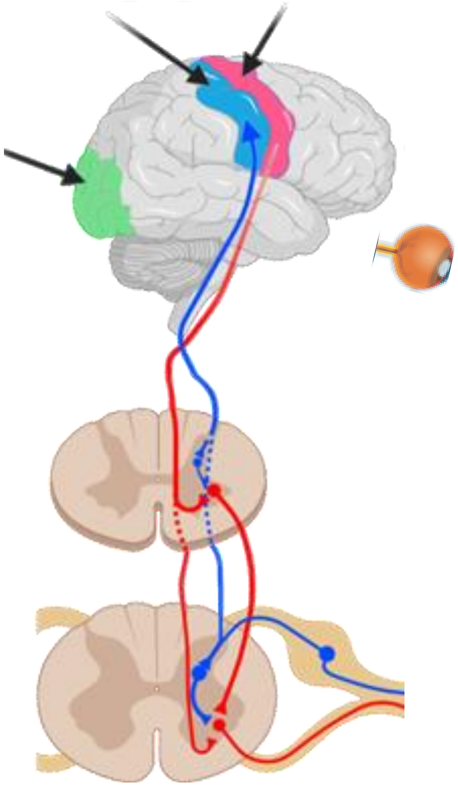
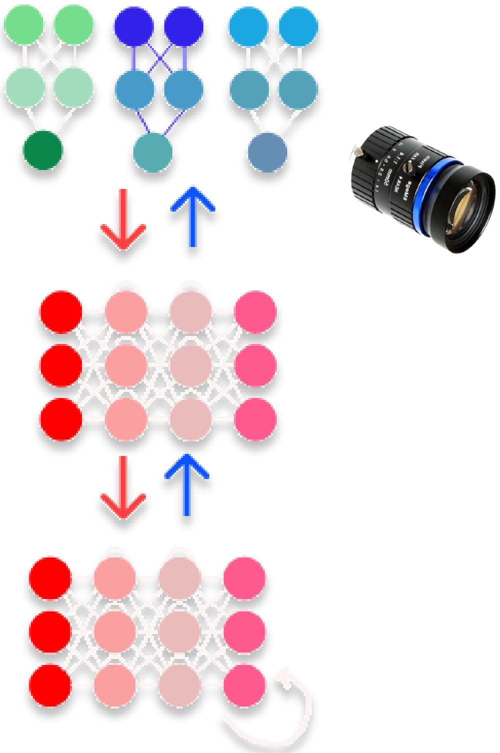
NX-414: Brain-like computation and intelligence

Alexander Mathis
alexander.mathis@epfl.ch

Lecture 7, April 2nd 2025

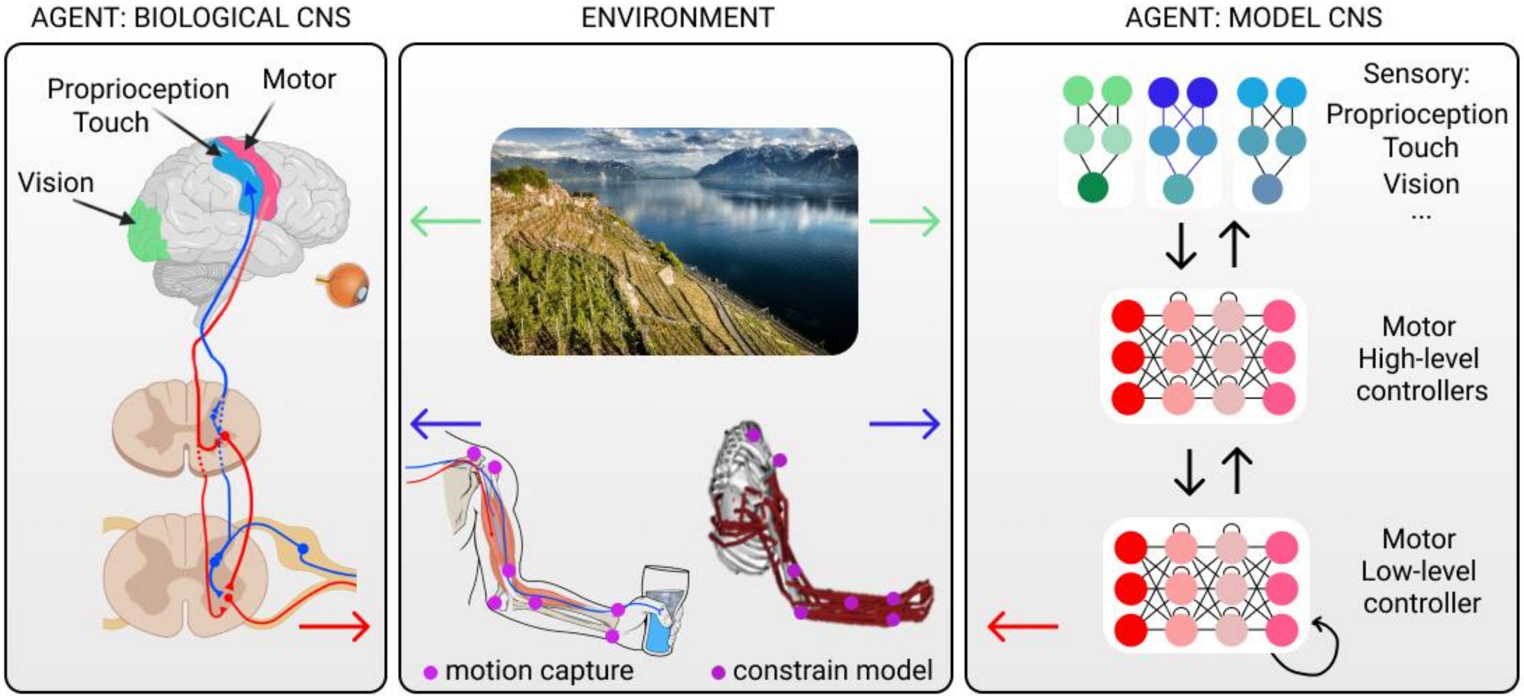
Biological Intelligence ⟷ Artificial Intelligence





Hausmann*, Marin-Vargas*, Mathis**, Mathis**, Curr op. in Neuro., 2021

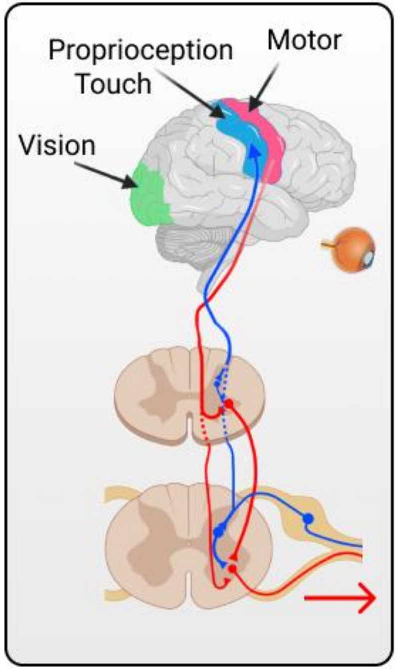
Reverse engineering neural circuits



Hausmann*, Marin-Vargas*, Mathis**, Mathis**, Curr op. in Neuro., 2021

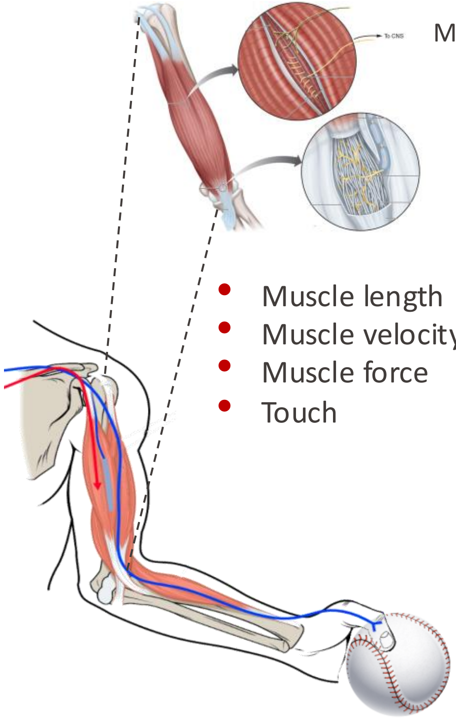
Motor skills need sensory feedback

AGENT: BIOLOGICAL CNS



Sensory feedback

Motor commands



Muscle spindles

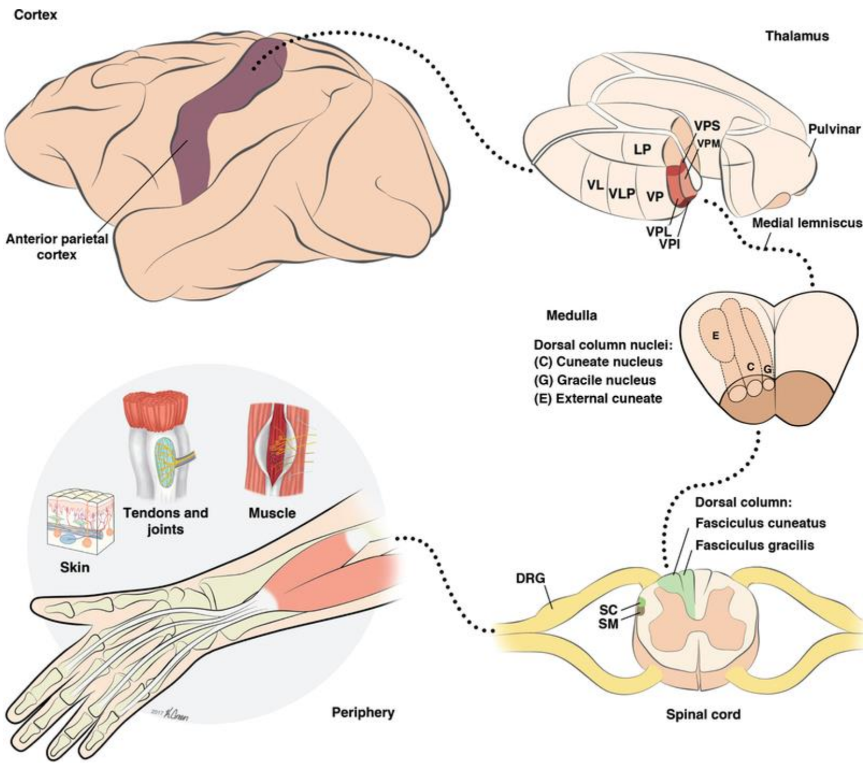
GTOs

- Muscle length
- Muscle velocity
- Muscle force
- Touch

Simple skills require feedback

- Video taken from Roland Johansson Lab - Department of Integrative Medical Biology. Umea University, Sweden

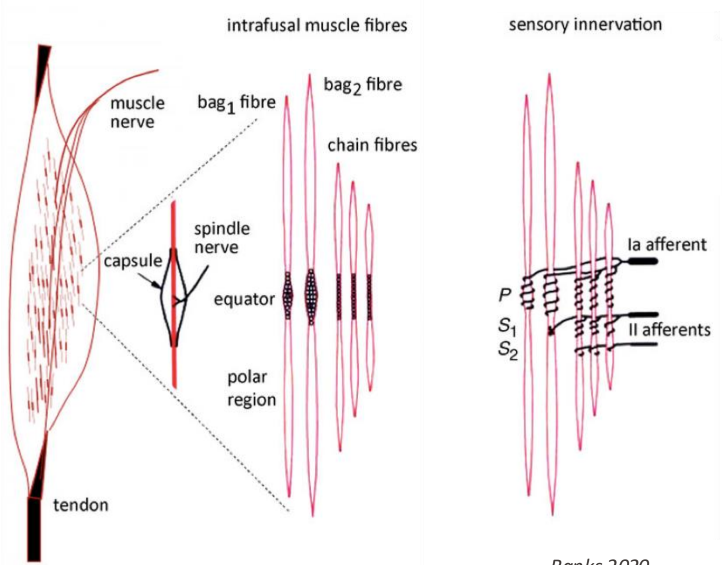
Proprioception (the sense of posture)



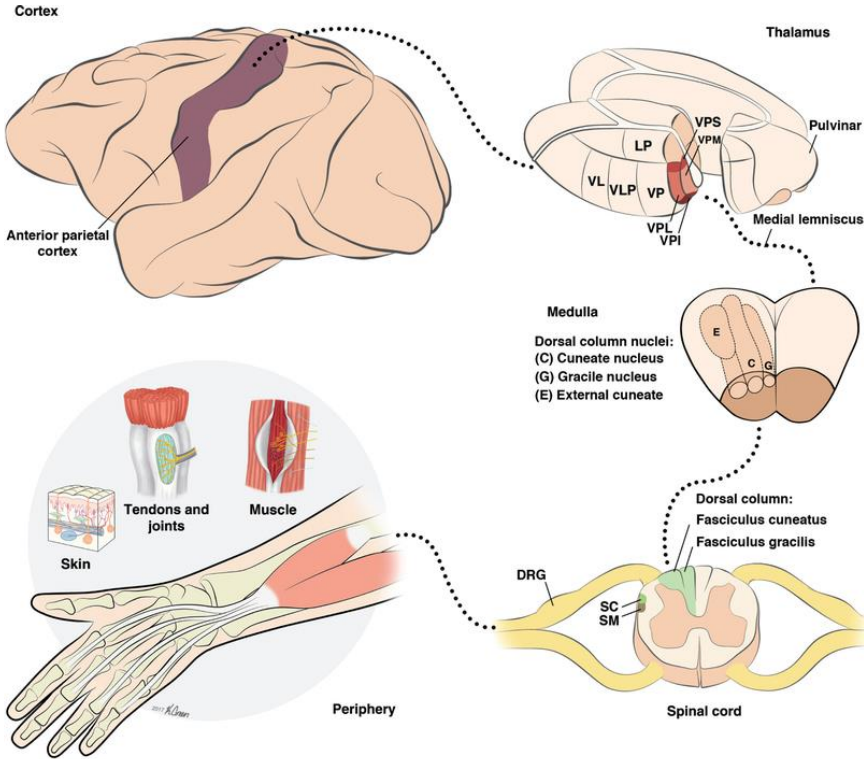
Delhaye et al., 2018

Proprioception (the sense of posture)

Muscle spindle

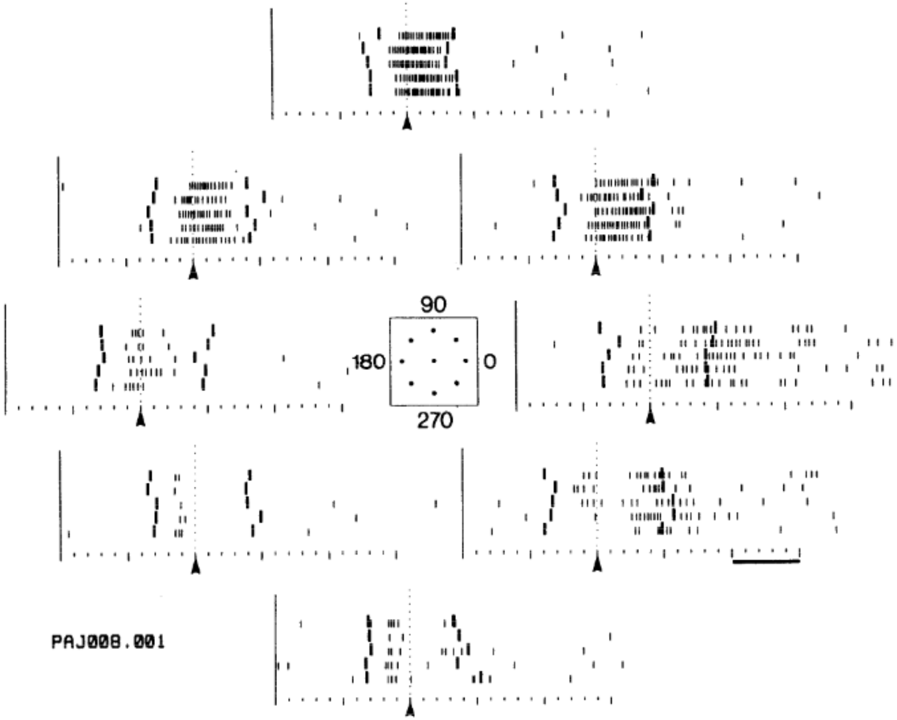


Banks 2020

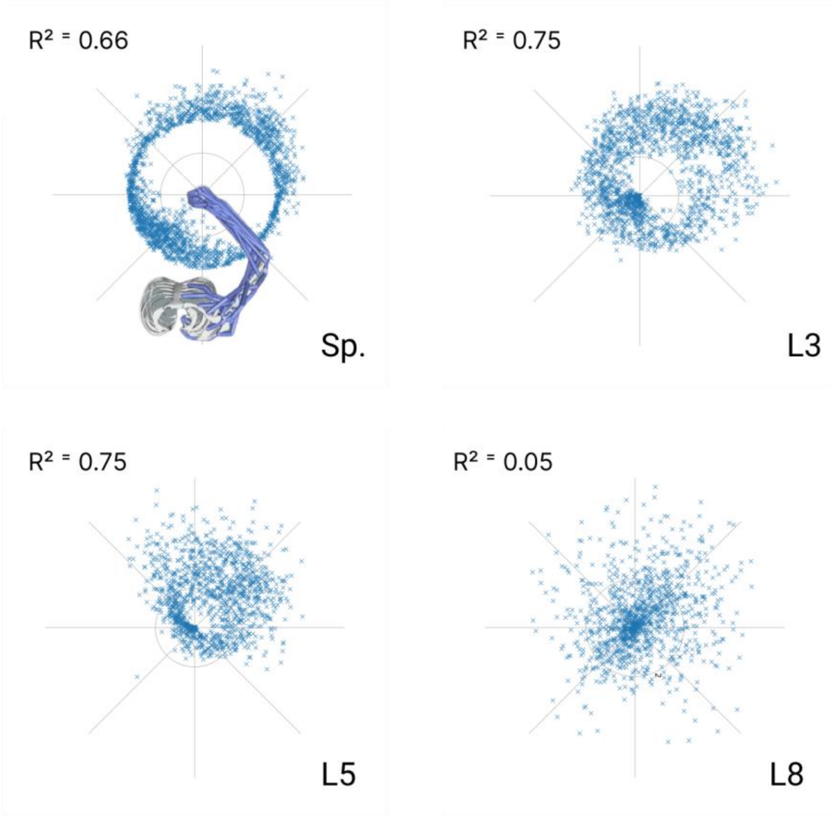


Delhaye et al., 2018

Tuning curves in somatosensory cortex



Prud'homme and Kalaska 1994

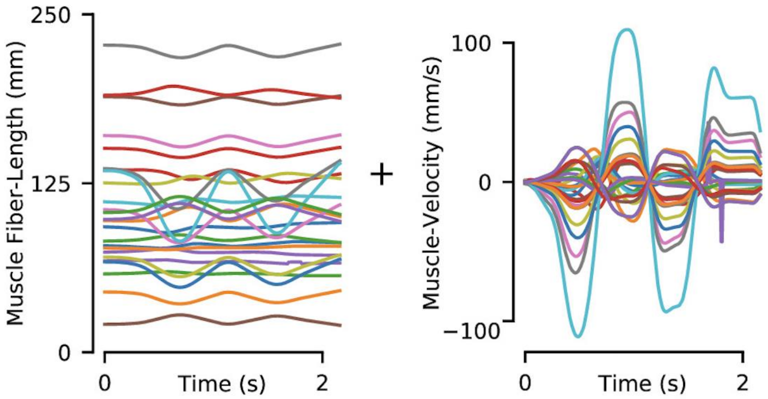


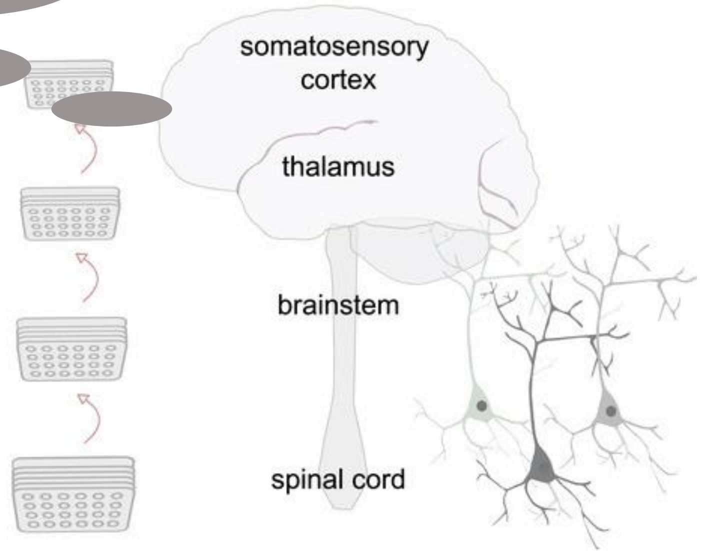
Sandbrink*, Mamidanna*, et al. eLife 2023

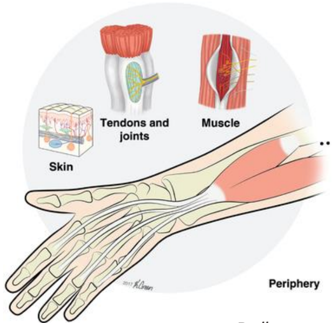
- Known: Direction, velocity, acceleration tuning…

What's the trajectory of my limbs?

What is the integrative logic of proprioception?

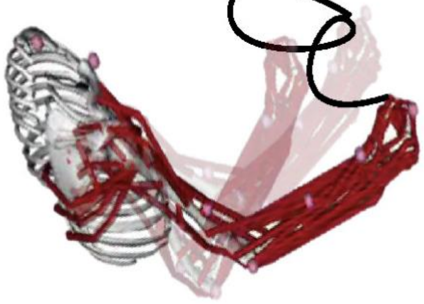




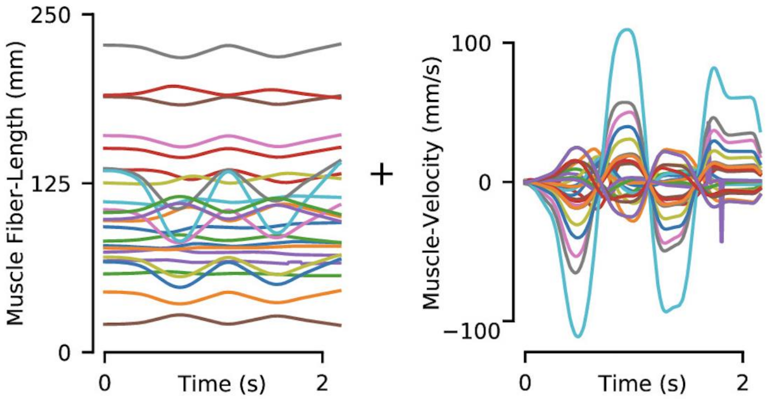


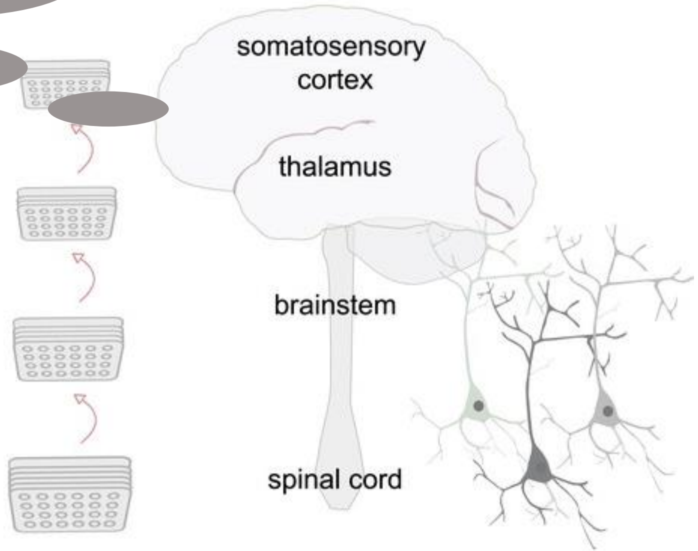
Delhaye et al., 2018

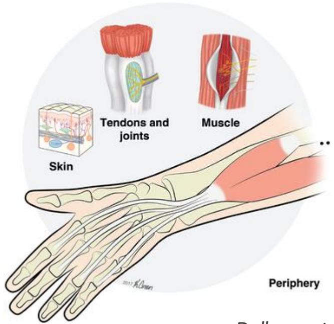
W y limbs?



What is the integrative logic of proprioception?





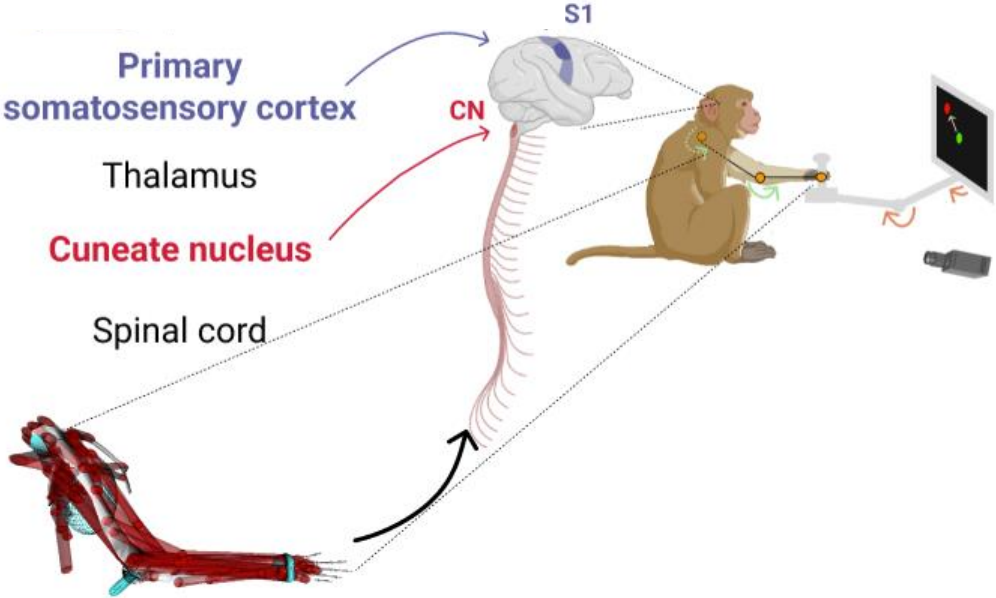


Delhaye et al., 2018

Reverse-engineering proprioception

Alessandro Marin Vargas

Axel Bisi
(MA student, now PhD student with Carl Petersen)



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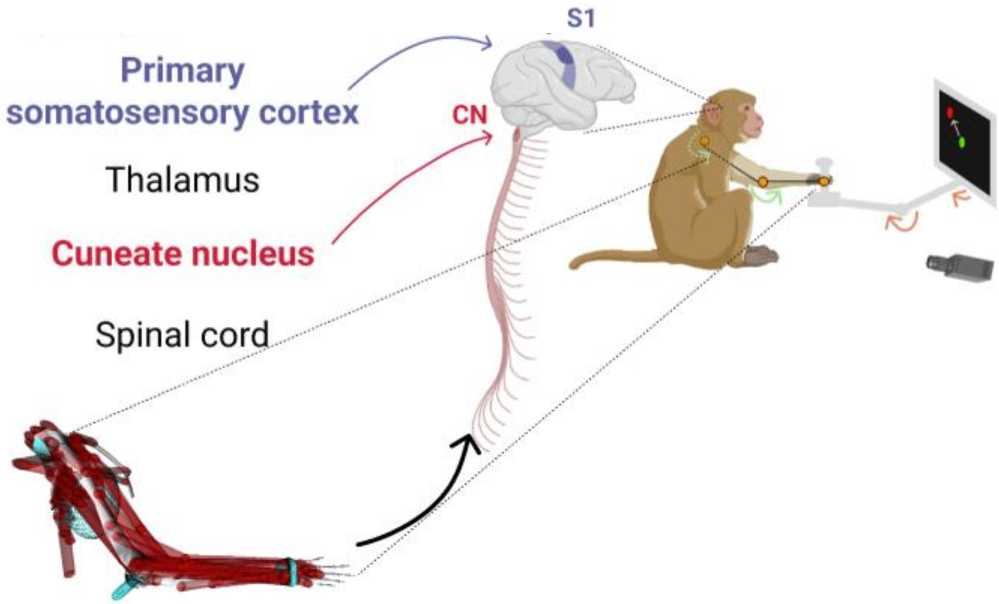
Reverse-engineering proprioception



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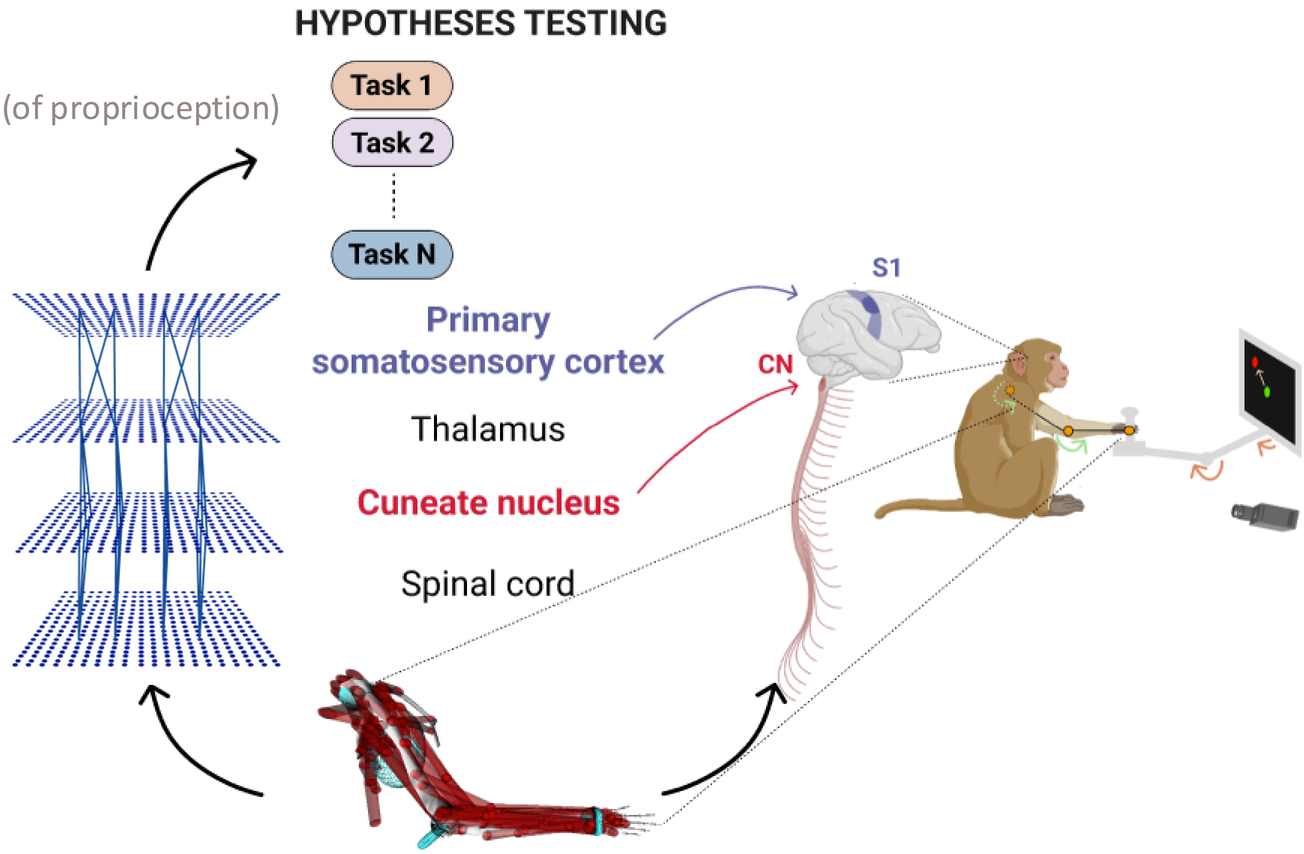
Creating task-driven models of proprioception

Ingredient 3:
Putative goals (of proprioception)

Ingredient 2:
ANNs



Ingredient 1: simulating spindle dynamics at scale

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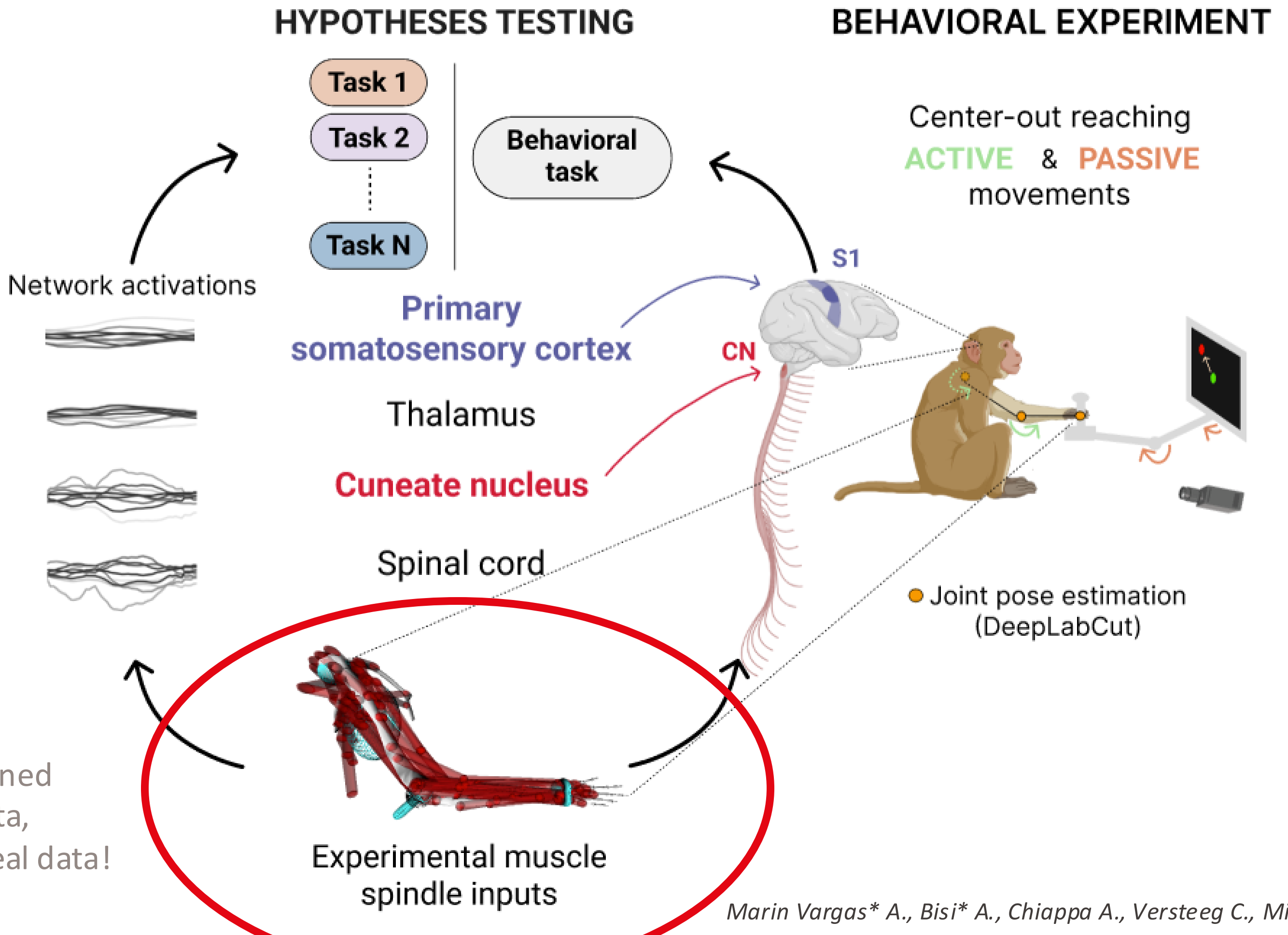
Assessing task-driven models of proprioception



Note: models trained with synthetic data, but tested with real data!

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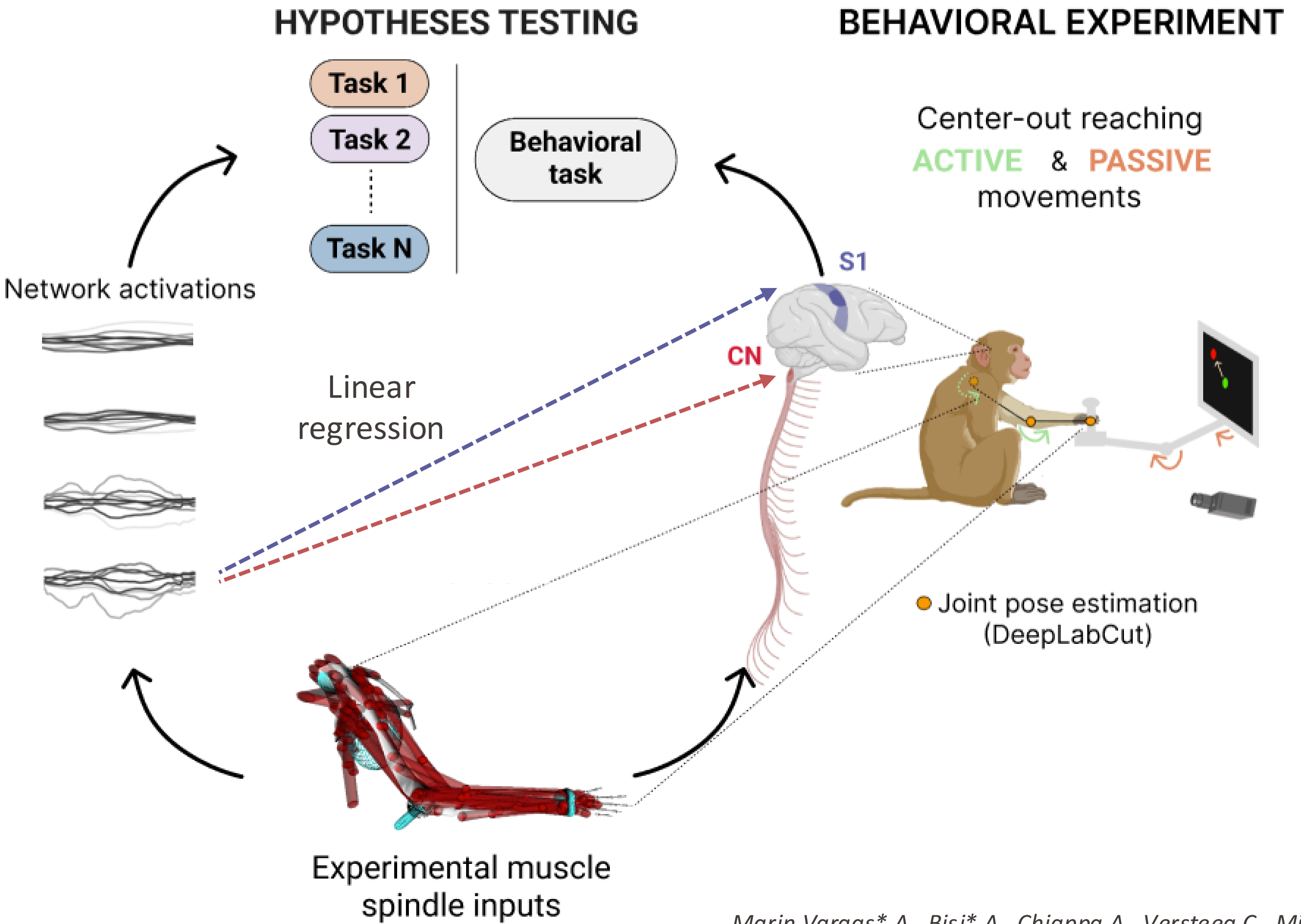
Reverse-engineering proprioception



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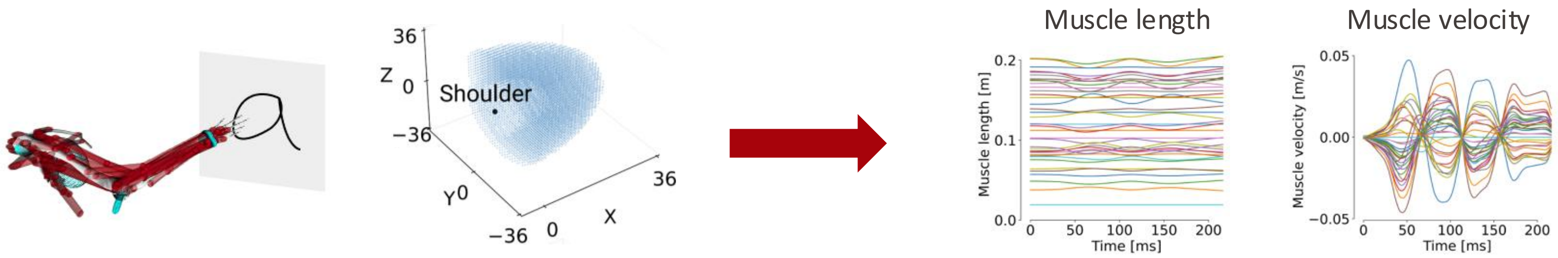
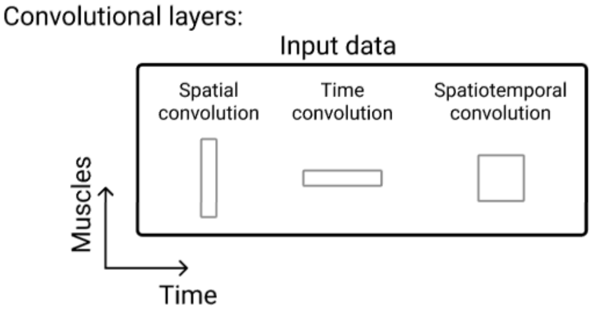
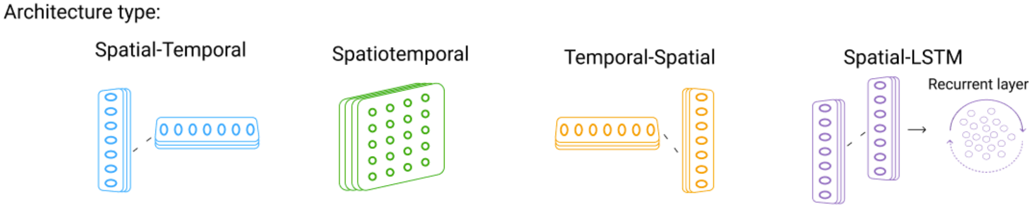
Creating synthetic data & candidate models

- Use biomechanics simulators to estimate spinal cord input at scale (muscle spindles)



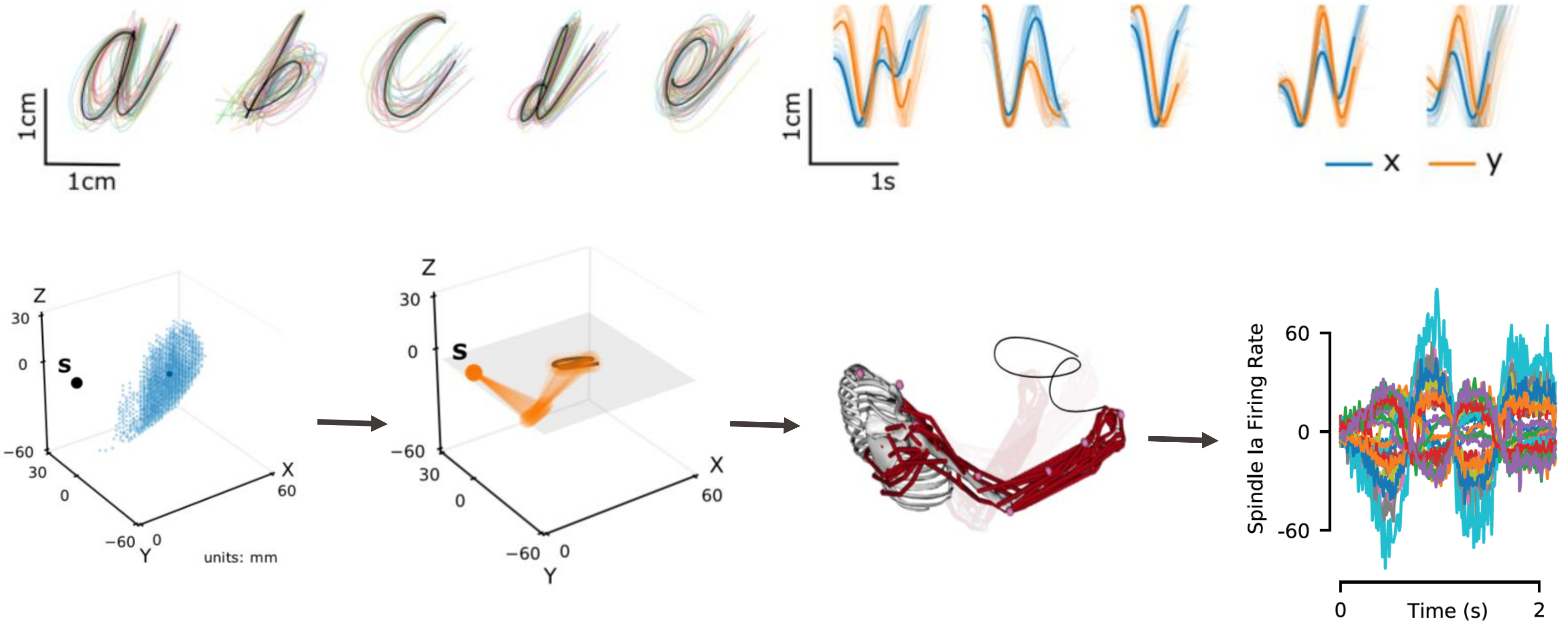
- Develop neural networks models that process information across muscles & time





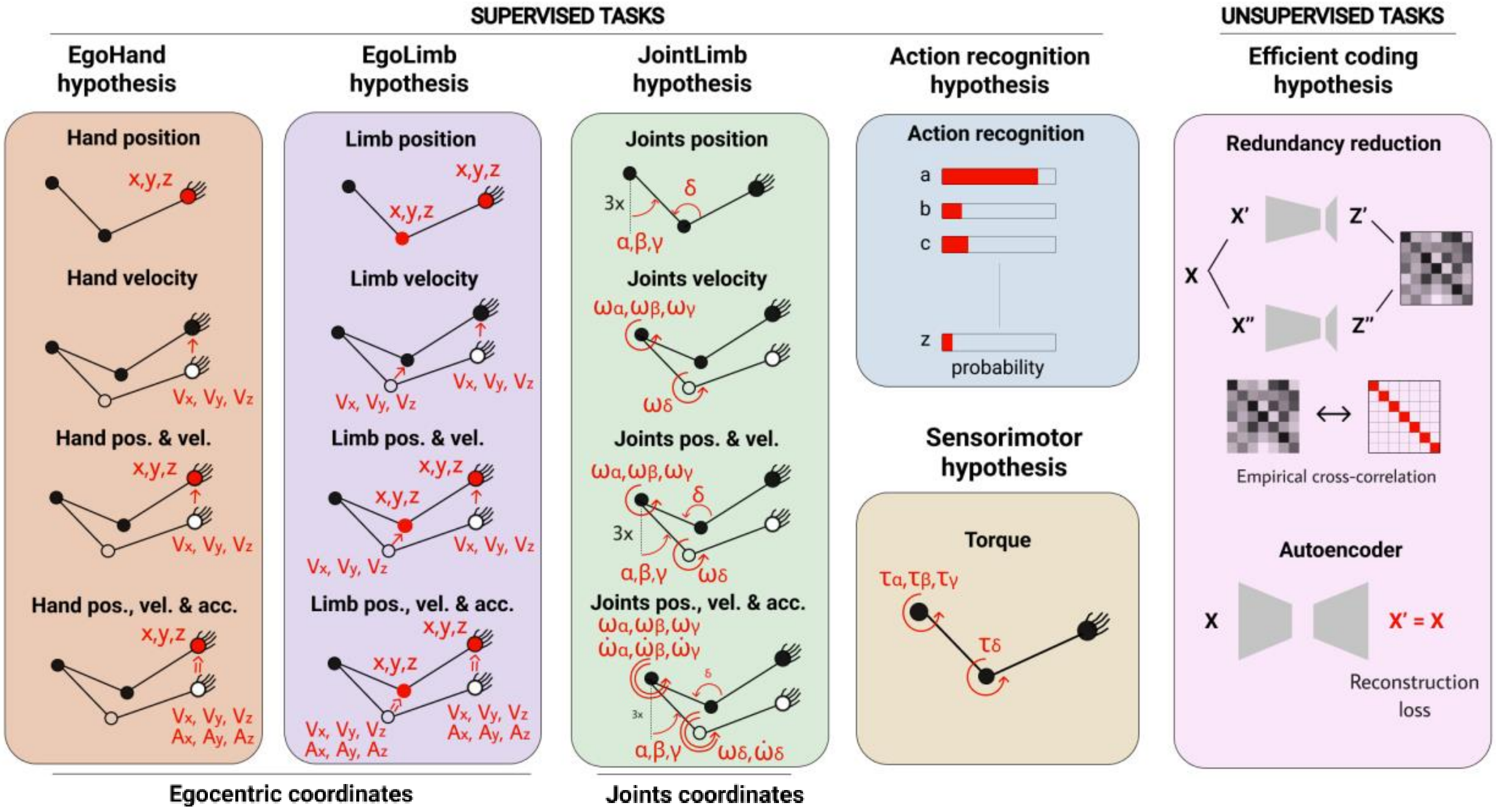
Method adapted from our previous work: Sandbrink, K. J., et al. "Contrasting action and posture coding with hierarchical deep neural network models of proprioception." *eLife* (2023)

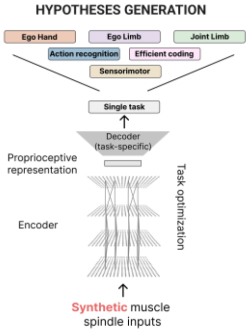
Dataset: Creating input statistics



Sandbrink*, Mamidanna*, Michaelis, Bethge, M. Mathis*, A. Mathis*, eLife 2023

16 computational tasks to create candidate models





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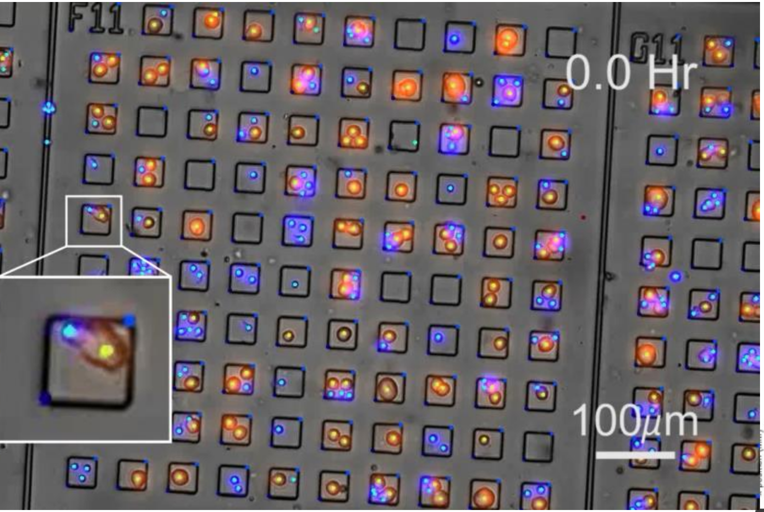
DeepLabCut: a toolbox for efficient markerless pose estimation

Cells

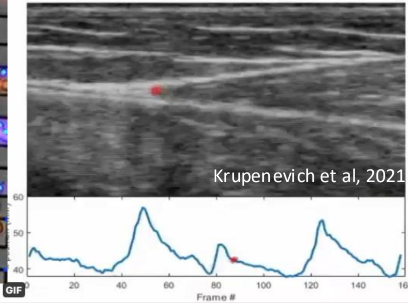
Tissues

Organisms



Cachot et al. 2021
Science Advances

Adamian et al, 2020
The Laryngoscope



Krupenevich et al, 2021

Lauer et al. 2022
Nature methods

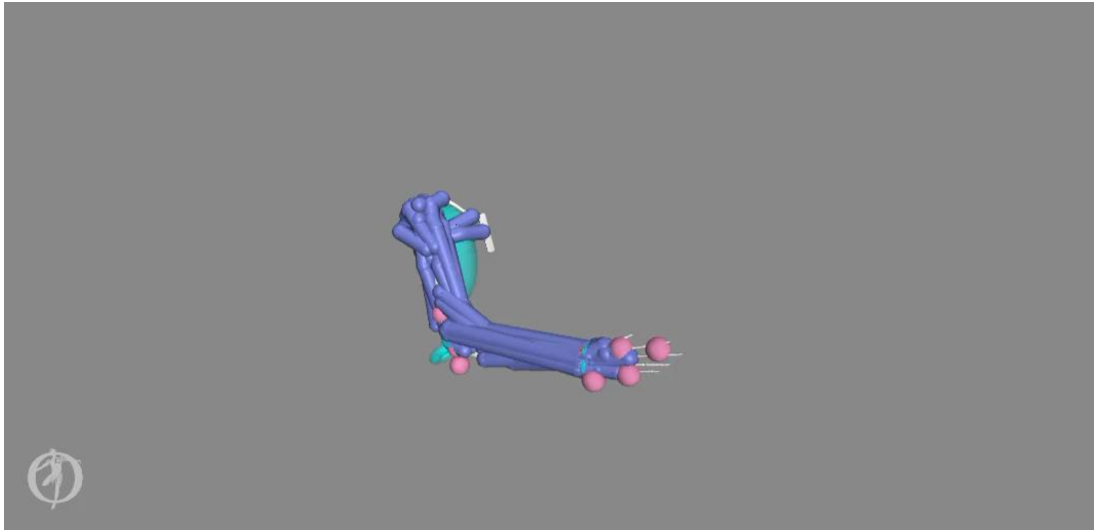
Joska et al. 2021
ICRA

- www.deeplabcut.org
- Active user community (i.e., help!)
- > 110 code contributors on GitHub
- > 800,000 downloads
- > 4,300 citations for Nat Neuro '18
- Used in over 1,000 labs and institutes around the world

Chan Zuckerberg Initiative

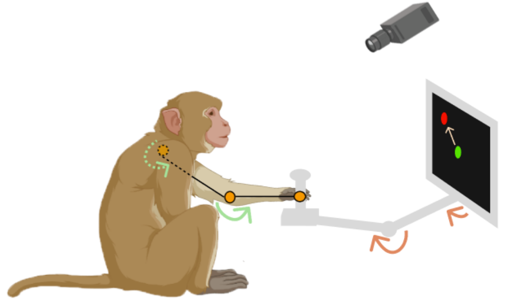
Nature Neuro 2018, Nature Protocols 2019, Neuron 2020, WACV 2021, ICRA, 2021, CVPR-W 2021, Nature Methods 2022, ICCV 2023, Nat Comms 2024

EXPERIMENTS TO TEST GENERALIZATION of the learned features



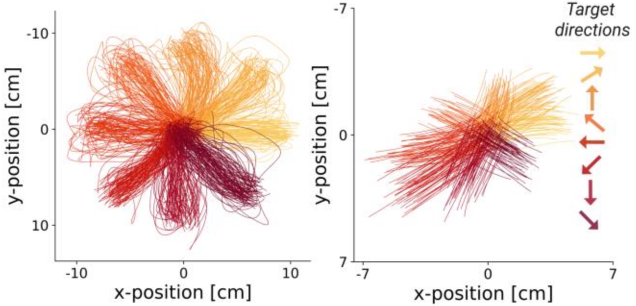
BEHAVIORAL EXPERIMENT

DeepLabCut
Mathis et al. Nat Neuro 2018



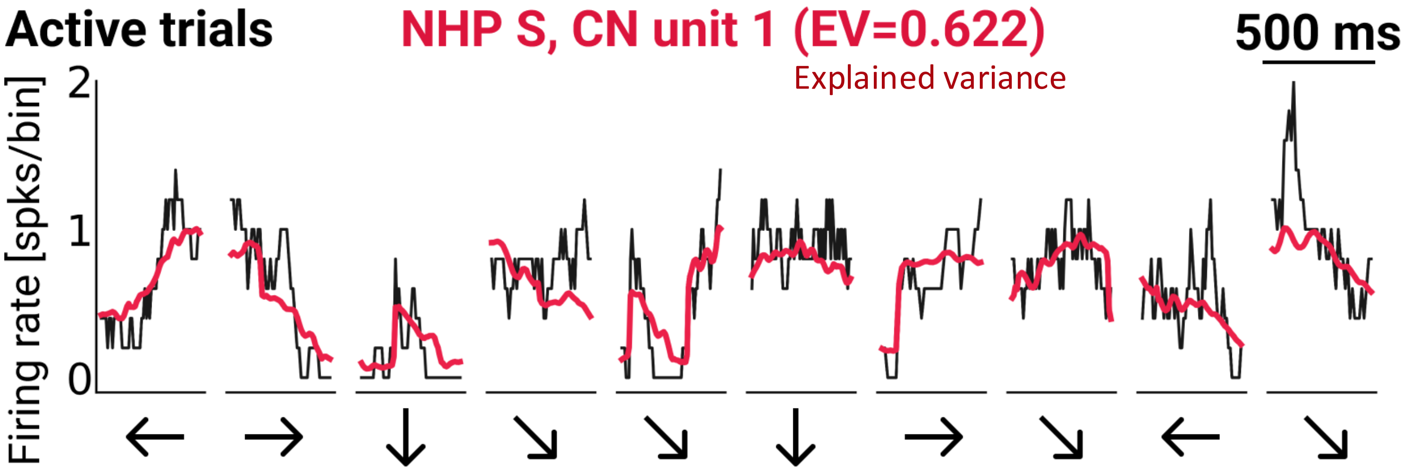
Joint pose estimation

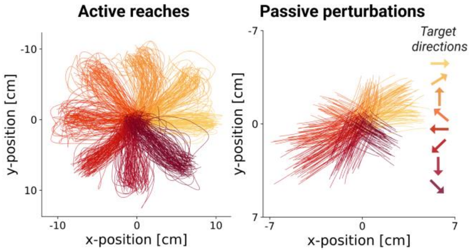
PASSIVE
ACTIVE



Data from **Lee Miller's Laboratory of Limb Motor Control,** Northwestern University, Chicago.

Task-trained models predict single neuron dynamics





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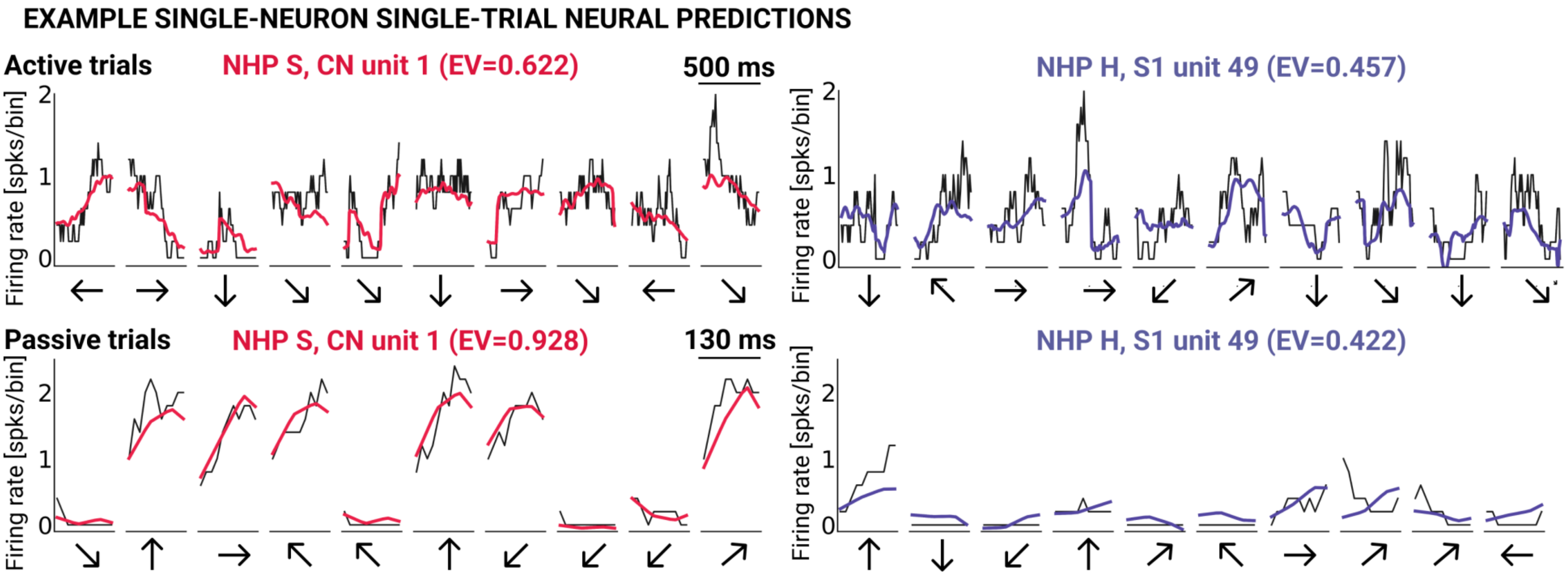
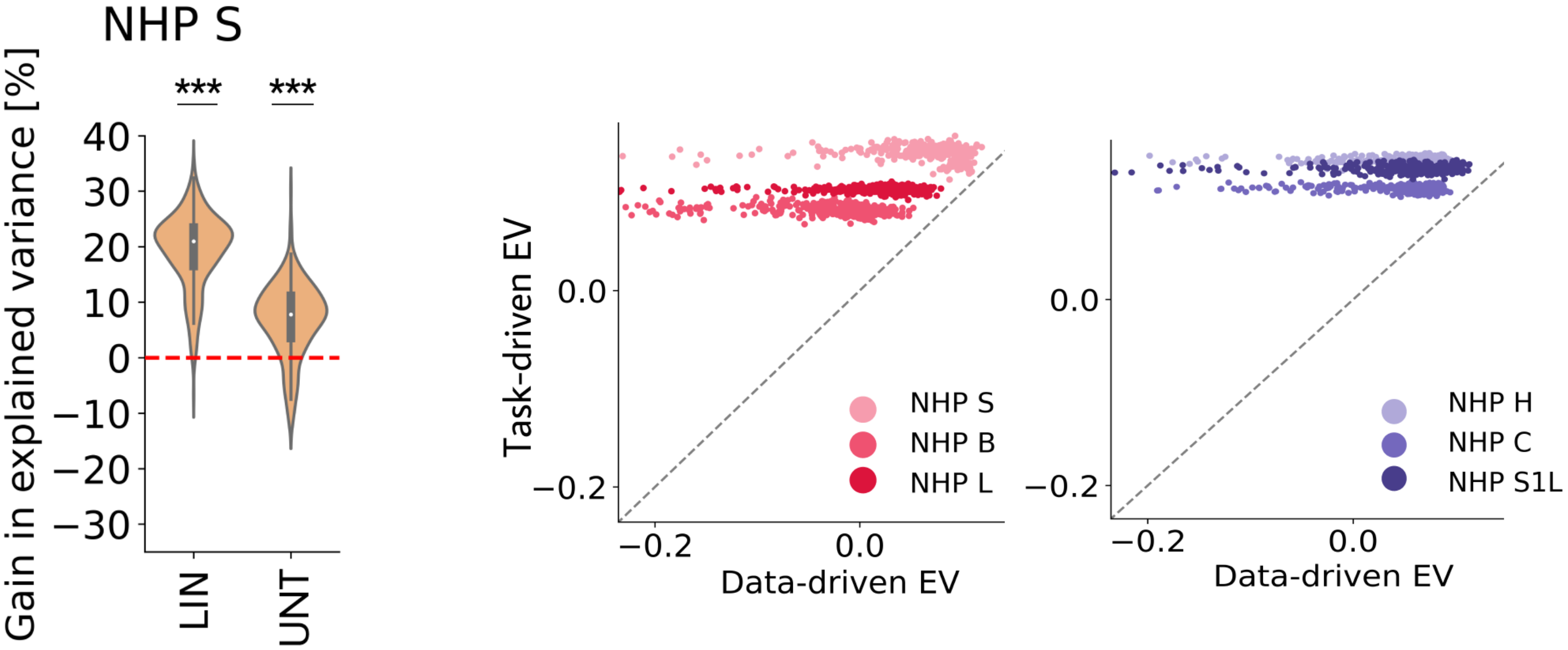
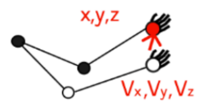
Task-trained models predict single neuron dynamics



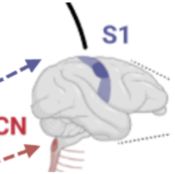
Task-trained models outperform linear, randomly initialized and data-driven models



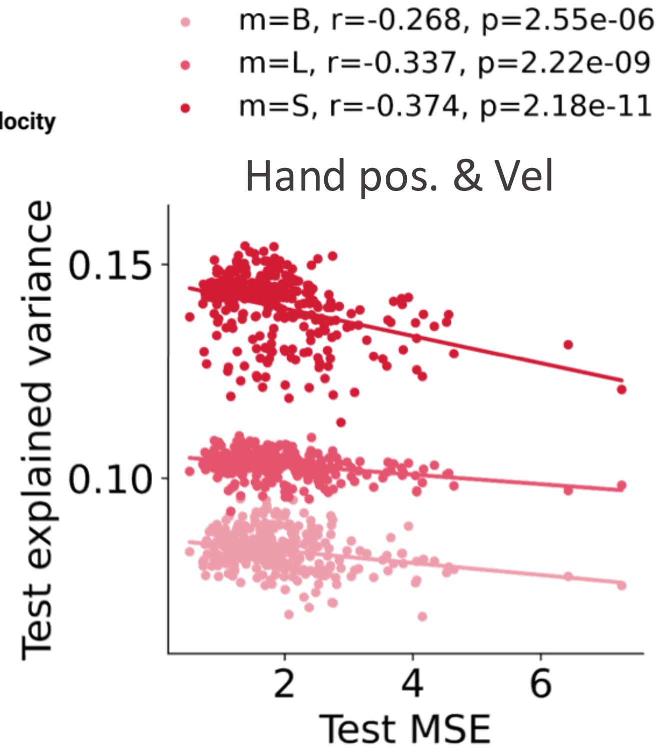
Task-performance and neural predictability are correlated

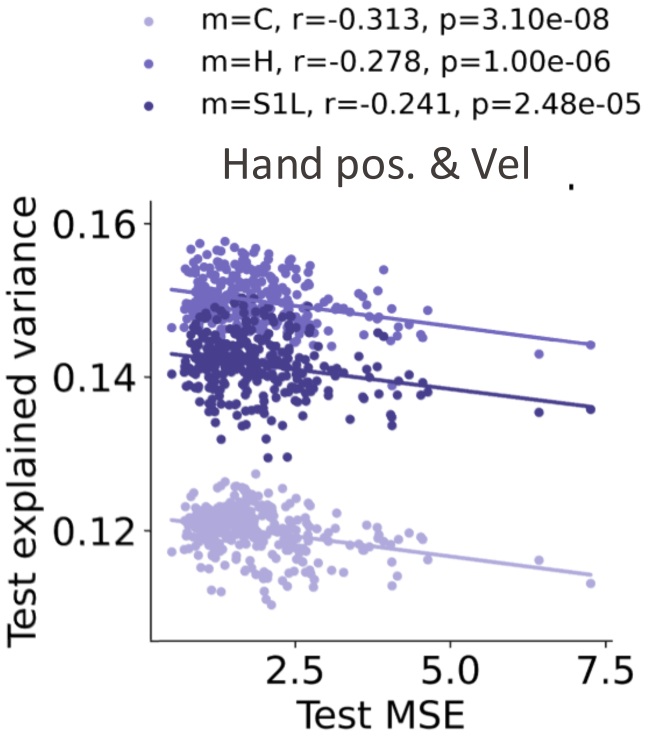


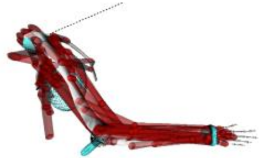
Hand position and velocity task (HP & HV)



Generalization to brain





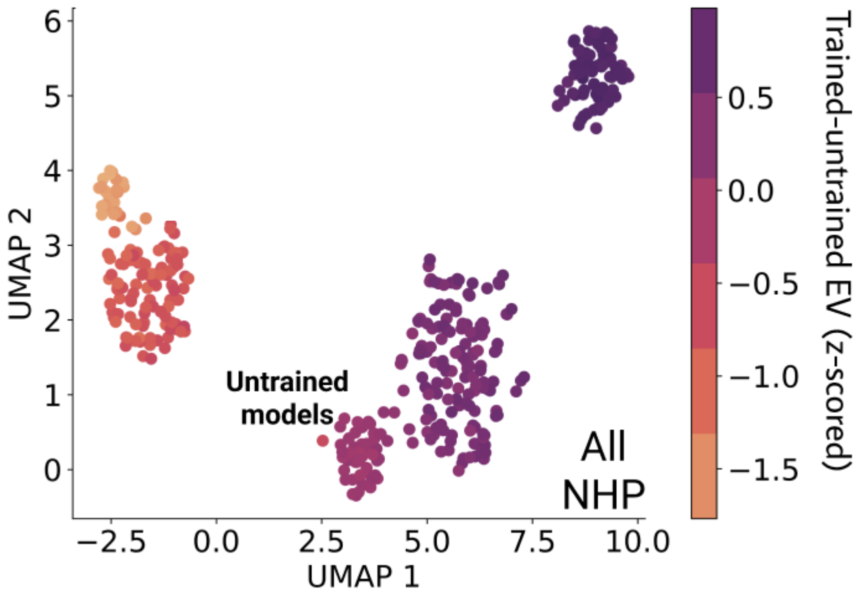


Optimized on biomechanics (body)

Different model architectures

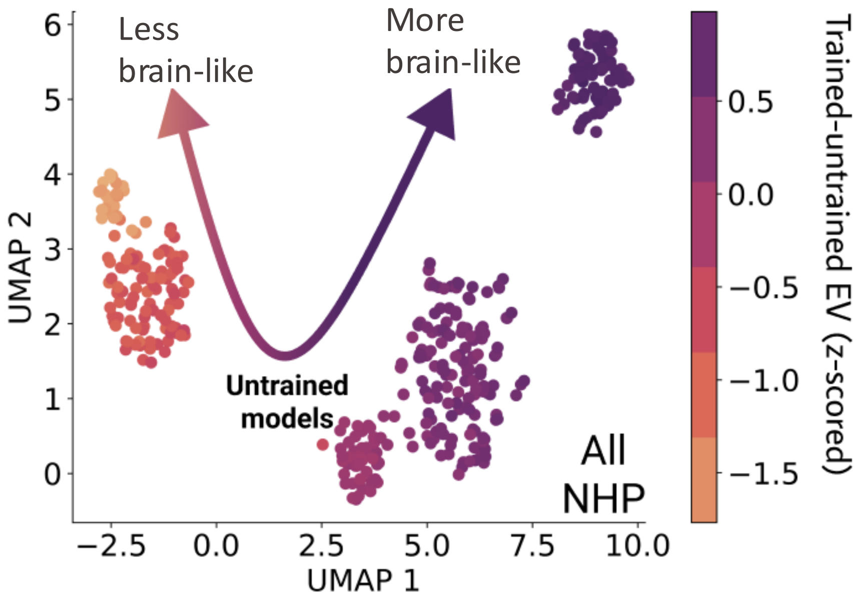
Unsupervised hypothesis comparison

ACTIVE



Unsupervised hypothesis comparison

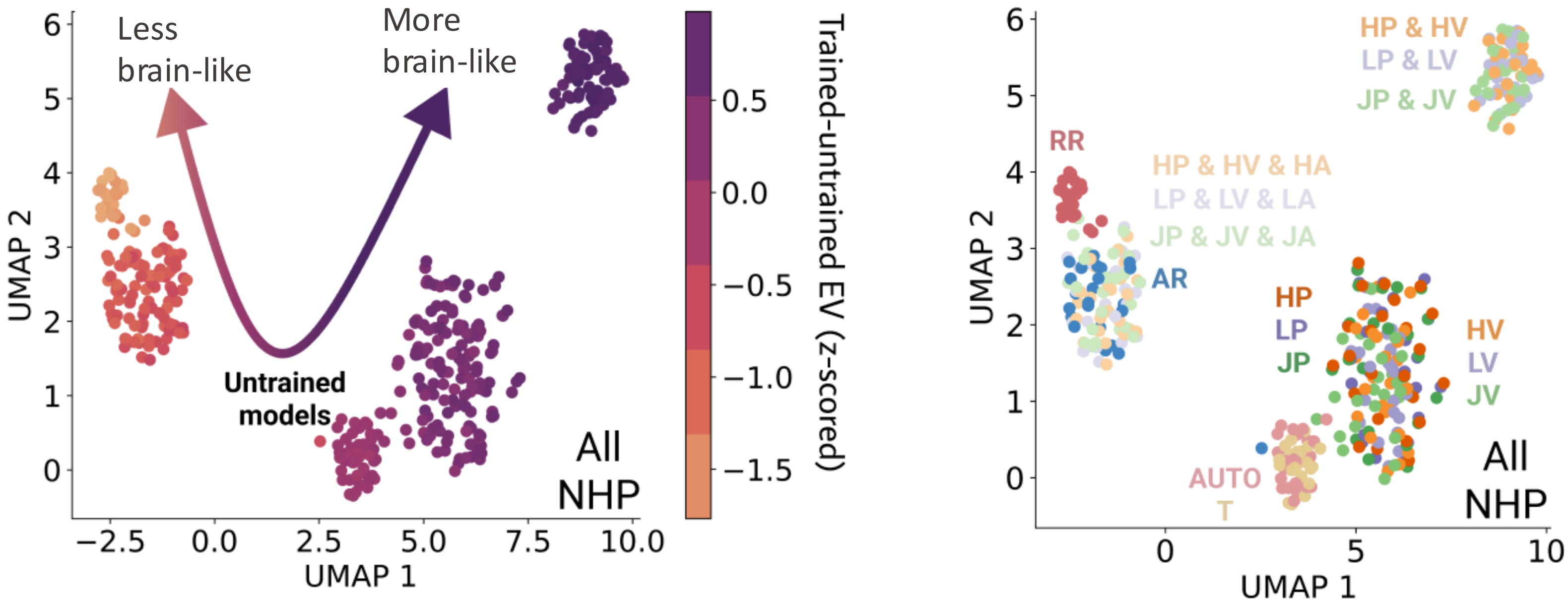
ACTIVE



Unsupervised hypothesis comparison

ACTIVE

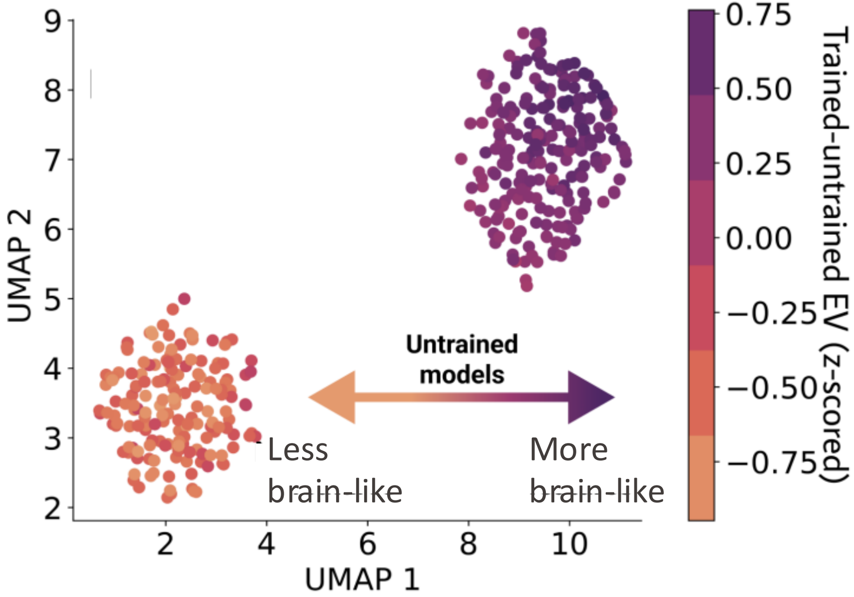
HP = Hand position
HV = Hand velocity
HA = Hand acceleration
LP = Limb position
LV = Limb velocity
LA = Limb acceleration
JP = Joint position
JM = Joint velocity
JA = Joint acceleration
RR = Redundancy Reduction
AUTO = Autoencoder
AR = Action Recognition
T = Torque

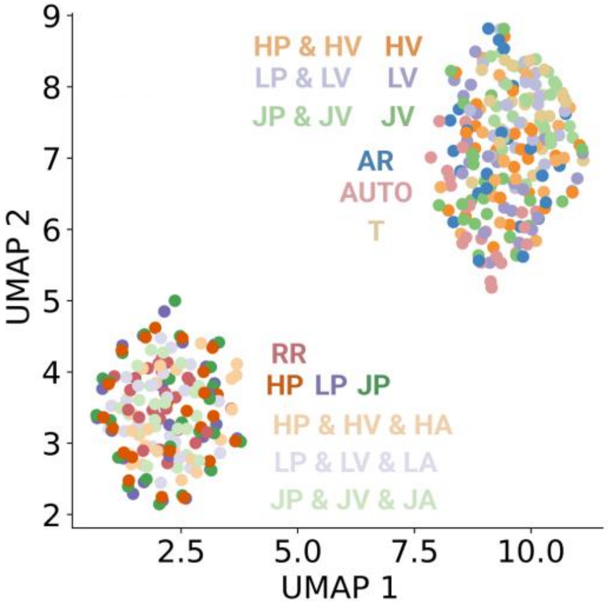


Unsupervised hypothesis comparison

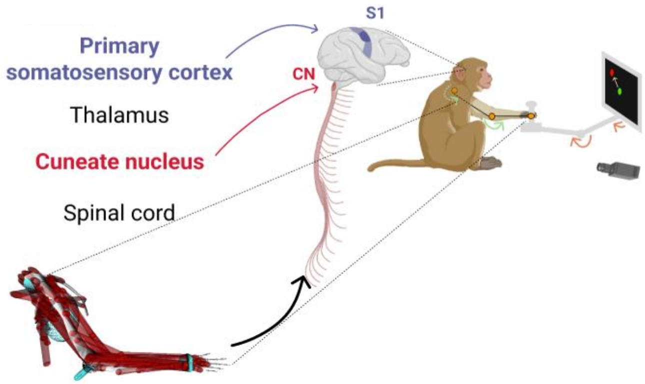
PASSIVE

HP = Hand position
HV = Hand velocity
HA = Hand acceleration
LP = Limb position
LV = Limb velocity
LA = Limb acceleration
JP = Joint position
JM = Joint velocity
JA = Joint acceleration
RR = Redundancy Reduction
AUTO = Autoencoder
AR = Action Recognition
T = Torque



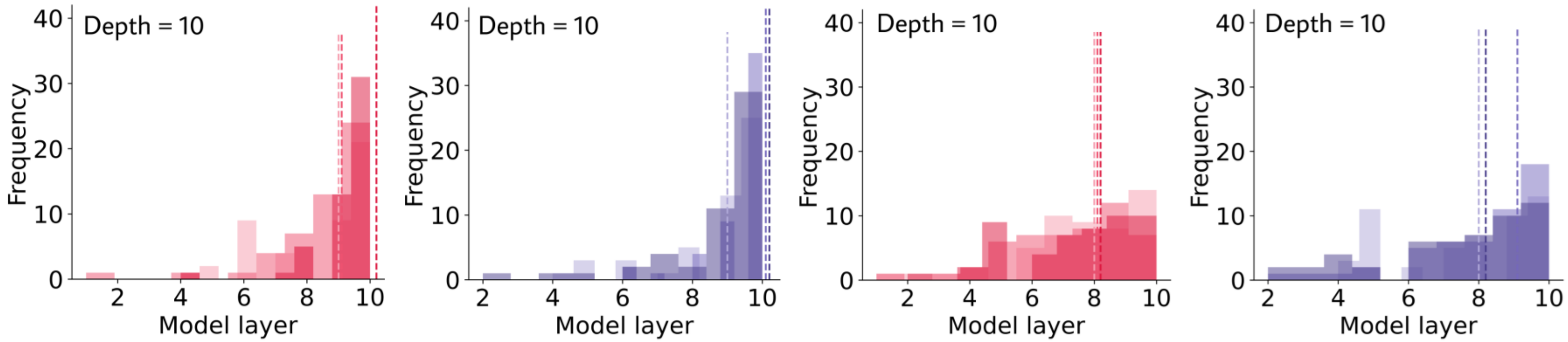


Lack of hierarchical representation



active

passive



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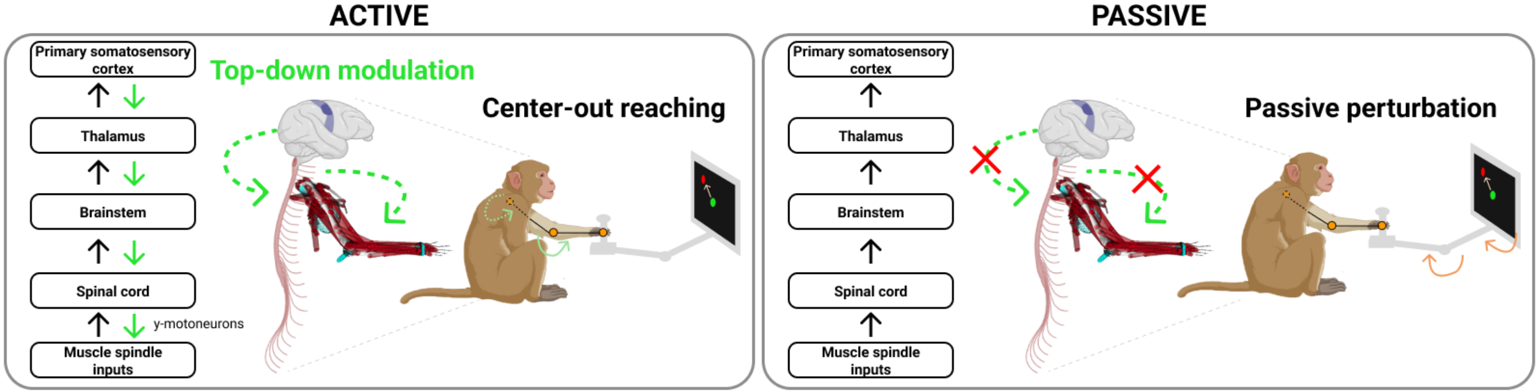
Discussion

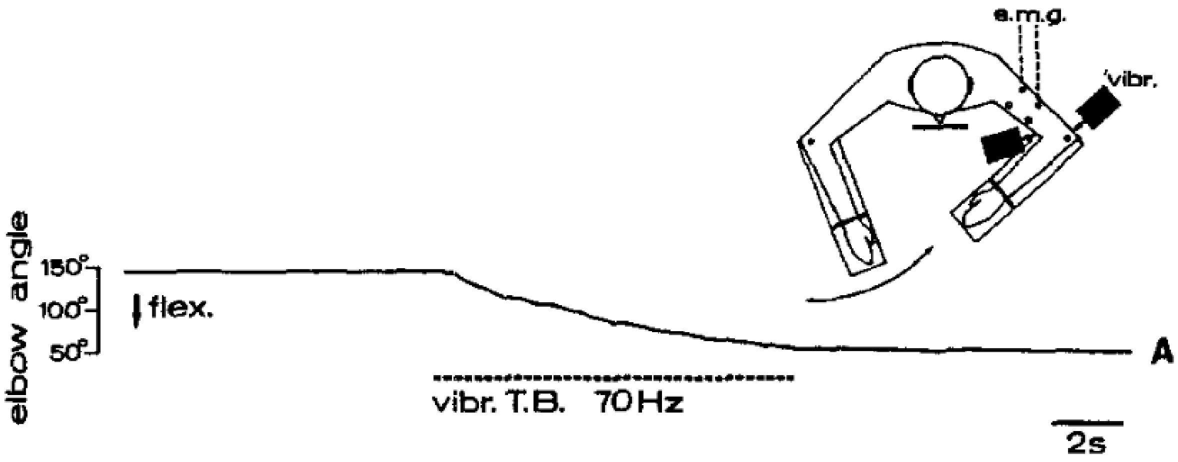
- For all 16 hypotheses, if a *computation* is better learned on synthetic, passive spindle data, then the model also generalizes better to neural data
- Neural data (*in the active case*) is best explained by the **hypothesis that proprioception is optimized to encode the location and velocity of the body** (irrespective of coordinate framework)
- Lack of evidence for hierarchical processing; this suggests that proprioception even in the brain stem is dominated by efference copies



Quaedam sunt in intellectu non prius in sensu. -- cf: *H Charlton Bastian. Brain, 1887.*

Proprioceptive illusions

Illusions of movement with muscle-tendon vibrations



Roll and Vedel Exp Brain Research. 1982

Effect on afferent firing rate

J.P. Roll and J.P. Vedel: Muscle Spindle Contribution to Kinaesthesia 183

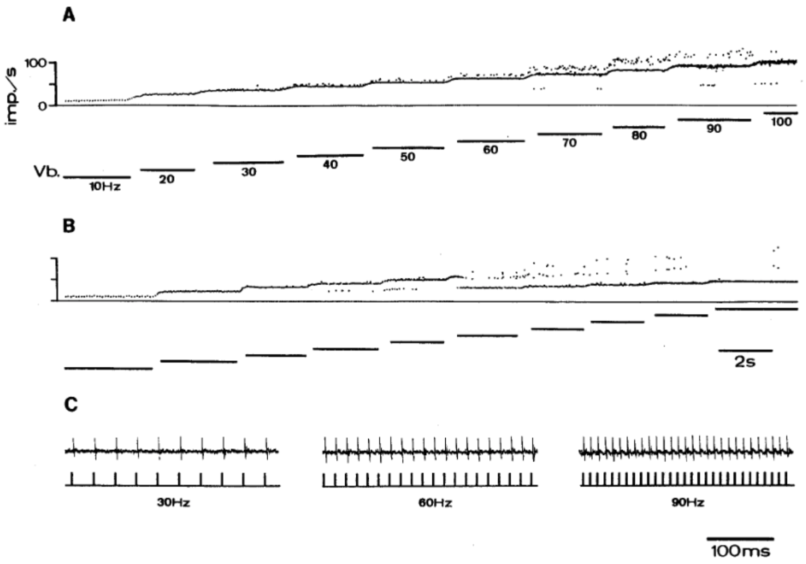


Fig. 4A–C. Driven activity (instantaneous frequency) of a spindle primary ending by mechanical vibration applied to the tendon of the receptor-bearing muscle (TA). **A** Optimal primary ending activation by tendon vibration from 10 to 100 Hz. **B** The same primary ending can eventually respond by a sub-harmonic discharge frequency to a particular vibration frequency (60 Hz in the example). **C** One-to-one primary ending responses to 30, 60, and 90 Hz tendon vibration

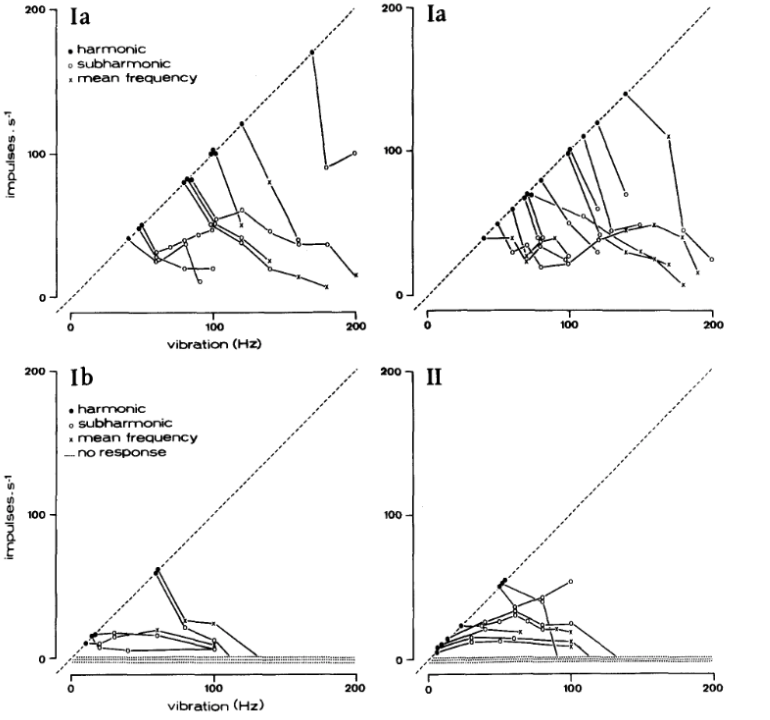
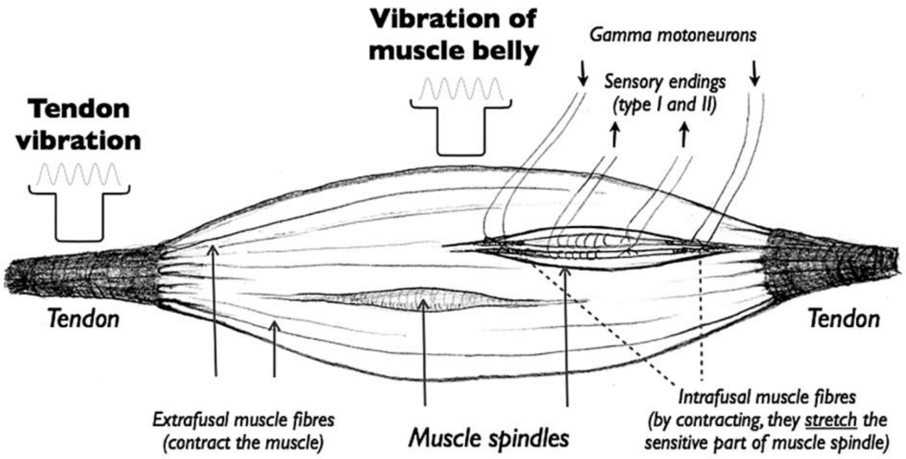


Fig. 1. Driving modalities of muscle spindle primary (Ia) and secondary (II) endings and tendon organ (Ib) activities induced by mechanical

Roll & Vedel. Exp Brain Research. 1982

Roll, Vedel, and Ribot. Exp Brain Research. 1989

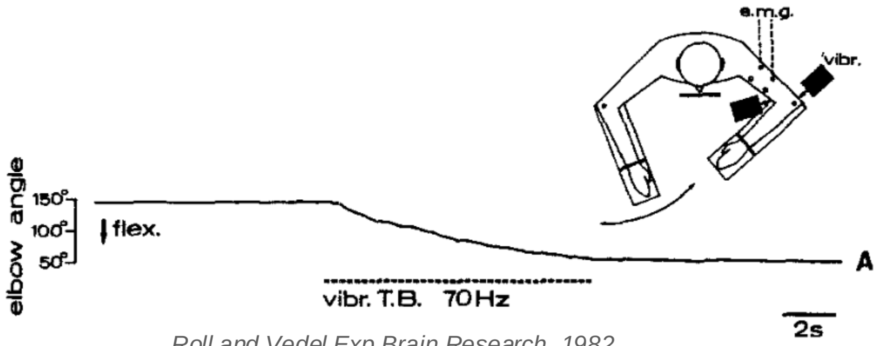
Details of vibration-induced illusions



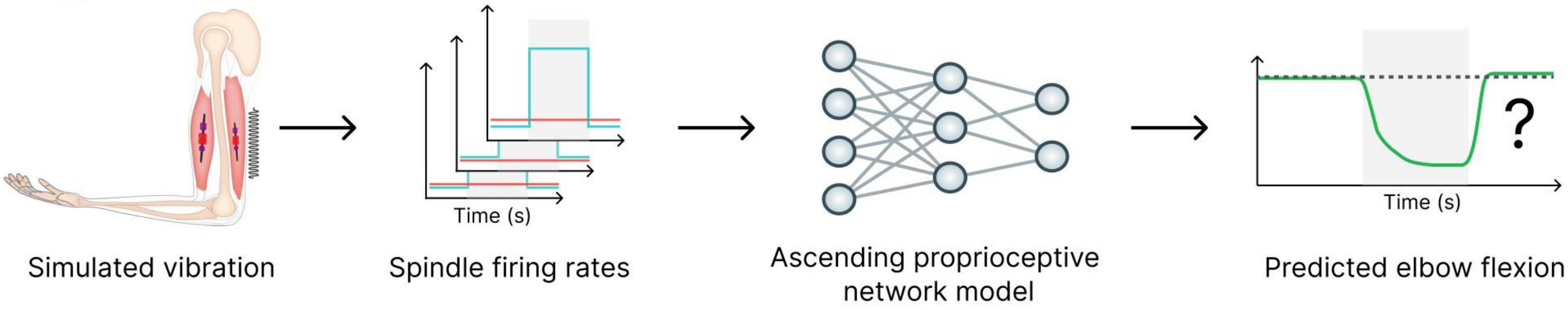
- Vibration over the tendon or muscle belly at ~100Hz
- Vibrations mainly affect Ia afferent output
- Limb muscle vibration creates an illusory limb movement in the direction corresponding to lengthening of the vibrated muscle.

Taylor, Taylor, Seizova-Cajic. Multisensory Research, 2017

Studying the effect of tendon vibrations



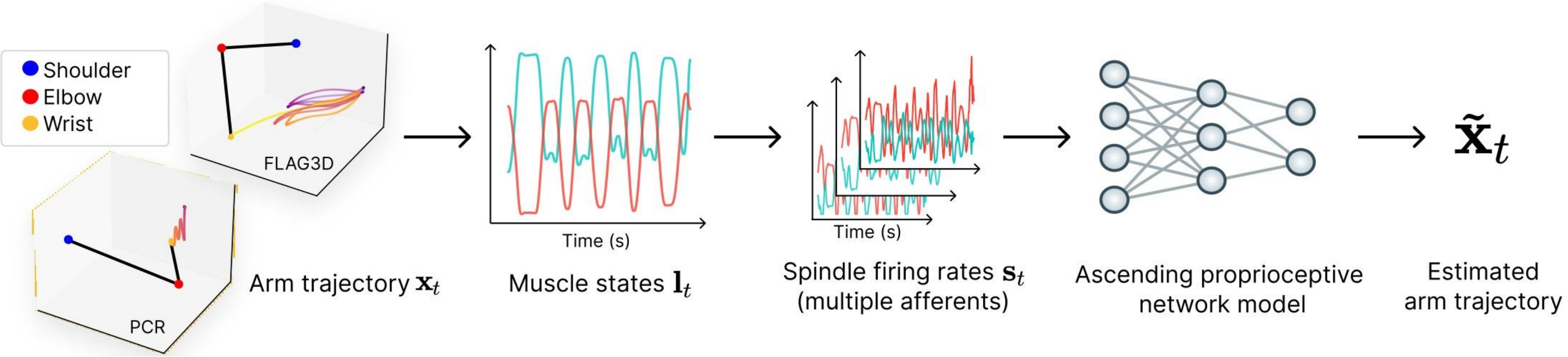
Roll and Vedel Exp Brain Research. 1982



Modeling proprioceptive perception

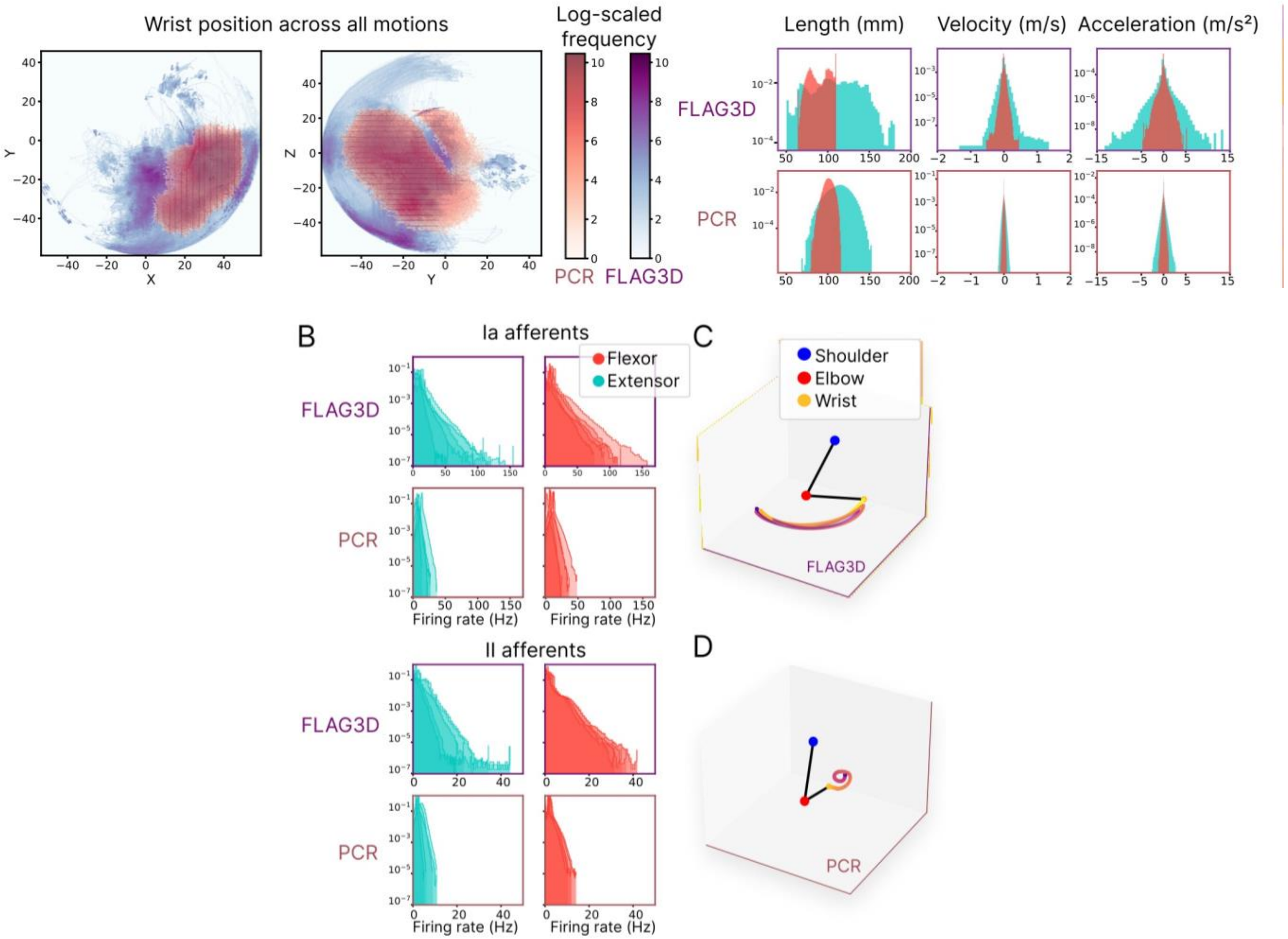
Adriana
Perez Rotondo

Merkourios Simos



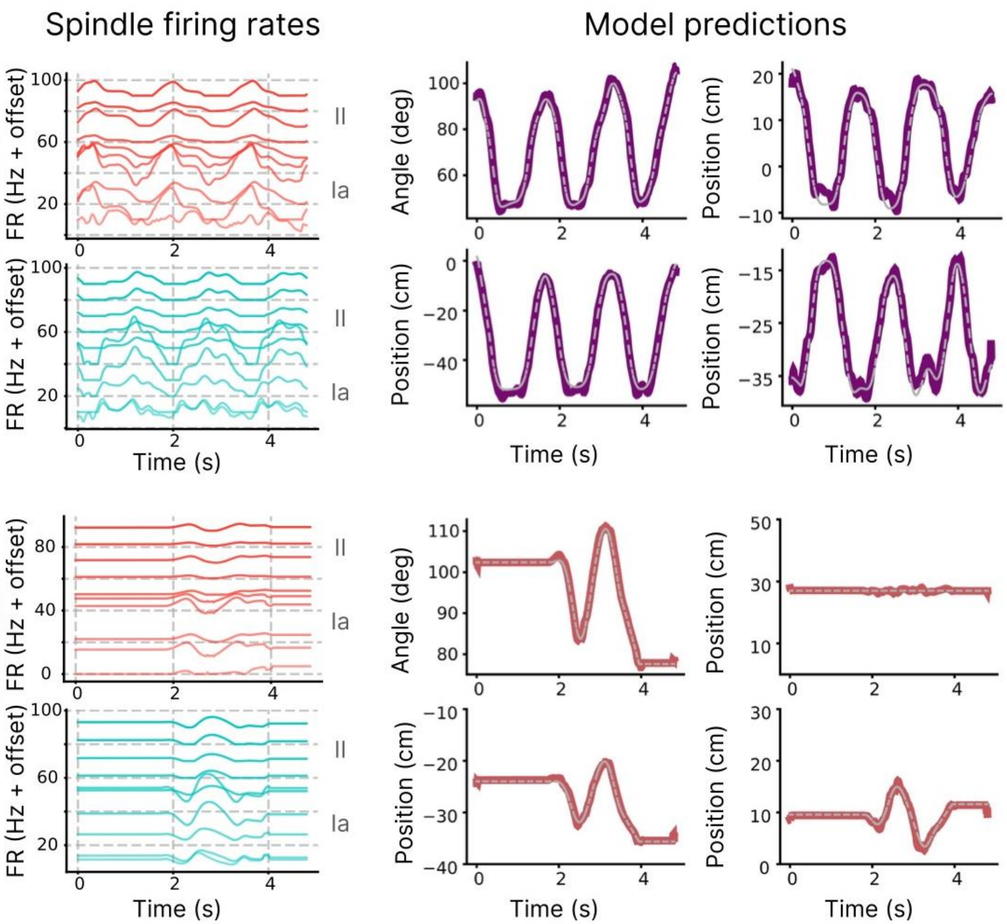
Perez Rotondo A., Simos* M., David F., Pigeon S., Blanke, O., Mathis A. Experimental Physiology (in press) and BioRxiv 2025*

Dataset statistics

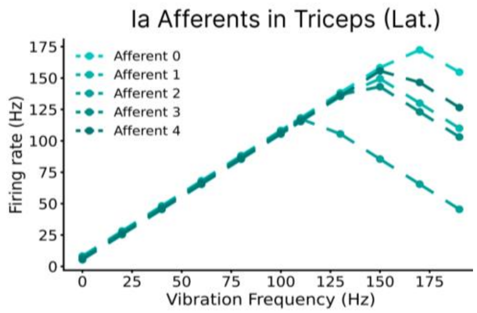


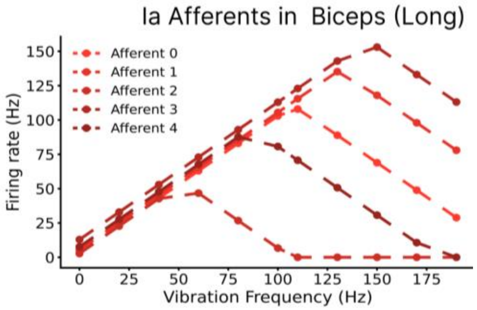
Adriana Perez Rotondo

Model predictions



Modelling tendon vibrations





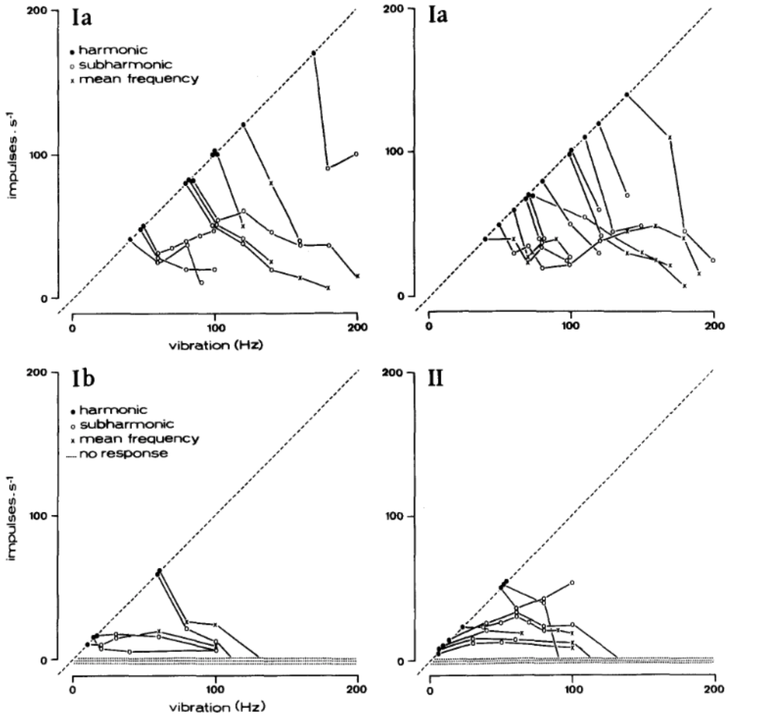
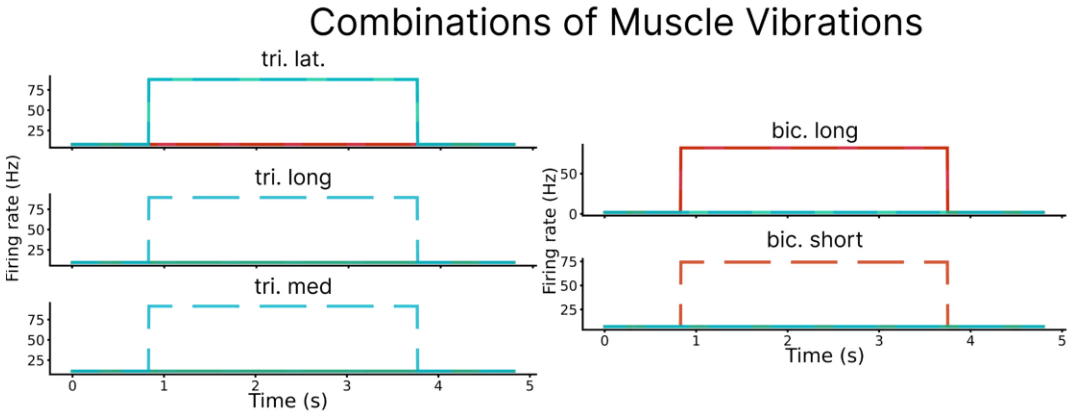


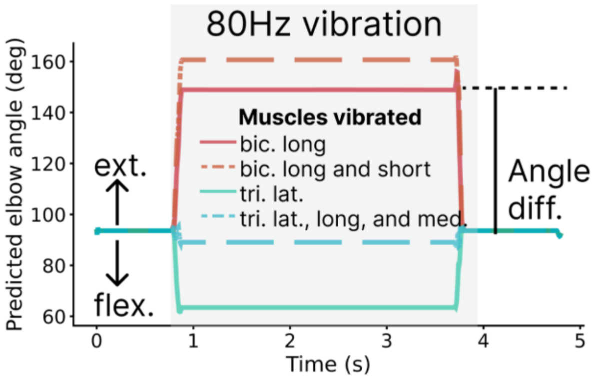
Fig. 1. Driving modalities of muscle spindle primary (Ia) and secondary (II) endings and tendon organ (Ib) activities induced by mechanical

Perez Rotondo A., Simos* M. et al. 2025*

Roll , Vedel, and Ribot. Exp Brain Research. 1989

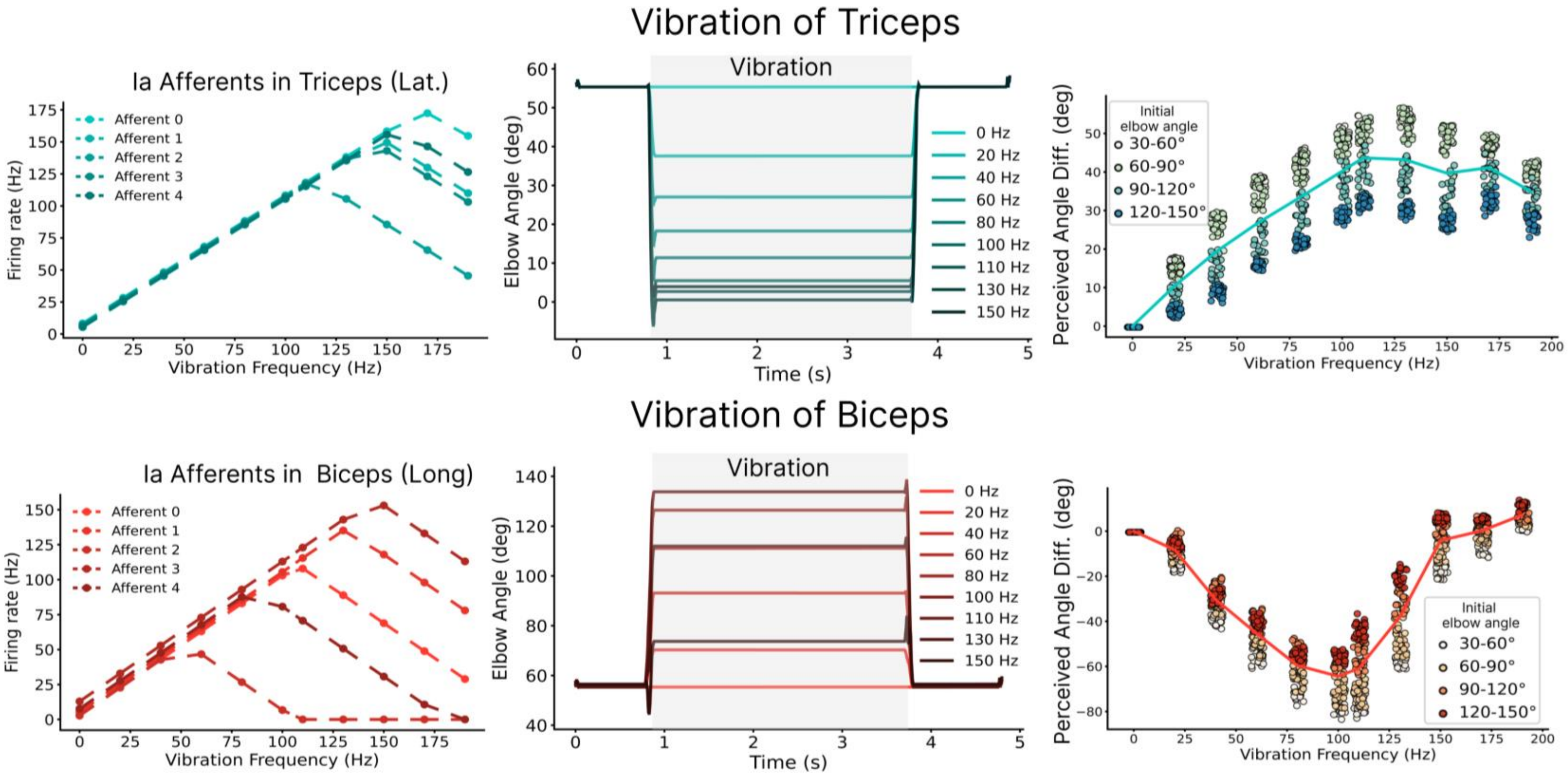
Effect of (simulated) vibrations





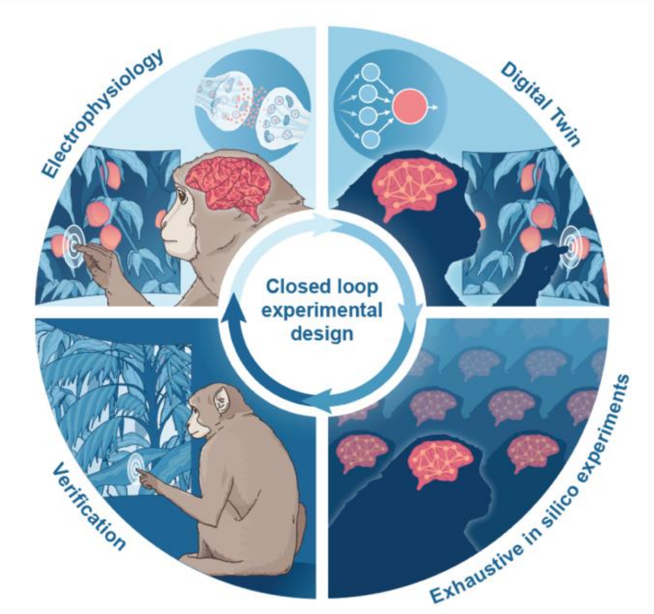
Perez Rotondo A., Simos* M., David F., Pigeon S., Blanke, O., Mathis A. Experimental Physiology (in press) and BioRxiv 2025*

Effect of simulated vibrations



Statistical models

- We can build powerful models (data-driven or task-driven)
- We can compare hypotheses and scaling of models (*why* questions)
- Enables novel experiments (behavioral, physiology …)



M. Mathis, Perez Rotondo, Cheng, Tolias, Mathis Cell 2024

Take-home messages

- To study proprioception: we combined biomechanics, representation learning & neural data analysis.
- Networks trained on synthetic (muscle) data generalize to predict single-trial neural activity in the brain stem and cortex of primates performing limb center-out movements
- Architectures that are better at solving the tasks are also better at predicting the neural data.
- Models trained to predict the limb position and velocity were the best to predict neural activity. Note this could be supervised by vision.
- Thus, task-driven modeling allowed us to test multiple hypotheses
- Task-trained models are also susceptible to proprioceptive illusions
- NOTE: We simplified the system by *purposefully* isolating the sensory part of proprioception