation

***Objective**: chronically record from motor units in ventral roots and evaluate their viability as a source for neuroprosthetic control*

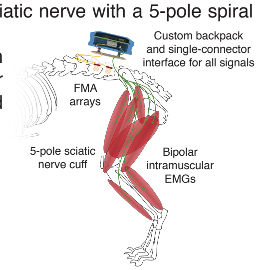
Methods

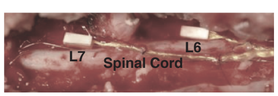
Sterile surgery

- 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
- Muscle and nerve signals were sampled at 20kHz
- 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

Individual units are classified as motor units if they are

- active during a walking trial but not during anesthetized sessions,
- not recorded from the same electrode as other units that are active during anesthetized sessions,
- and they must not violate 'motor unit-like' firing rates.

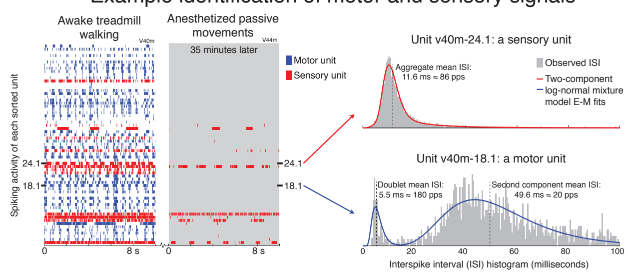
Motor units typically have a mean firing rate of 20-30 pps, but they sometimes also have rapid doublets with instantaneous rates of over 100 pps which rapidly increase muscle force. These two interspike interval (ISI) regimes are fit by a two-component logarithmic Gaussian mixture model. The unit is motor neuron-like if:

- the aggregate cumulative distribution function is less than 0.1 at 20 ms

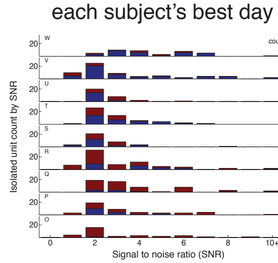
or

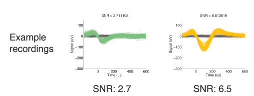
- the two components are significantly different (d' > 1) and
- the mean of the smaller ISI component is less than 10 ms and
- the cumulative distribution of the larger ISI component is less than 0.1 at 20 ms

Example identification of motor and sensory signals

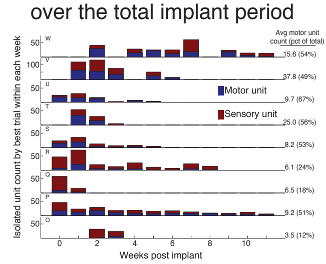


Recording quality (SNR) on each subject's best day

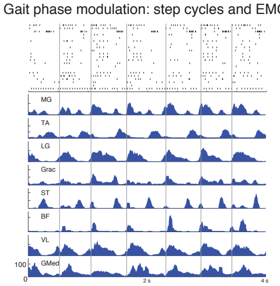




Performance of each subject over the total implant period

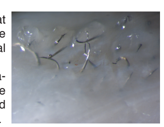


Gait phase modulation: step cycles and EMG



Why did we get worse at targeting motor units?

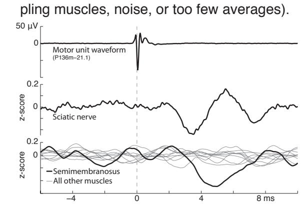
- Dissections revealed that we had driven some of the arrays through the spinal nerves (pictured).
- We began recording intra-operatively to ensure some sensory signals remained on the shallower channels.
- But we over-compensated, yielding more sensory signals than desired.



Identifying Target Muscles

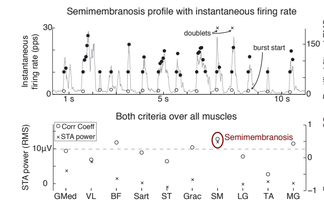
Spike-triggered average (STA) of raw EMG

The EMG signals during walking were averaged in 24ms windows about every motor unit action potential, and the RMS power of the last 10 ms was computed with the first 10 ms serving as the baseline. This can sometimes reveal the action potential passing through the nerve to the end-plate potential at the muscle (but may fail due to subsampling muscles, noise, or too few averages).



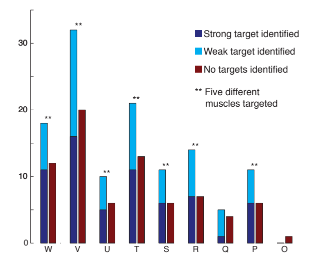
Frequencygram correlation with rectified and filtered EMG

As a secondary method, rectified smoothed EMG profiles for each muscle were constructed and compared to the instantaneous firing rate (frequencygram) of each unit, with doublets omitted and burst starts altered to the overall mean rate. While not as definitive, a high correlation coefficient (CC) still demonstrates a functional relationship.



A threshold for large STA responses was determined by examining the RMS responses in unit-muscle pairs that had anticorrolated frequencygrams (CC < 0) as a distribution of negative responses, and the 99.5th percentile (10 μV RMS) was chosen. Large frequencygram correlations were defined to be those greater than 0.25 through manual inspection. Unit-muscle pairs that satisfied both thresholds were categorized as strong, and those that only satisfied the frequencygram threshold were ranked as weak.

Units on each subject's best day



Across all sessions:

- 334 units (26% of all motor units) found to have a strong target
- 503 (39%) have a weak target
- 441 (35%) had no target identified
- 0.6±0.3 unique muscles targeted per unit within each session

Summary & Future Directions

- Successfully targeted ventral roots and recorded motor units
- Were able to identify almost two-thirds of all motor units' targets
- Examine decoder strategies that incorporate muscle target information and are able to exploit nonlinearities like doublets

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