Current approaches to the neural control of movement must account for the fusimotor system.

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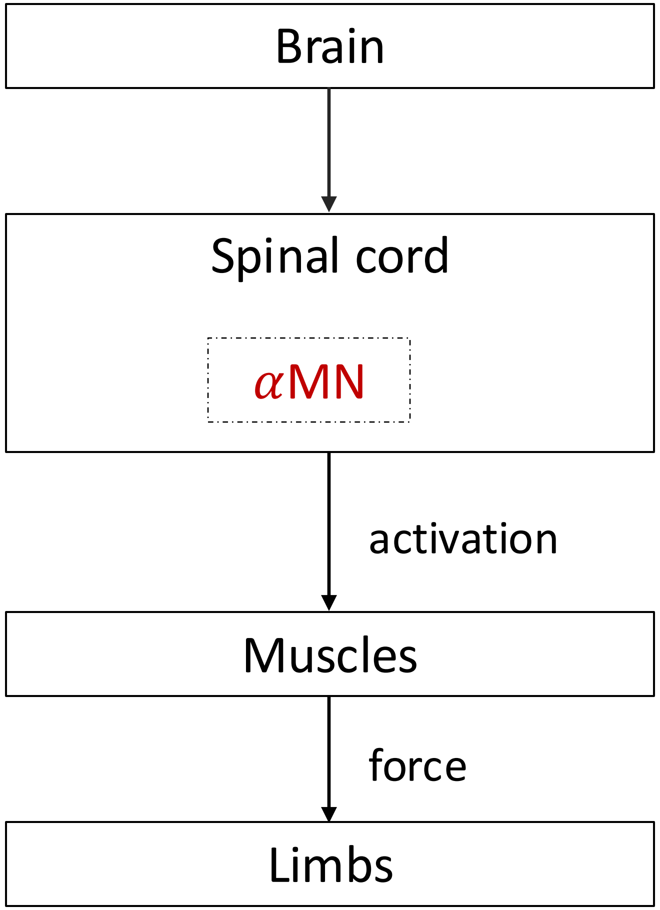
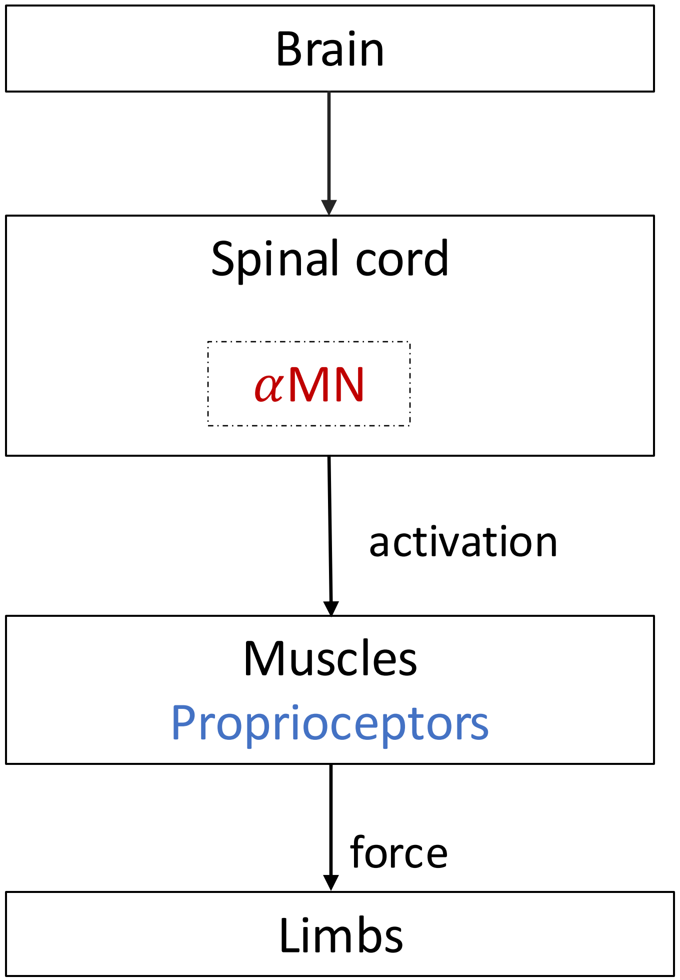
How does voluntary movements happen in the presence of muscle afferentation ?

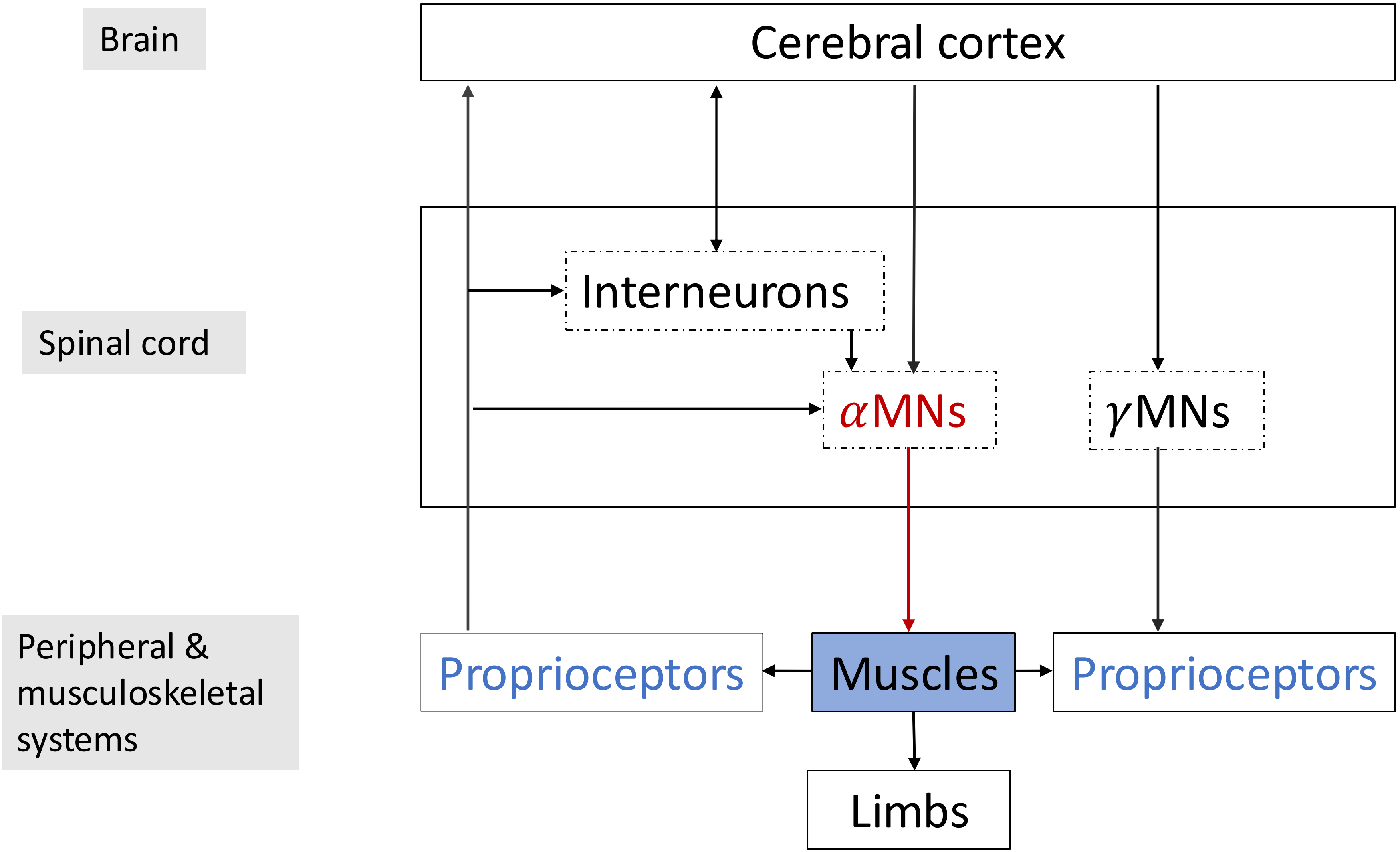
Movement commands originate from brain to spinal cord, and to muscles which generate forces that drive limbs.



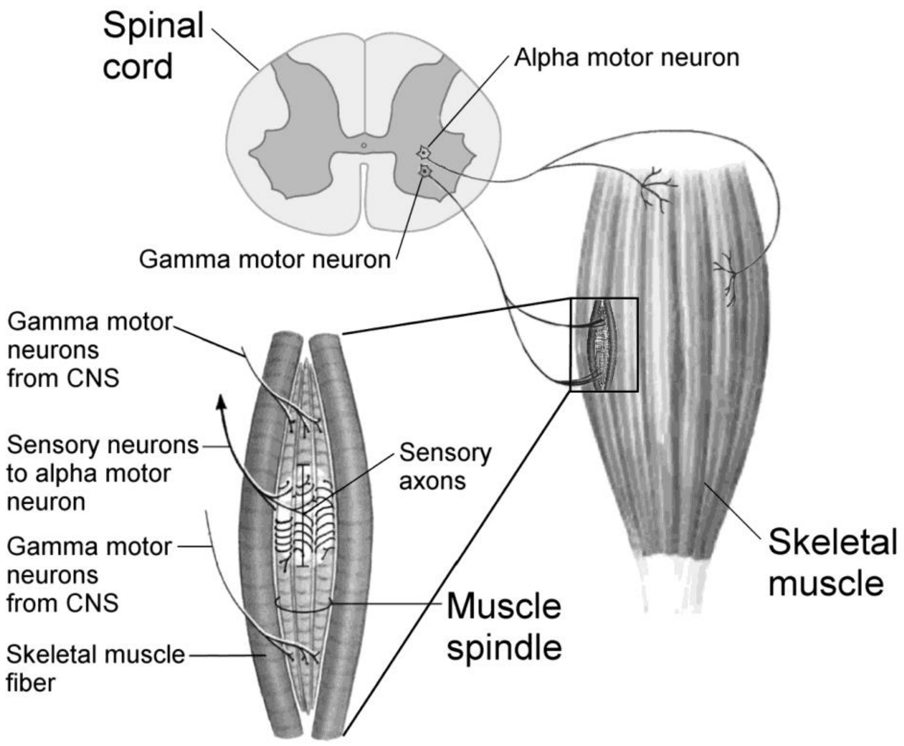
Proprioceptors: Muscle spindles and Golgi tendon organs provide proprioceptive signals to the CNS.



The activation of α-motoneurons (MNs) is the result of the integration of thousands of synaptic inputs from cortical, propriospinal, and sensory signals (Pierrot-Deseilligny and Burke, 2005; Schieber, 2011;Loeb and Tsianos, 2015).



Fusimotor system and spindle afferent

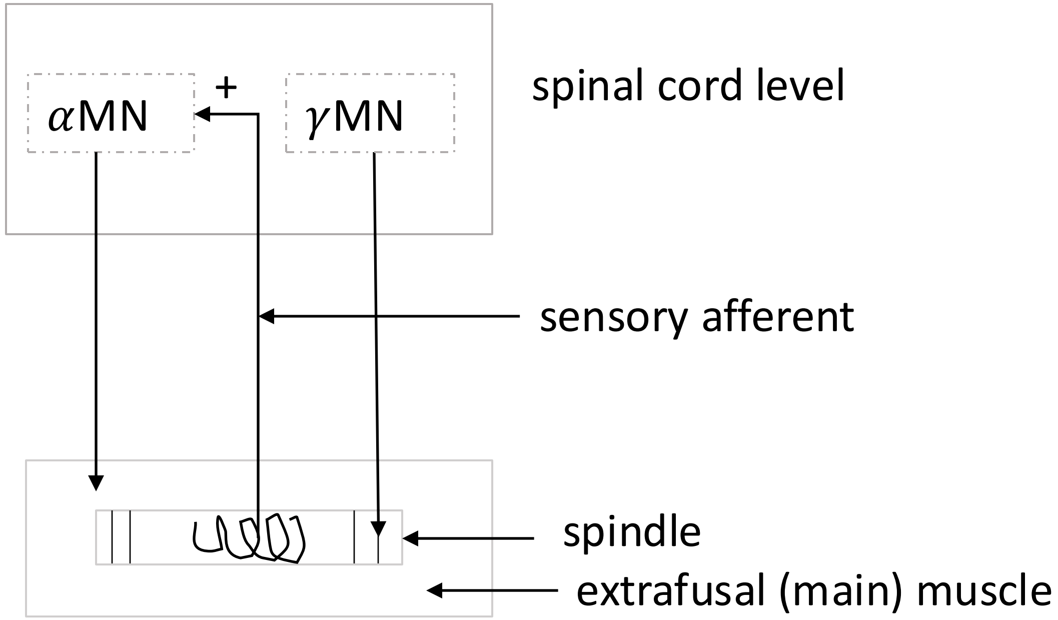


- Spindles encode muscle length and velocity signals(Gardon ,1994).
- Gamma efferent (γ-static & γ-dynamic) adjust the spindle sensitivity to changes in muscle length and velocities that occur during movement.
- Monosynaptic excitation drive to the α-motoneuron is the foundation of muscle tone and stretch reflexes (Liddell & Sherrington, 1924).

Spindle afferent and servo-control theory

Servo action (Marsden, Merton & Morton, 1972):

- Muscle spindles contraction due to reflexes or voluntary movements, via gamma MNs lead to afferent discharges from the sensory endings.
- This induce, via a spinal stretch reflex arc, contraction of the extrafusal (main) muscle.
- Automatic correction of unexpected changes in the load against which the muscle is working.



Can a servo-control perspective explain the role of spindle afferents during voluntary movements?

Motivation & Goals

- Muscles are afferented and the sensory outputs flood the spinal cord.
- Therefore, afferent signals must be regulated in a context sensitive way that is useful for movement.

Demonstrate in simulation that modulation of gamma motoneurons suffice to enable voluntary movements in the presence of muscle afferent.

Approach

1. Simulate spindle afferent during movement
2. Test our hypothesis

Approach 1: Simulation of spindle afferent during movement

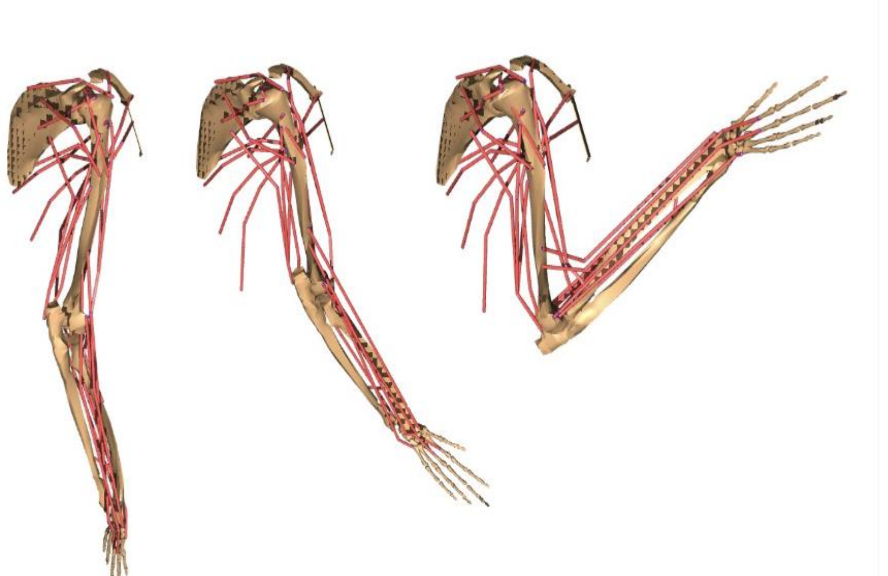
Goals:

a. Simulate movements without afferentation
b. Add a simple, constant spindle-like afference
c. Quantify the effects of spindle afferent on limb kinematics

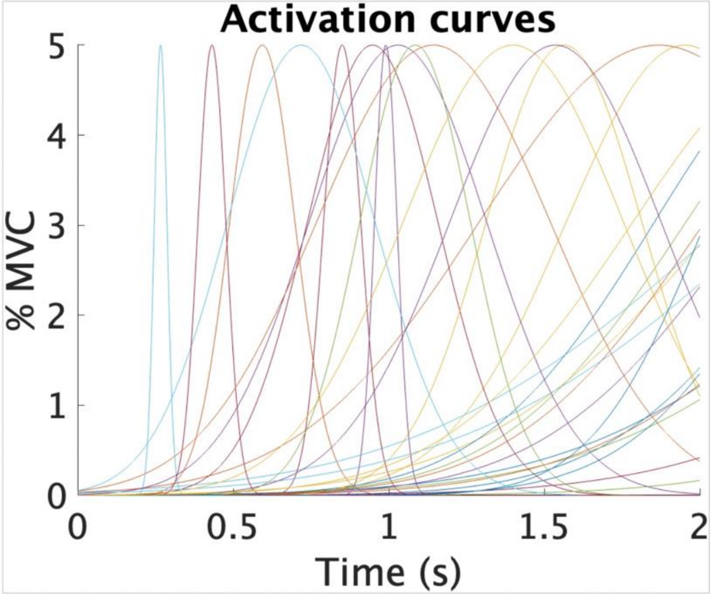
Methods

Biomechanical Model:

- Convert and modify Chan and Moran's SIMM model of macaque arm into MuJoCo model (Chan & Moran, 2006).
- 31-muscle *rhesus macaque* model with:
  - 7 DOFs
  - 5 segments: upper arm, ulnar side and radial side of lower arm, hand, and torso as the initial frame.



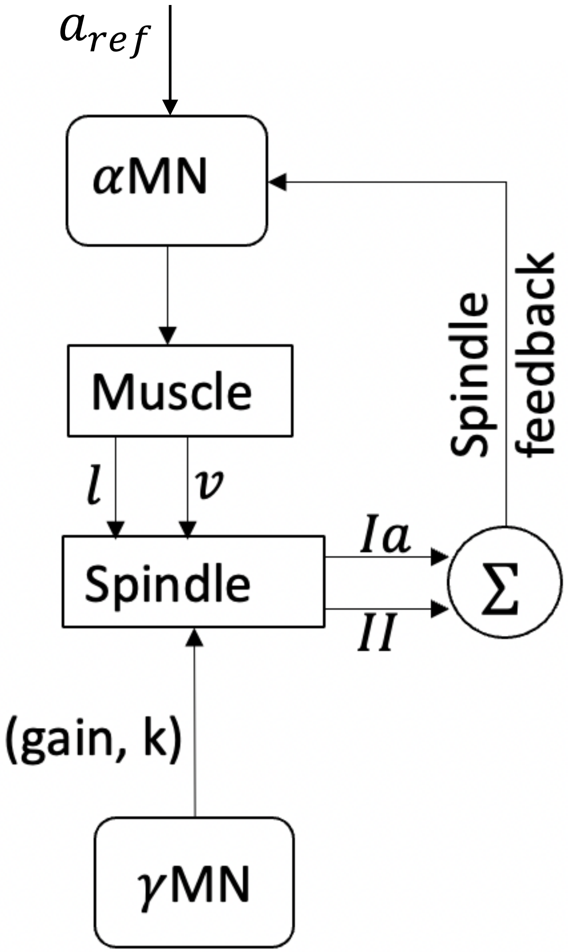
Right macaque arm model



- Use Monte Carlo method to create 100 sets of feed-forward cortico-spinal activation (bell shape).
- 2-seconds MuJoCo simulation of the macaque arm model.

Methods

- Spindle model



- Record eccentric length & velocity signals from each muscle, and the endpoint trajectories

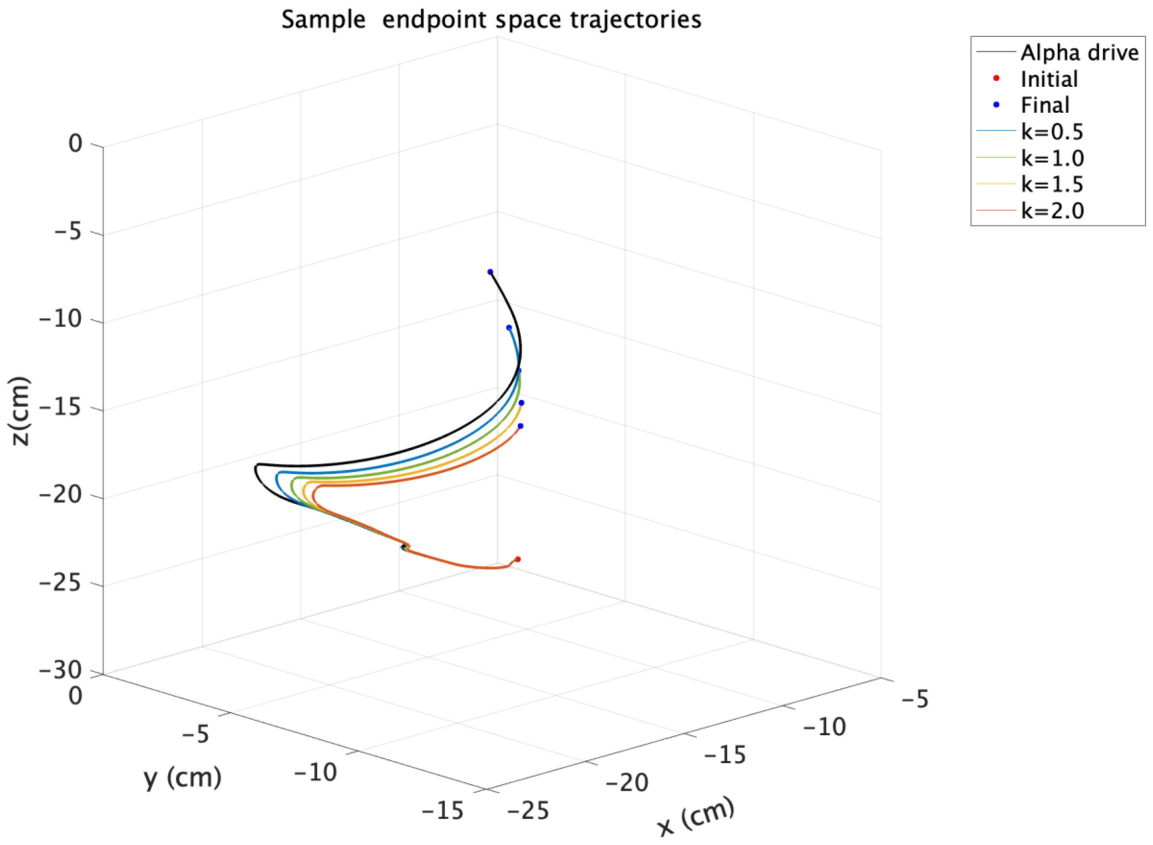
Activation equation

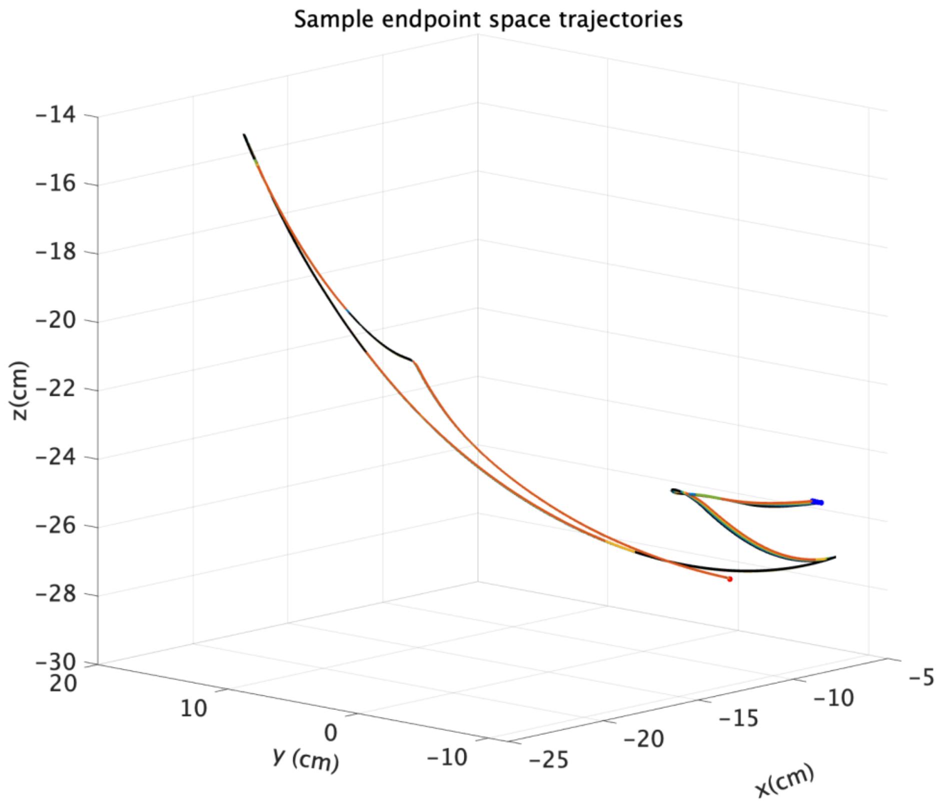
$$a_m(t)_i = a_{ref}(t)_i * [1 + k * (l - l_o)_m + k' * v_m]$$

a_{ref} : activation with no spindle afference
l_o: initial muscle length
l: muscle length
v: muscle velocity

- Compute trajectory errors and terminal errors with respect to to the reference trajectories without afferentation.

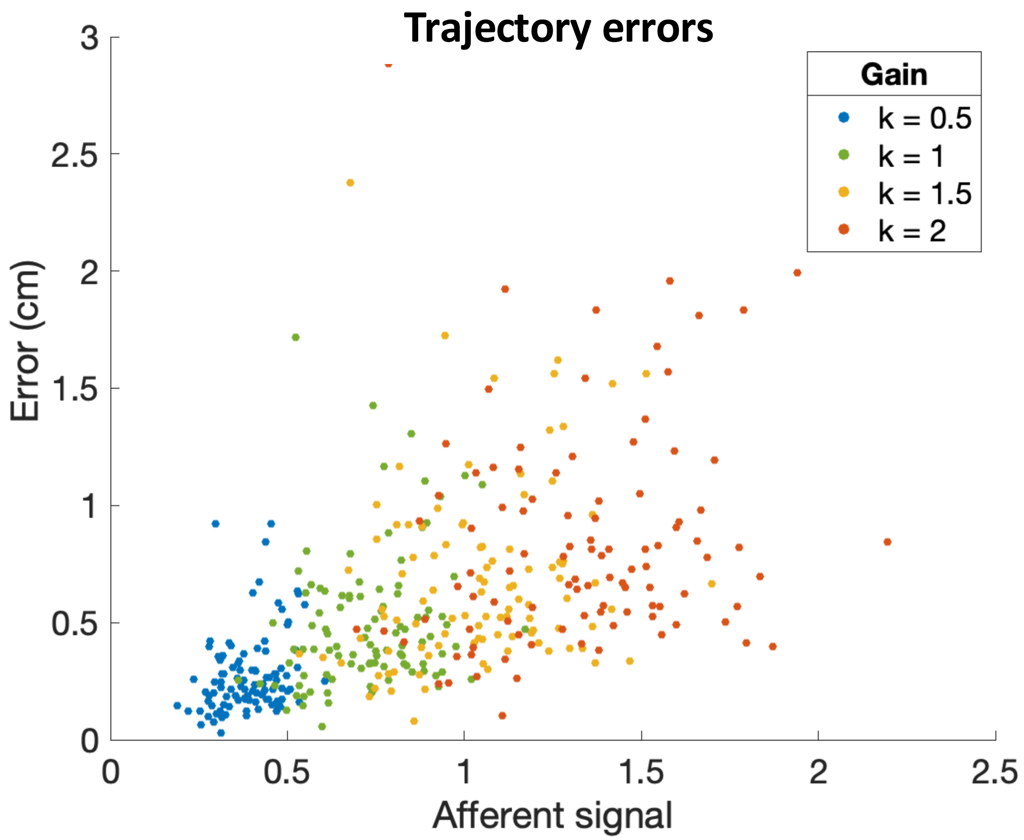
• Disruption in endpoint space trajectories

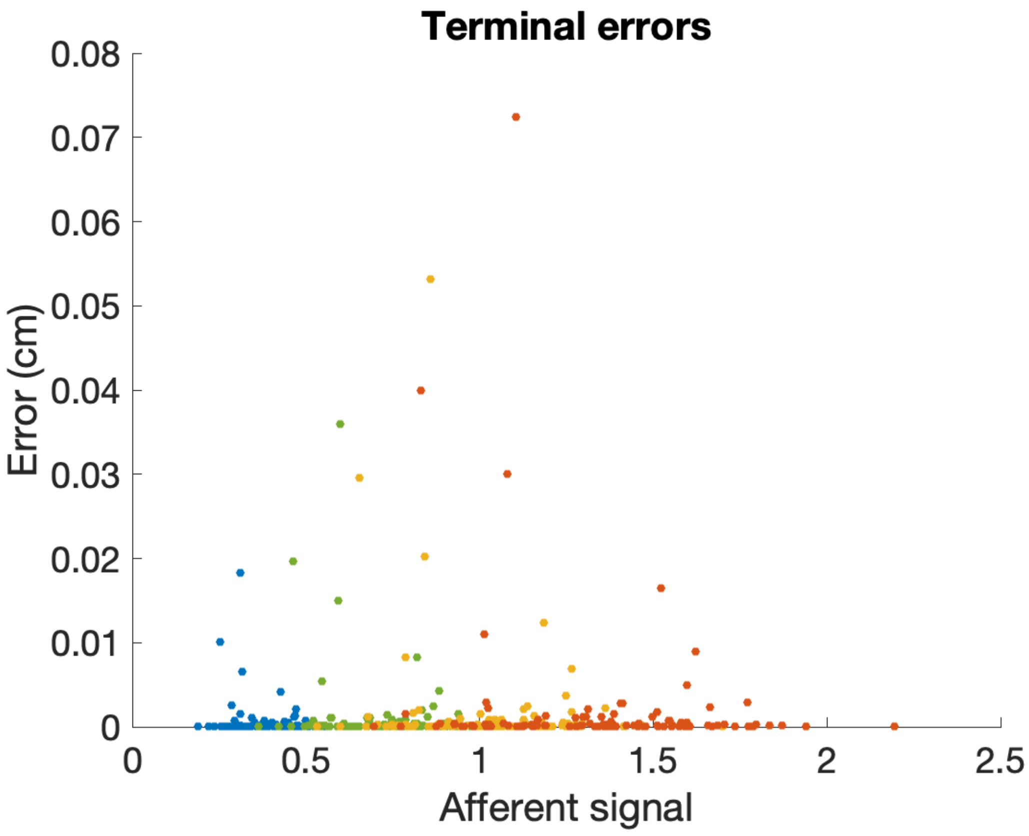




- As expected, afferentation is an internal perturbation.
- However, sometimes, the perturbations are big or small.
- Therefore, the effects of afferentation are context-dependent like Shadmehr and Mussa-Ivalidi 's perturbation to curl fields (Shadmehr and Mussa-Ivaldi, 1994).

- Trajectory & terminal errors w.r.t reference trajectories





- Overall, increase in spindle sensitivity to muscle stretch signals lead to increase in both trajectory and terminal errors

Current directions

- Use more biologically realistic spindle models (Mileusnic et al., 2006)

- Test our hypothesis in approach 2:

❖ Demonstrate in simulation that modulation of gamma motoneurons suffice to enable voluntary movements in the presence of muscle afferent.

Relevance of the work

- Understand and disambiguate the fundamental contributions of the spinal circuits to movements.

- This will allow us to understand the neural and neuromechanical contributors to versatile function, and how its disruption creates disability.

- Potential contribution to prostheses and assistive devices.

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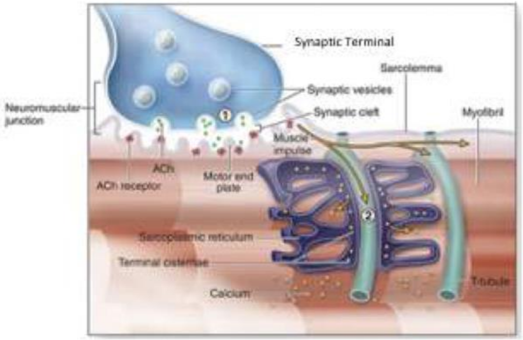
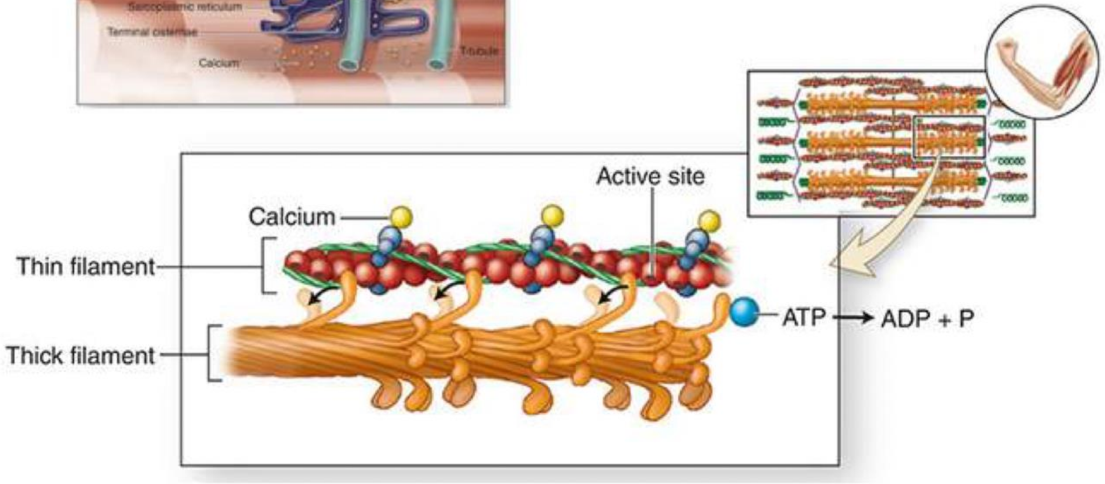
Thank you ☺

Supplement materials

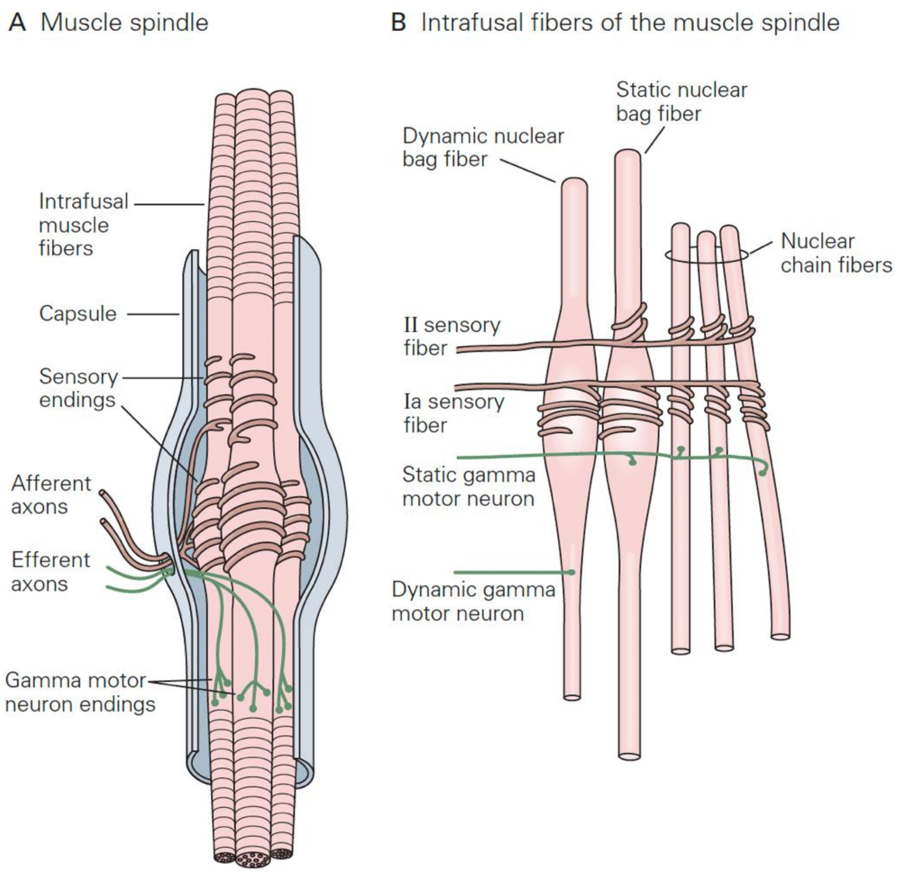
Motor unit and muscle action

- Transmission of action potential at the motor end plate cause release of neurotransmitter at the sarcolemma.
- Change in membrane electrical properties triggers release of Ca+ ions.
- calcium cause a conformational change in troponin and tropomyosin, thus exposing the active binding sites on the actin filaments.
- Myosin binds to the actin filaments
- Muscle contraction is a consequence of interaction between the actin and myosin filaments





Fusimotor system : Gamma Motor neurons & Muscle Spindles



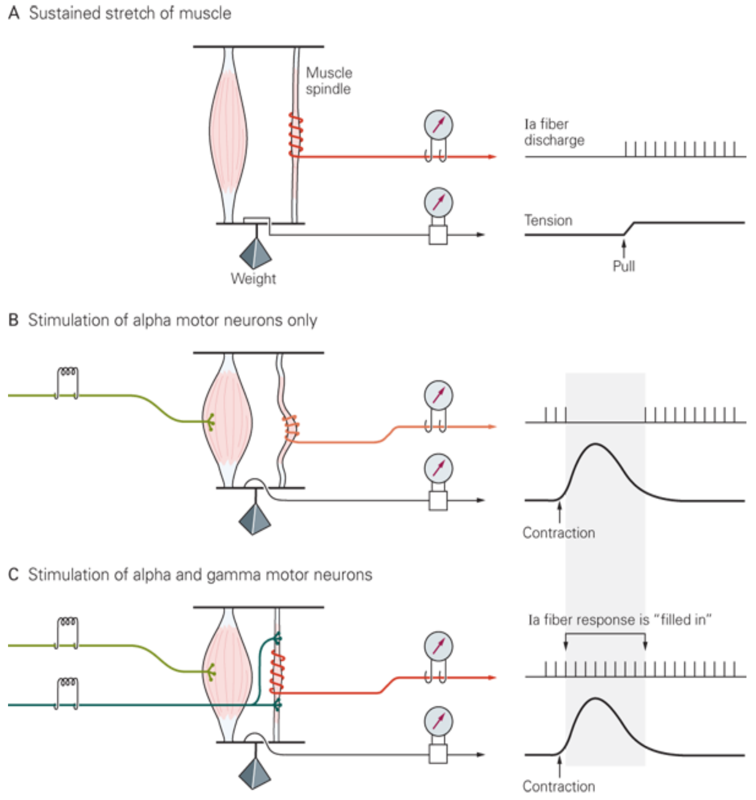
Adapted from Principles of neural science, 7th ed

How should gamma motoneurons be modulated ?
(Alpha-gamma coactivation vs Independent control)

Alpha-gamma coactivation

- Muscle is stretched cause increase in Ia firing
- Activation contraction of muscle (muscle shortening) lead to spindle unloading.

- Simultaneous simulation of alpha and gamma MNs will prevent spindle from slackening



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Independent modulation

Loeb & Hoffer, 1981:

- Ia afferent behave differently depending on the contraction profile (shortening or lengthening) of the muscle of origin.

- High activation of gamma MN during muscle contraction via shortening .

- Relatively little activation of gamma MN during muscle contraction via lengthening.