Cortical Involvement in the Recruitment of Wrist Muscles

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Abstract

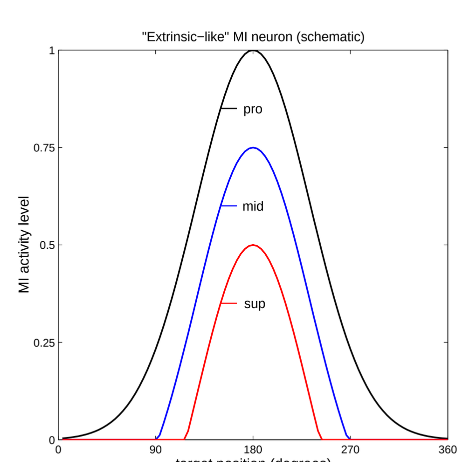
In executing voluntary movement, we must transform an extrinsic representation of a task into a muscle recruitment pattern. Past studies have argued for either an extrinsic or an intrinsic (muscle-space or joint-space) representation of movement in primary motor cortex (MI). In a recent two-dimensional step-tracking experiment, Kakei *et al.* (1999) described both extrinsic-like and muscle-like neurons in primate MI. This result was interpreted as evidence for a cascade of transformations within MI from an extrinsic representation of movement to a muscle-space representation which was responsible for commanding muscles. We present a model examining the complexity of the transformation from extrinsic space to the muscle space that implements the movements described in Kakei *et al.* (1999). Given a realistic extrinsic-like representation of movement, a simple linear network is capable of representing the transformation from the extrinsic-like cells directly to the necessary muscle activation pattern. This suggests that cells exhibiting extrinsic-like qualities can be involved in the direct recruitment of spinal motor neurons and calls into question models that presume a serial cascade of transformations in which only muscle-space neurons command muscles.

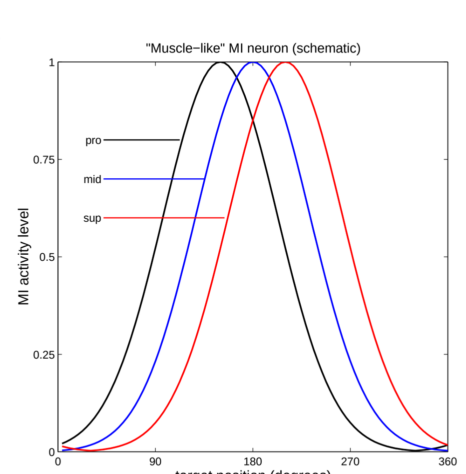
Experimental Task *(Kakei et al. 1999)*

- Monkey controls a cursor on a computer screen with wrist flexion/extension and radial/ulnar deviation
  - wrist fixed in a pronated, midrange or supinated posture
- Center-out task: move cursor from the center to a target on a circle
- Peak agonist EMG vs. target direction follows a truncated cosine shape
- Three distinct coordinate frames can be described:
  - ***joint space***: wrist rotates 180° from pro to sup
  - ***muscle space***: muscle preferred directions (PDs) rotate 46° - 90° as the wrist rotates from pro to sup
  - ***extrinsic space***: cursor movement, unaffected by wrist posture

MI Neural Activity *(Kakei et al. 1999)*

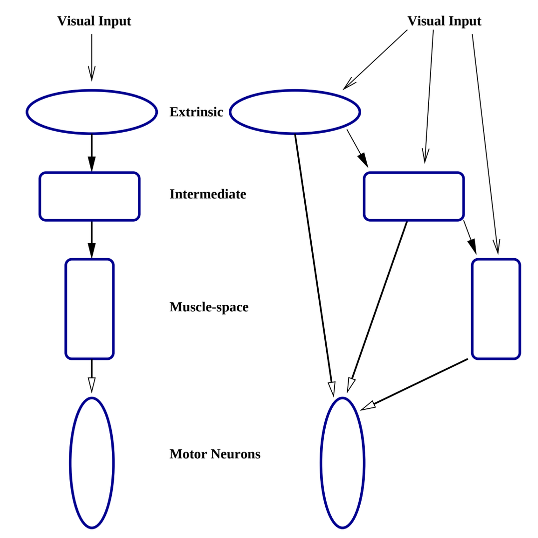
- Neural activity exhibited a truncated cosine behavior
- Extrinsic-like (50%) *(top figure)*
  - PD did not shift as wrist rotated
  - magnitude of activity varied with wrist posture in some cases
- Muscle-like (32%) *(bottom figure)*
  - PD shift: 40° - 110° (similar to muscles)
- Of the rest...
  - none were joint-like (defined by PD shift of ~180°)





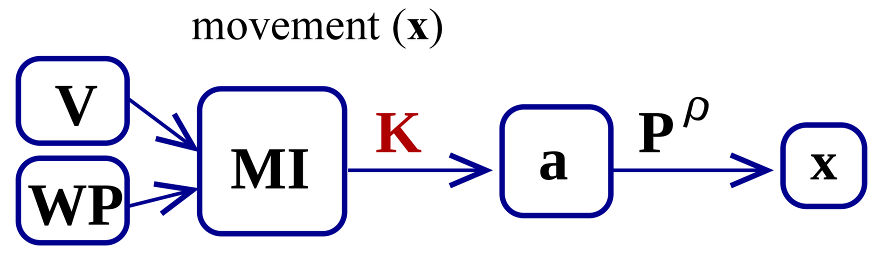
How Might MI Encode Movement?

- Serial scheme *(left part of figure)*
  - only muscle-like MI neurons directly command muscles
- Parallel scheme *(right part of figure)*
  - different types of MI neurons can directly command muscles

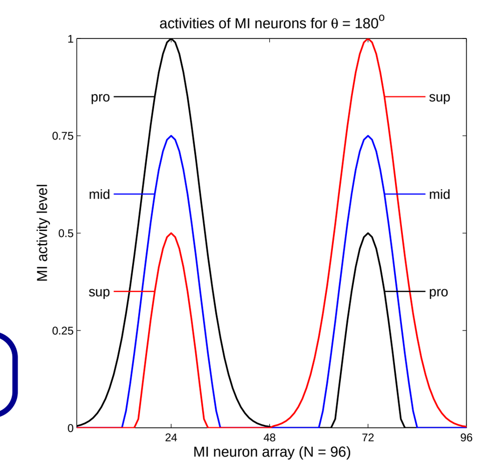


The Model

- Employs ***only*** extrinsic-like neurons modulated by wrist posture:
  - exhaustive projections (**K**) from MI to muscles
  - muscle activity (**a**) determines movement (**x**)



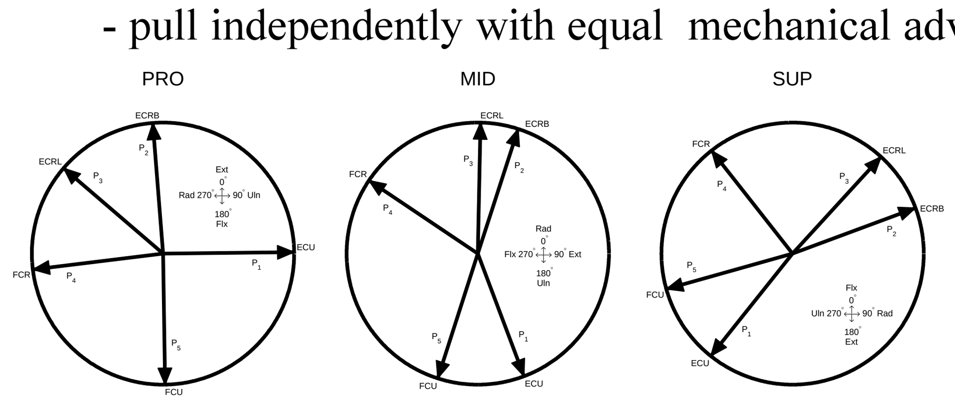
V: *visual representation*, **WP**: *wrist posture representation*, **MI**: *neuron array*, **a**: *muscle activation*, **x**: *endpoint of movement*, **K**: *exhaustive connections from* **MI** *to* **a**, **P**: *pulling direction of a muscle*, *ρ: wrist posture.*



Activity of the array of MI neurons when the target is at 180°.

- Focus on 5 muscles - prime movers of the wrist; assume that they:
  - pull wrist in a straight line (in joint space)
  - pull independently with equal mechanical advantage

$$a_i = \sum_j K_{ji}\, MI_j$$



Pulling directions of the five muscles for the pronated (left), midrange (center), and supinated (right) wrist postures (data from Hoffman, 1999 personal communication).

- Endpoint of wrist movement **x** is computed as: $\mathbf{x} = \sum_{i \in A} \mathbf{P}_i^\rho a_i$
  - a_i : activation of muscle i (in set A)
  - $\mathbf{P}_i^\rho$: pulling direction of muscle i with wrist in posture ρ

Selecting the MI-to-Muscle Parameters (K)

- Error function for a single target/wrist posture:

$$E(\mathbf{x}_{\mathbf{targ}}, \rho) = \frac{1}{2}\left\| \mathbf{x}_{\mathbf{targ}} - \sum_{i \in A} \mathbf{P}_i^\rho a_i \right\|^2 + \frac{\lambda}{2}\|\mathbf{a}\|^2$$

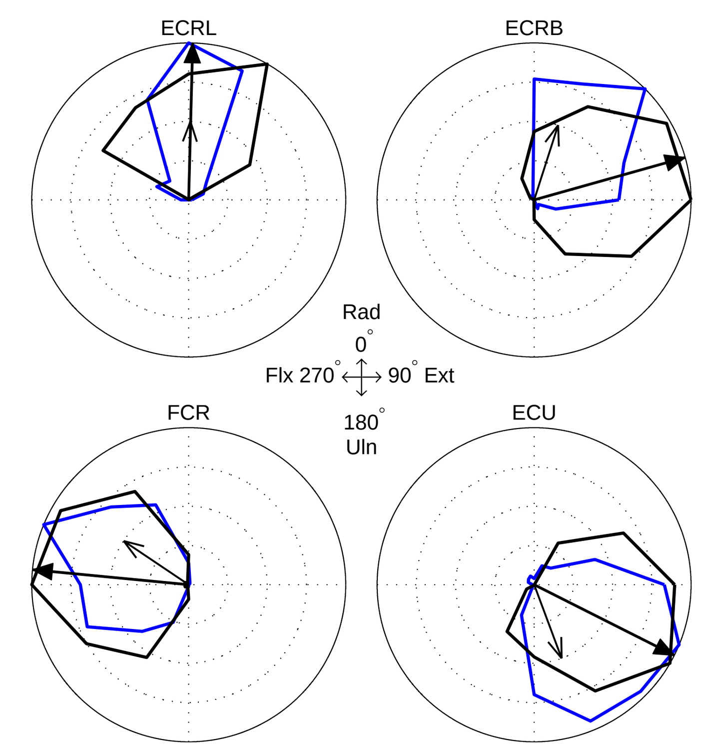
target error — *total muscle activation*

$\mathbf{x}_{\mathbf{targ}}$: vector representing target location
$\lambda = 0.02$ is a regularization parameter
$\mathbf{a}$: vector of muscle activations
$a_i \geq 0 \;\forall\, i \in A$: muscle activation must be non-negative

- We use a gradient descent method to select connections (**K**) to minimize the error over all targets/wrist postures, i.e., $\Sigma E(\mathbf{x}_{\mathbf{targ}}, \rho)$

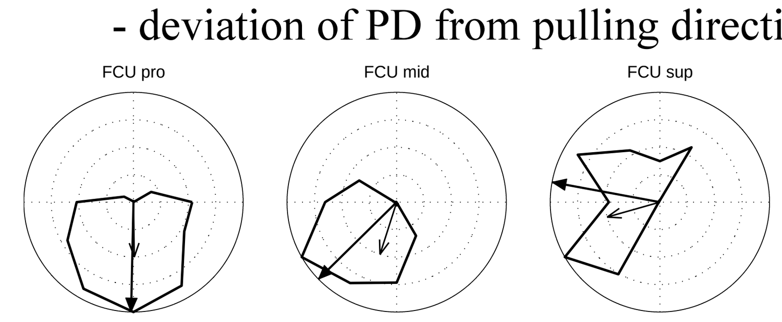
Results

- Muscle activation patterns:
  - unique solution
  - produced accurate movements
- Average target error: .044±.05
- Average muscle activation vector length: 1.19±.37



Muscle activation as a function of target direction for four wrist muscles in the midrange wrist posture as produced by the model (black) and monkey (blue; Hoffman and Strick, 1999). Included are the pulling directions (open arrows) and the modeled muscles' PDs (closed arrows).

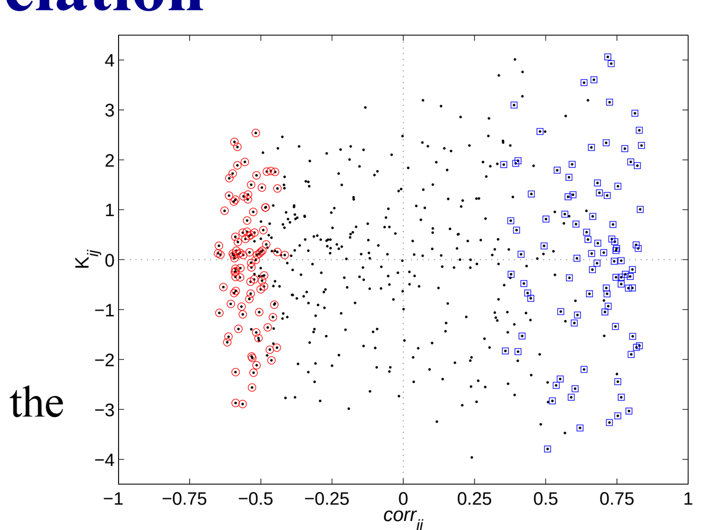
- Preferred direction behavior as wrist rotated from pro to sup:
  - rotated ~90°
  - deviation of PD from pulling direction not constant



Muscle FCU activation as a function of target direction for all three wrist postures.

Neuron-Muscle Correlation

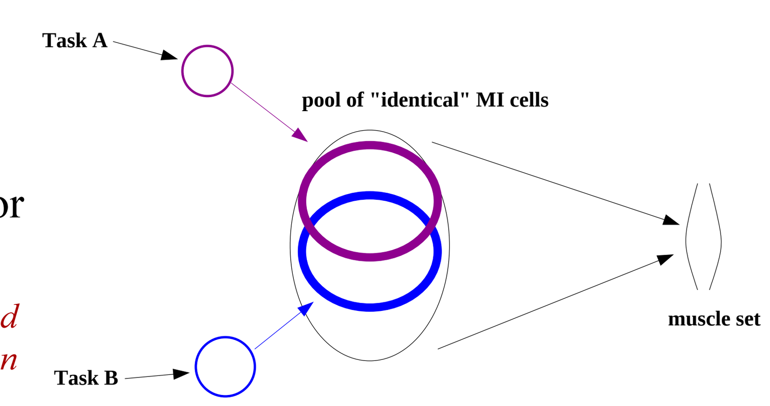
- All MI neurons correlate to a moderate degree with some muscle (0.4 - 0.8)
- All muscles correlate to a high degree with some neuron (0.7 - 0.8)
- Correlation is not predicted by the strength of connection from neuron to muscle



Scatter plot of connection strength between neuron i and muscle j (K_{ij}) versus their correlation ($corr_{ij}$). Blue squares indicate the highest correlation with respect to a single neuron, red circles indicate the lowest correlation.

Discussion

- Reduced target errors are possible with the introduction of non-extrinsic MI cells
- How do we describe the function of a neuron?
  - by how it is activated? or
  - by what it controls?



Different pools of MI neurons recruited for different tasks. Each pool can command the same muscle.

References and Acknowledgments

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