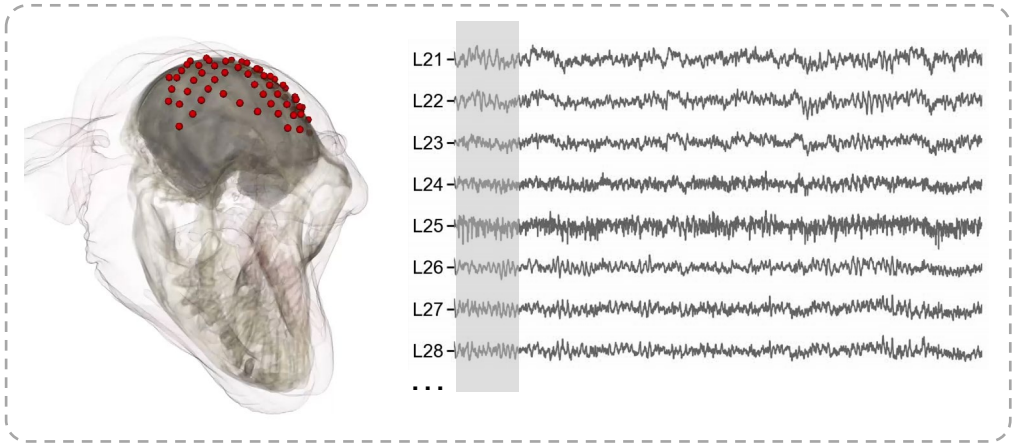


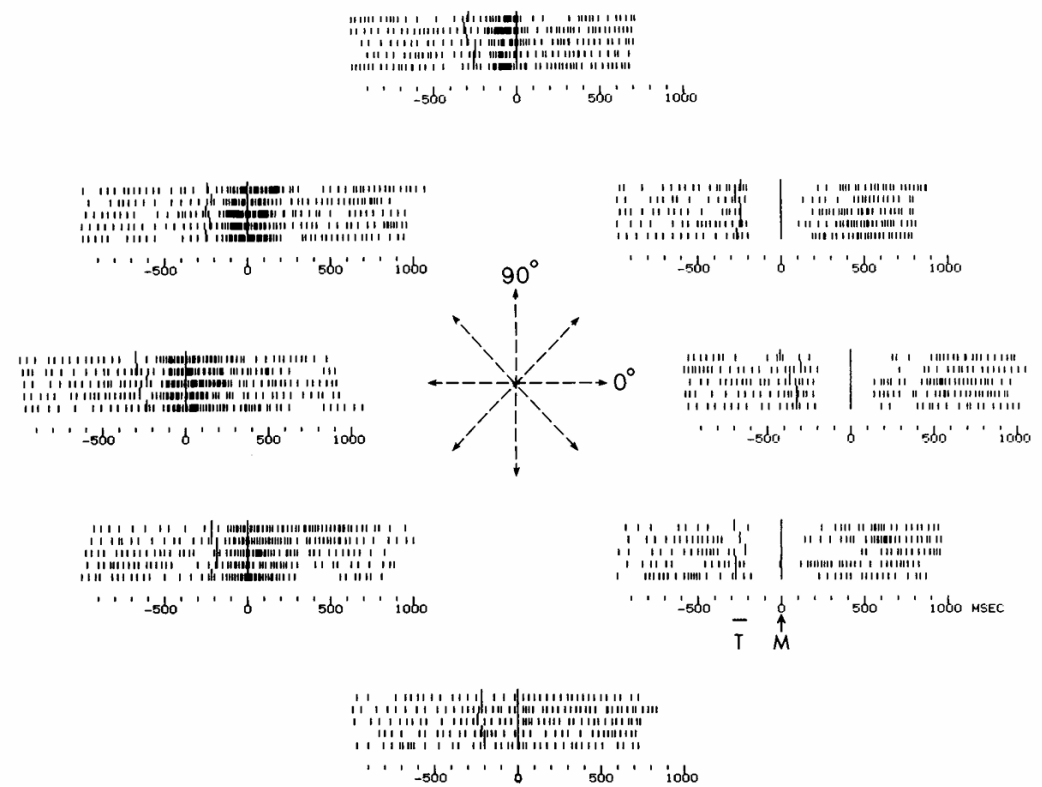
Neural-Behavioral Representation of Natural Whole-body Movement in Monkeys

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Decoding monkey upper-limb movements from motor neuron activity

- Motor neurons exhibited directional selectivity
- We can decode upper-limb movements from neural activity and thus control a robotic arm



Directional selectivity of motor neuron

Georgopoulos A P, Kalaska J F, Caminiti R, et al.
The Journal of neuroscience, 1982.

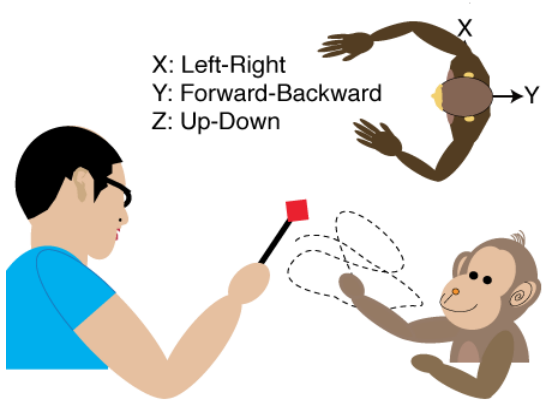


Control robotic arm using motor neuron

Velliste M, Perel S, Spalding M C, et al.
Nature, 2008.

Decoding natural whole-body movements poses challenges

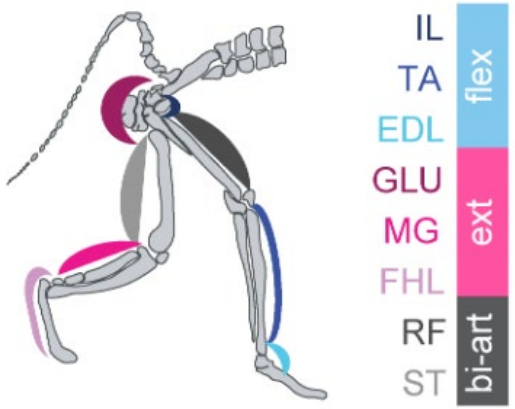
Upper limb





Chao Z C, Nagasaka Y, Fujii N. *Frontiers in neuroengineering*, 2010.

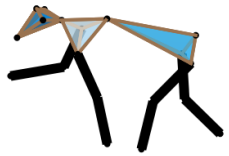
Lower limb





Borgognon S, Macellari N, Hickey A M, et al. *Nature communications*, 2025.

Whole body



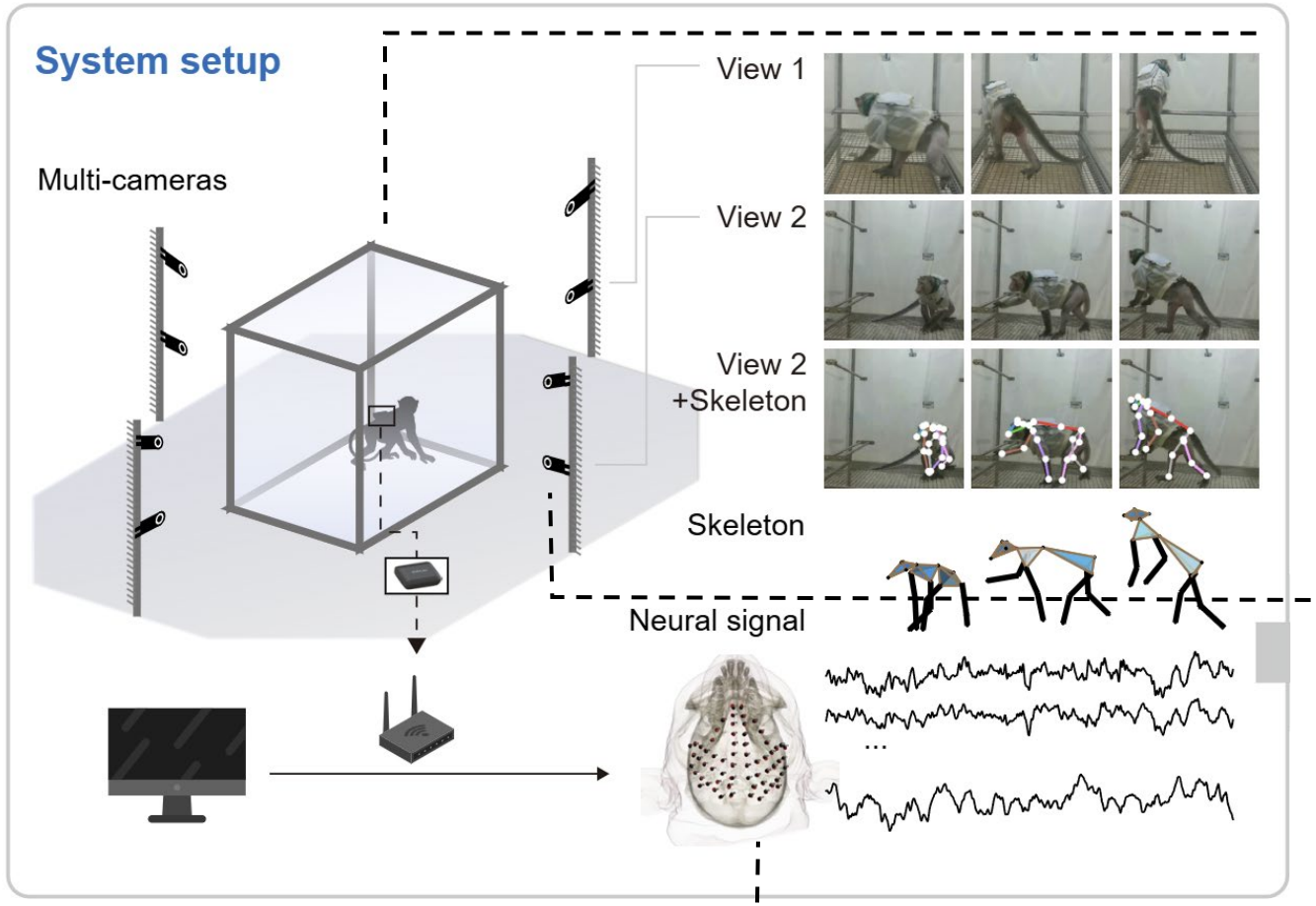
Head
Shoulder
Knee
…



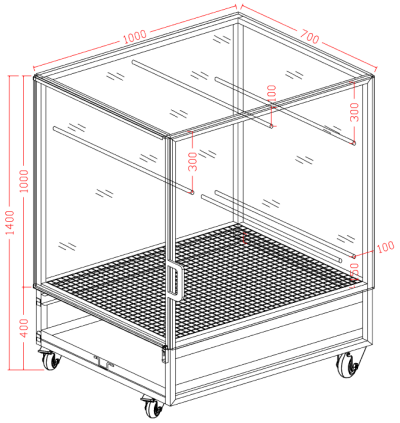
Ours

- **Richer** behavioral patterns
- **Higher-dimensional** output space
- **Artifacts** into neural recordings

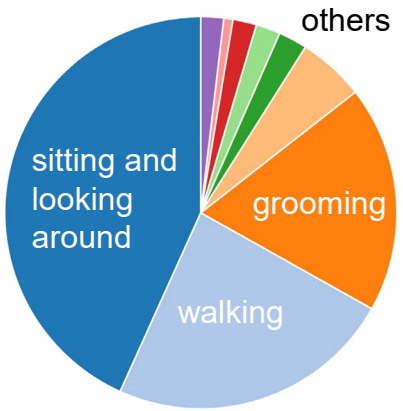
Setup synchronously captures distributed cortical activity and multi-view 3D whole-body kinematics in freely moving monkeys



- Behavior



Designed cage



Movement ethogram

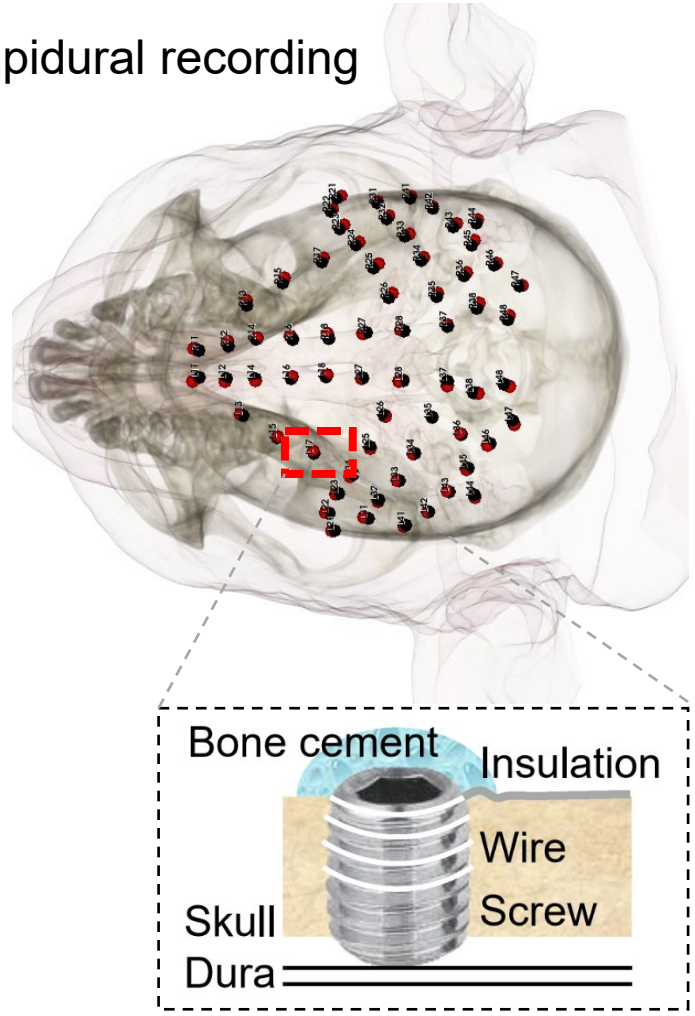
- 8 synchronized camera
  - 30 Hz, 720p

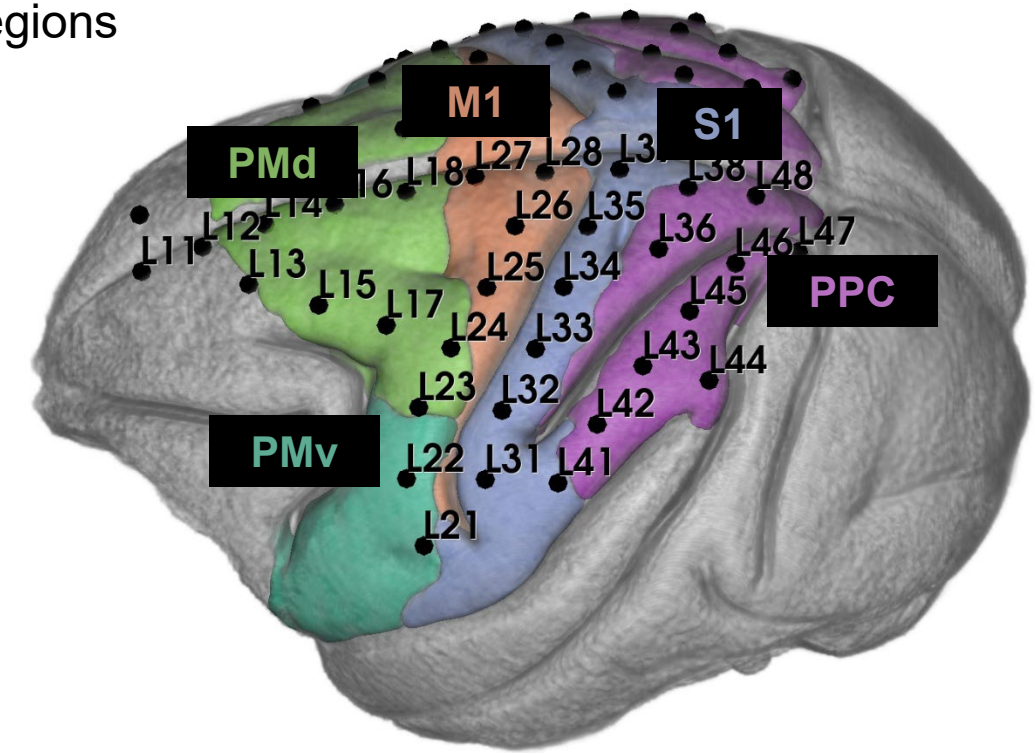
- 62 channel epidural recording
  - 2000 Hz

Location design & surgery

- The electrodes contacted the dura surface to record epidural signals
- 62 electrodes across multiple movement-related cortical regions

Epidural recording

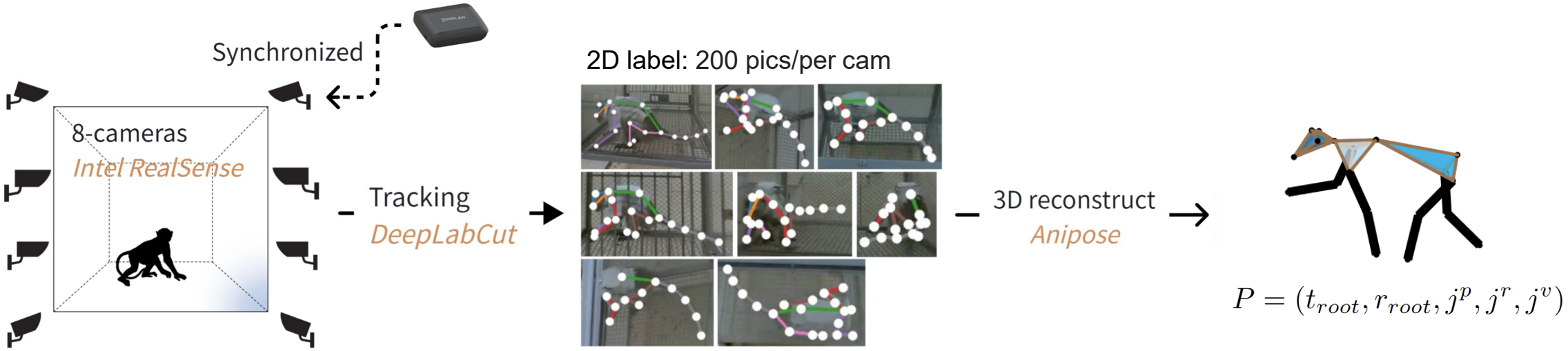




M1: Primary motor cortex
S1: Primary somatosensory cortex
PMd: Dorsal premotor cortex
PMv: Ventral premotor cortex
PPC: Posterior parietal cortex

A setup for capturing 3D kinematics of monkeys

- 8 cameras record simultaneously
- The video recordings are synchronized with the neural recordings
- Two-stage model for keypoint tracking
- Redundant kinematic representation to help the model learn a robust motion prior

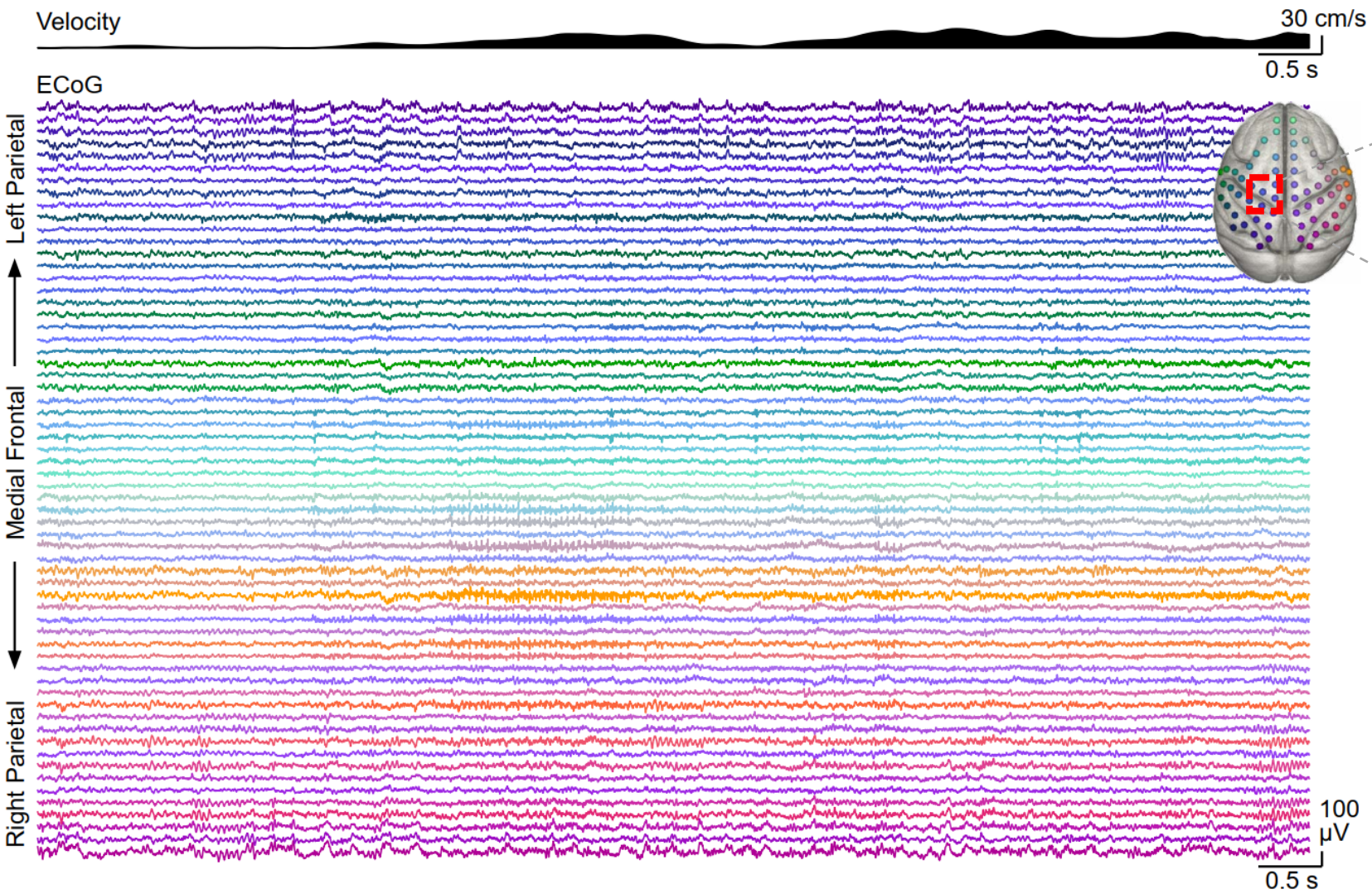


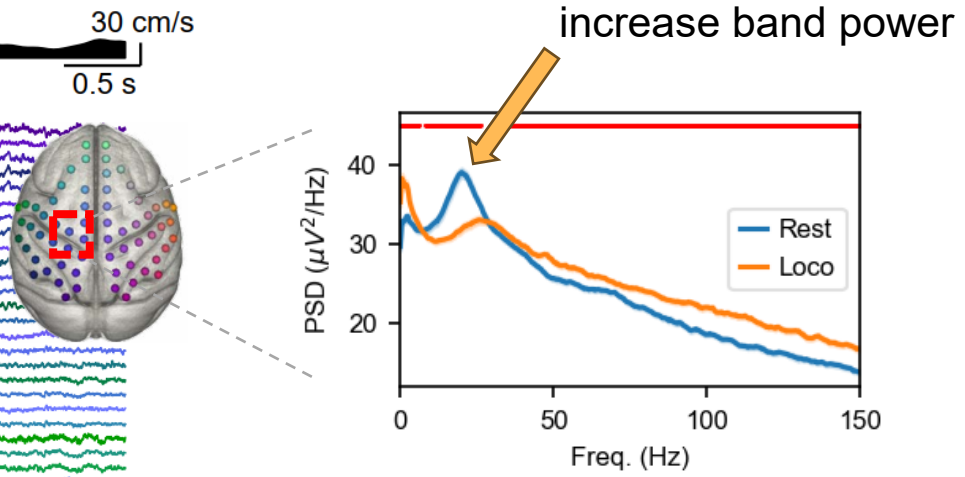
Synchronized camera

2D tracking

3D kinematic

The recorded signals are minimally affected by movement artifacts

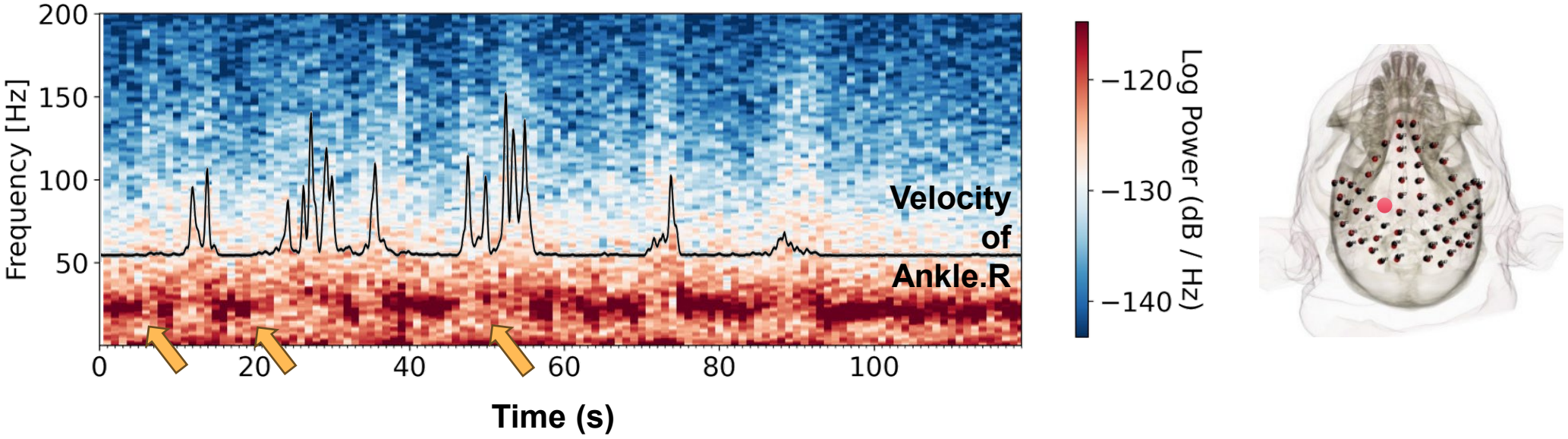




- No obvious motion artifacts
- A clear increase in α- and β-band power of M1 electrodes

Natural movements introduce abundant spontaneous neural activity

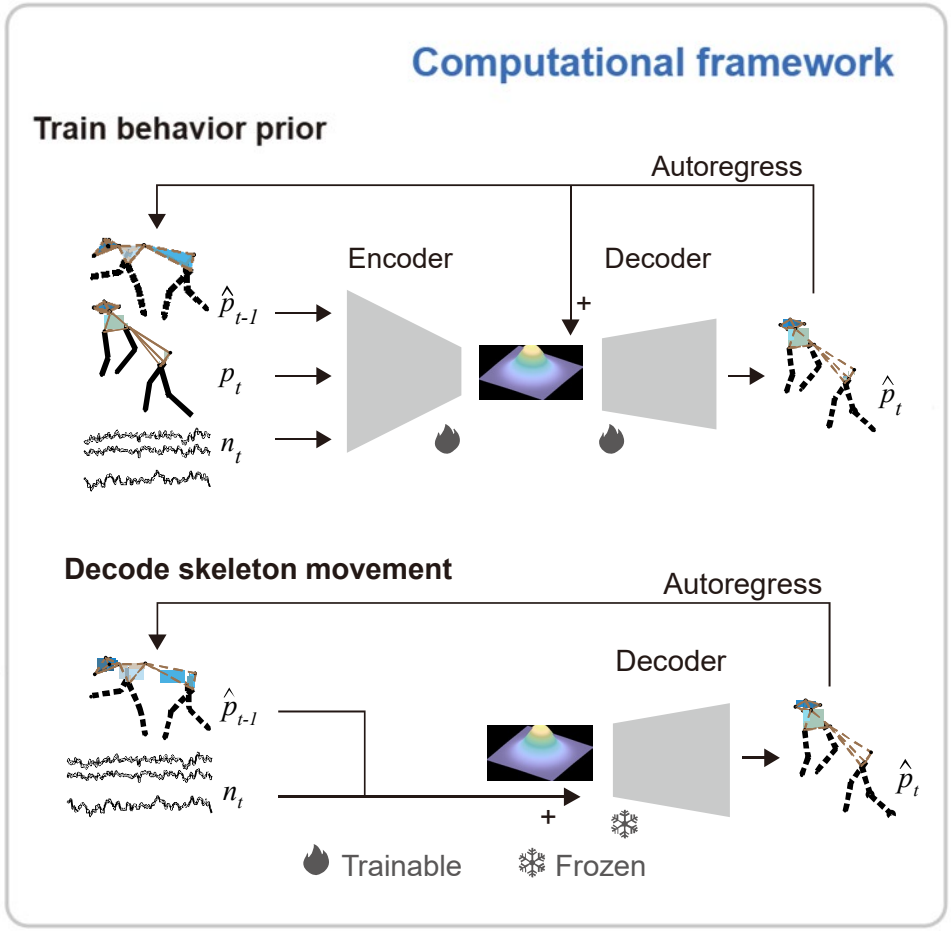
- Beta-band de-synchronization and gamma-band synchronization were not consistently observed



- Around 7 s and 22 s, no clear synchronous activity was observed
- During 50–55 s, the time–frequency features failed to capture rapid transitions

Using neural signals to guide the generation of monkey movements

- Predicted eight time steps during training
- Predicted with decoder only during testing



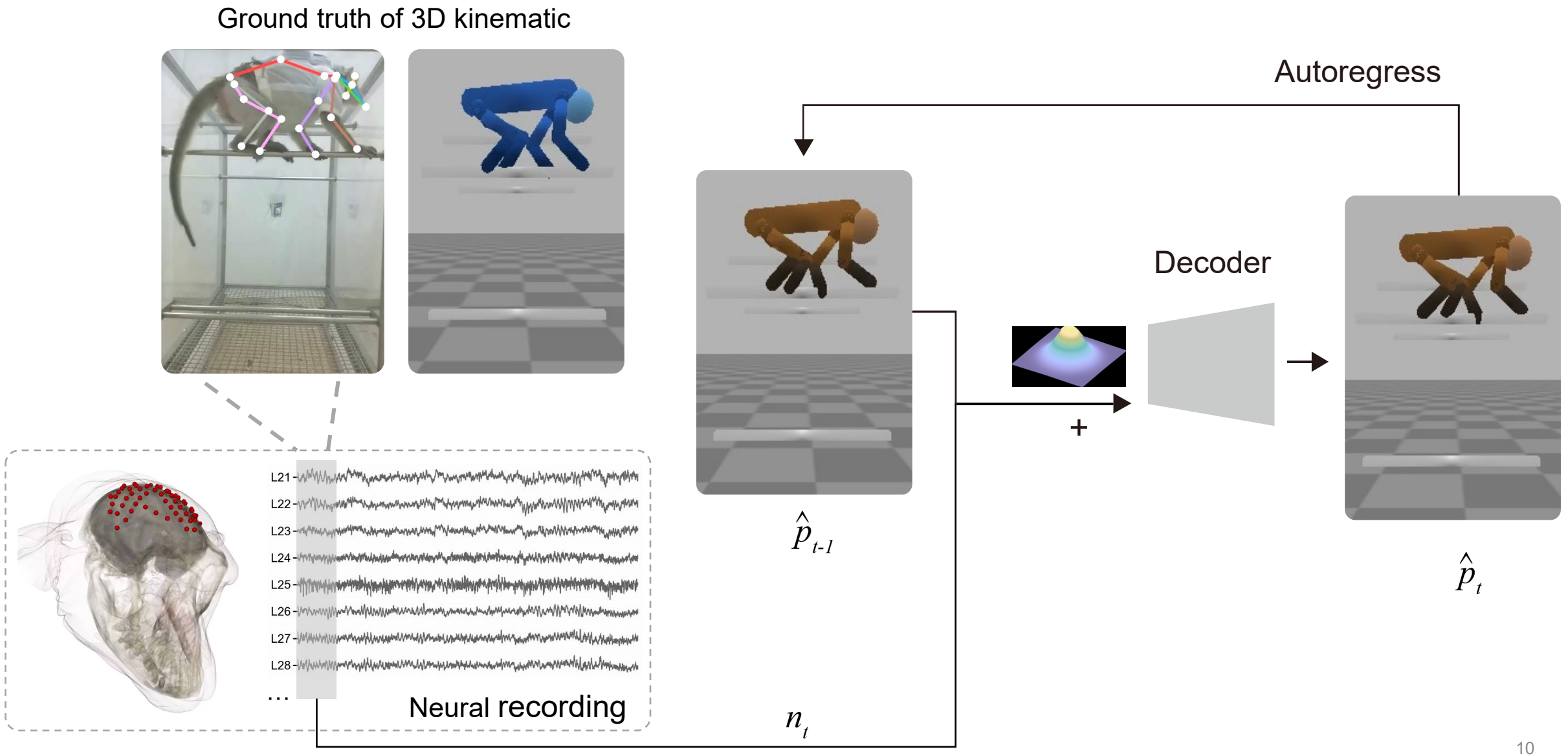
Neural-Behavioral Model:

$$P_\theta(p_0, p_1, ..., p_t) = P_\theta(p_0) \prod_{t=1}^{T} P_\theta(p_t \mid p_{t-1}, n_t)$$

$$P_\theta(p_t \mid p_{t-1}, n_t) = \int P_\theta(z_t \mid p_{t-1}, n_t)\, P_\theta(p_t \mid z_t, p_{t-1}, n_t)\, dz_t$$

p_t: predicted behavior
p_{t-1}: current behavior
n_t: current neural activity
z_t: latent variable

Reconstructing whole-body movements from neural signals



Performance evaluation

We evaluated the model's performance on the test sets of both monkeys

- Behavioral Model: The same architecture as the Neural-Behavioral Model, but without neural inputs n_t
- The Neural-Behavioral Model outperformed the Behavioral-only and LSTM Model

Monkey A

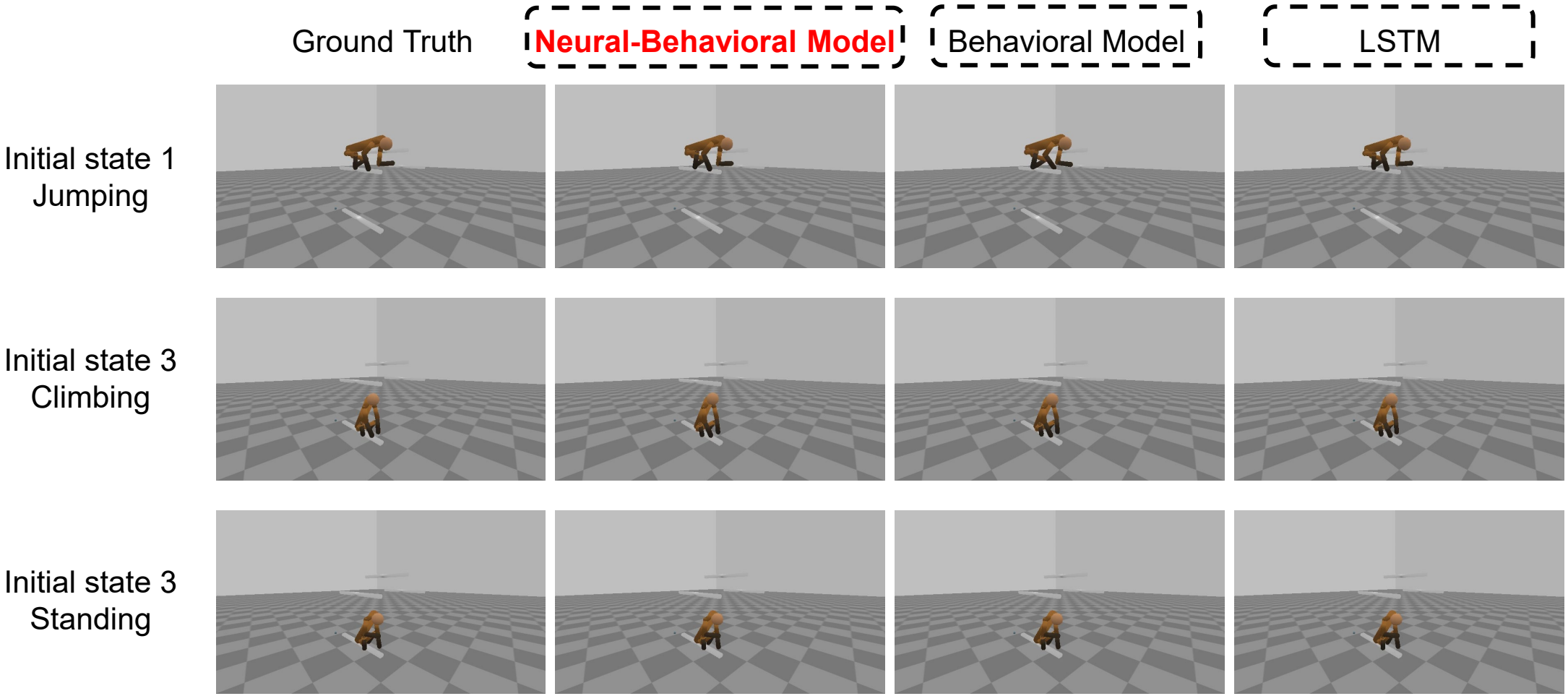
Model	Horizontal movement			Vertical movement		
	ADE	FDE	r	ADE	FDE	r
Neural-Behavioral	**6.97**	**14.94**	**0.47**	**6.18**	**13.56**	**0.40**
Behavioral	10.54	23.62	0.11	10.56	28.54	0.20
LSTM	9.39	18.54	0.24	8.95	22.74	0.30

Monkey B

Model	Horizontal movement			Vertical movement		
	ADE	FDE	r	ADE	FDE	r
Neural-Behavioral	**10.99**	**17.94**	**0.48**	**11.46**	**12.54**	**0.45**
Behavioral	12.38	21.28	0.41	12.64	19.16	0.34
LSTM	17.31	24.76	0.09	13.63	18.03	0.35

Visualizations of model performance

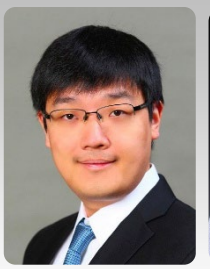
- The Neural-Behavioral Model outperformed the Behavioral and LSTM Model
- Behavioral model generated random but plausible movements
- LSTM failed to reconstruct bio-reasonable whole-body movements



Conclusion


Jieshi He


Puzhe Li


Yanan Sui


Mu-ming Poo

1. We introduce a setup captures large-scale neural activity and 3D kinematics in freely moving monkeys.

2. We provide the demonstration that whole-body movement of freely moving monkeys can be reconstructed from cortical activity.

3. Future work with larger longitudinal datasets, and more expressive models may further improve long-horizon prediction.

