Real-time Low-Latency Behavioral Analysis on Octopus Arm using Transfer Learning and Streaming Dimension Reduction

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Data & Experiment: Pelled Lab

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Why is behavioral analysis useful?

- In general, it provides insights into their cognition and emotional states
- In particular, we're interested in developing **neural prostheses** by studying animal movements in response to external stimuli

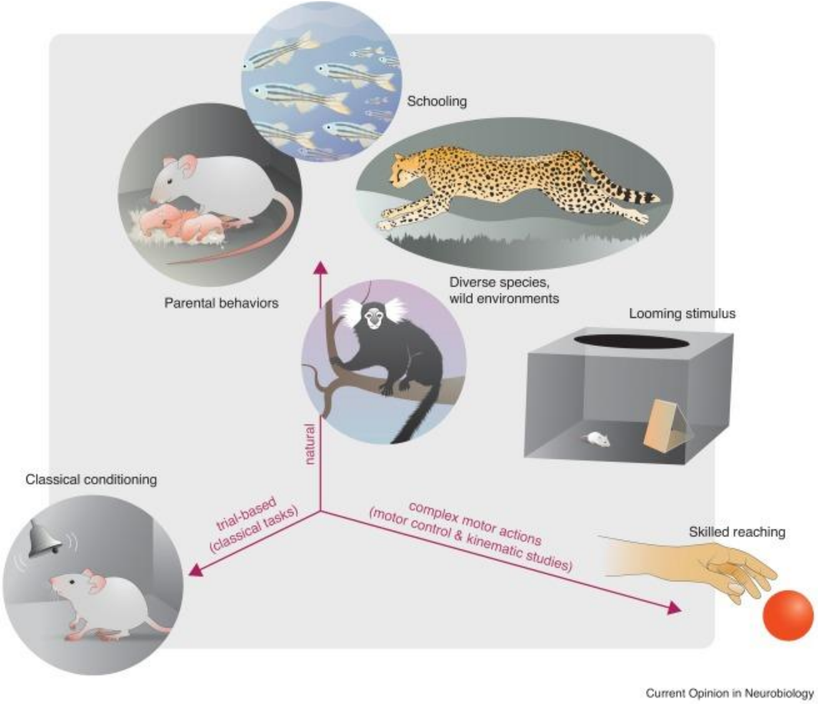

Image Courtesy: https://www.sciencedirect.com/science/article/pii/S0959438819301151
Image Courtesy: https://www.hdtglobal.com/product/prosthetics/

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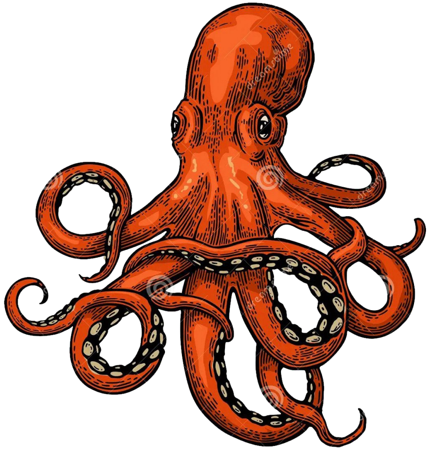
Octopuses are fascinating!

- We perform behavioral analysis on severed Octopus arm.
- What makes studying Octopus interesting?
  - **distributed neural control**: significant portion of neural processing takes place in their arms
  - **adaptive arm functionality:** ability to adapt their arms to perform various tasks with ease
  - **countless degree of freedom:** absence of a rigid skeletal structure allows highly complex movements.

Fun Fact: Severed Octopus Arms Have a Mind of Their Own

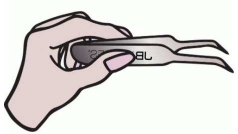
Octopus tentacles still react up to an hour after being severed from their dead owner, and even try to pick up food and feed a phantom mouth



Experiment - stimulation elicits behavior

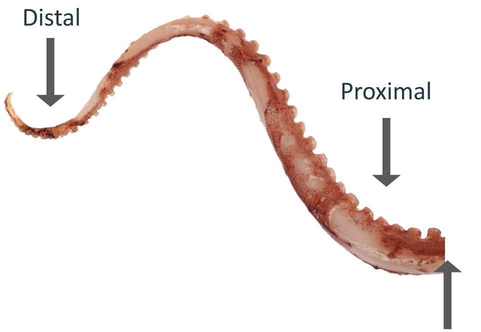
Stimulation

Electrical
100Hz/5mA/50ms



Mechanical
Pinch/touch

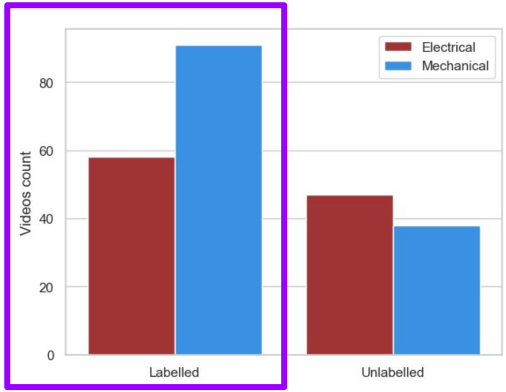
Stimulus Locations

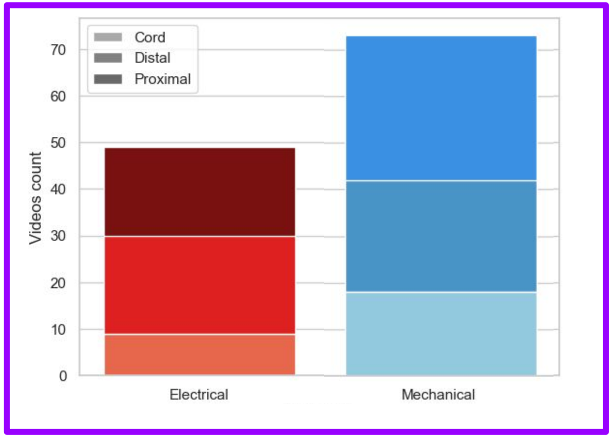


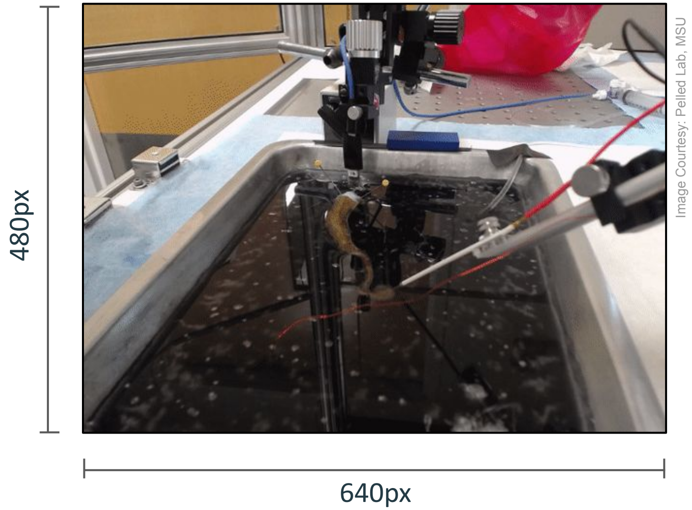
Motion Behavior

Image Courtesy: Pelled Lab, MSU

Exploratory Data Analysis







- videos: 20-30 sec long
- 30 frame/sec

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Transfer Learning

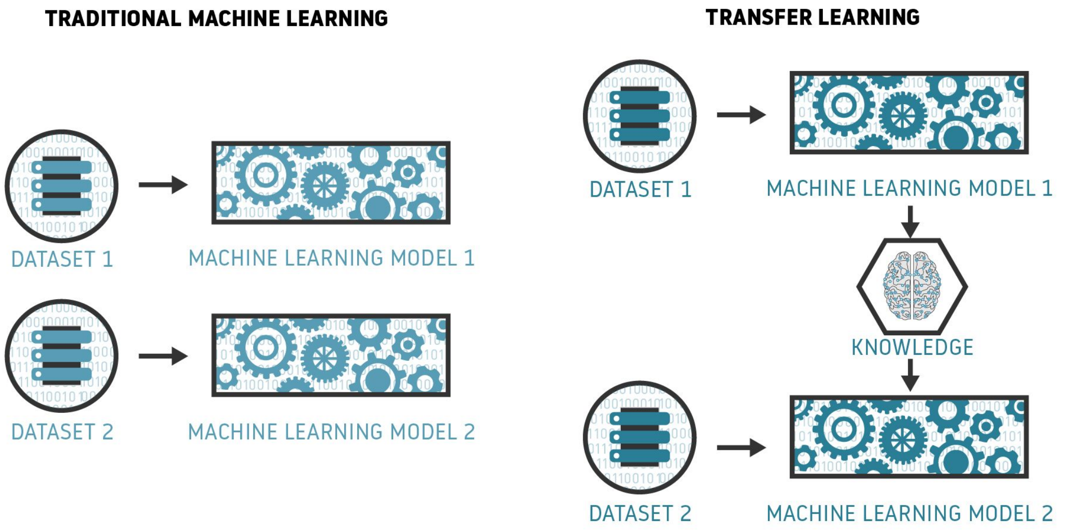


Image Courtesy: https://datascience.aero/transfer-learning-aviation/

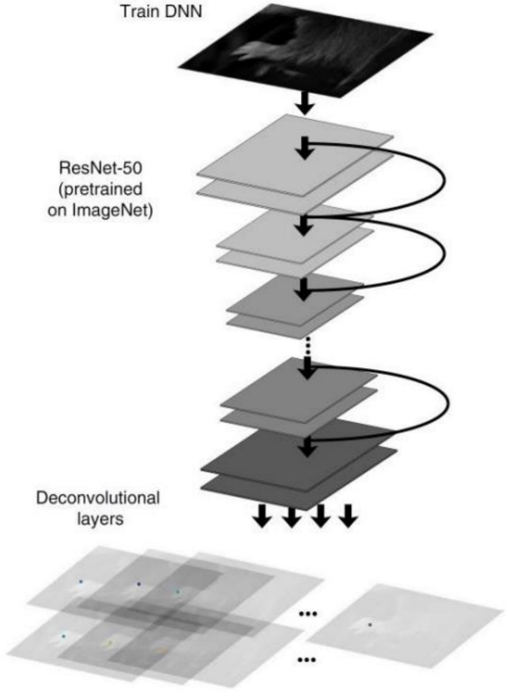
DeepLabCut

developed by Mathis Lab, EPFL

DeepLabCut: a software package for animal pose estimation

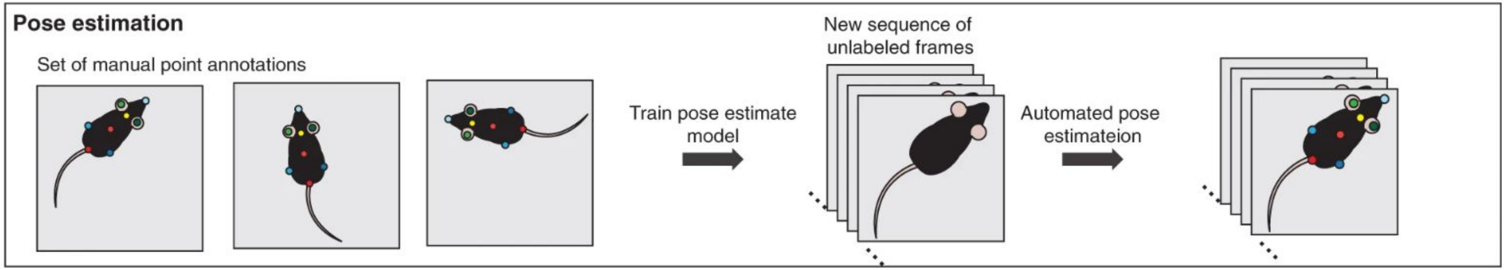
- **for what:** 2D/3D markerless pose estimation
- **how:** transfer learning with deep neural networks
- **why use this:**
  - achieves excellent results with minimal training data
  - **versatile:** tracks various body parts in multiple species across a broad collection of behavior

Image Courtesy: Mackenzie Mathis

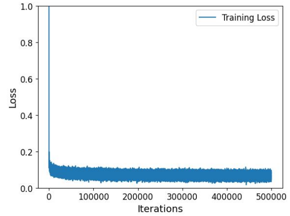


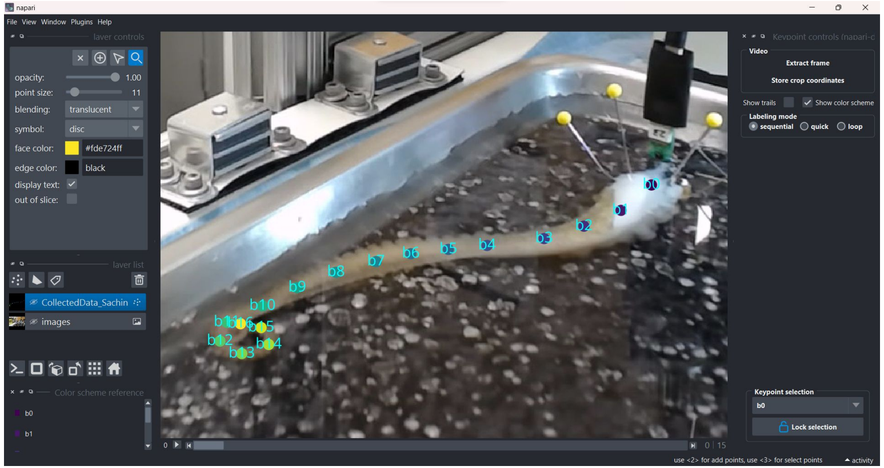
DeepLabCut ResNet-50 architecture

Pose Estimation using DeepLabCut

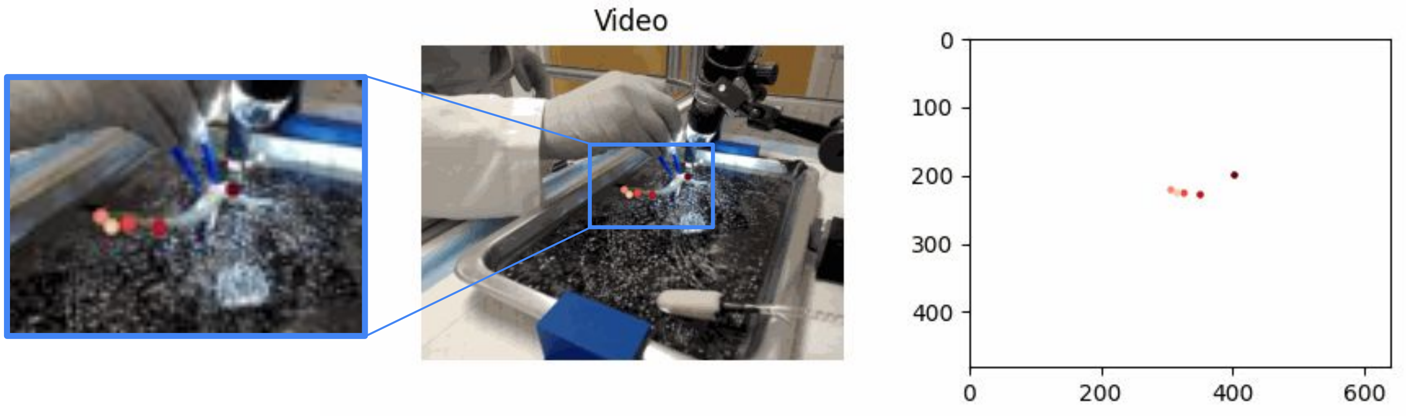


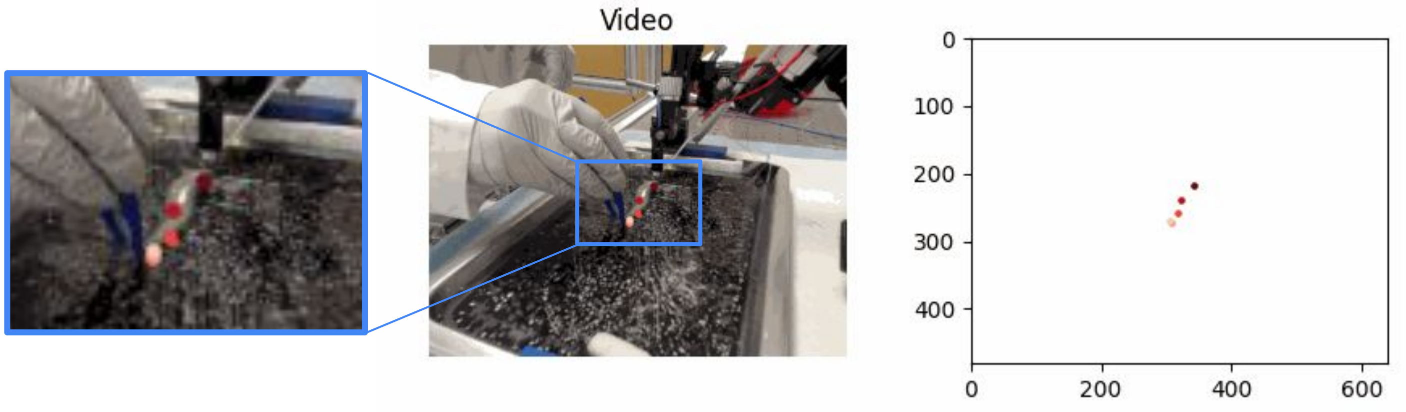
1. Extracted 250+ frames – ~16 frames each from 18 videos in different setting
2. Annotated 17 keypoints for each frame using DeepLabCut GUI
3. Trained the model using this data for 500k iterations (2 days)



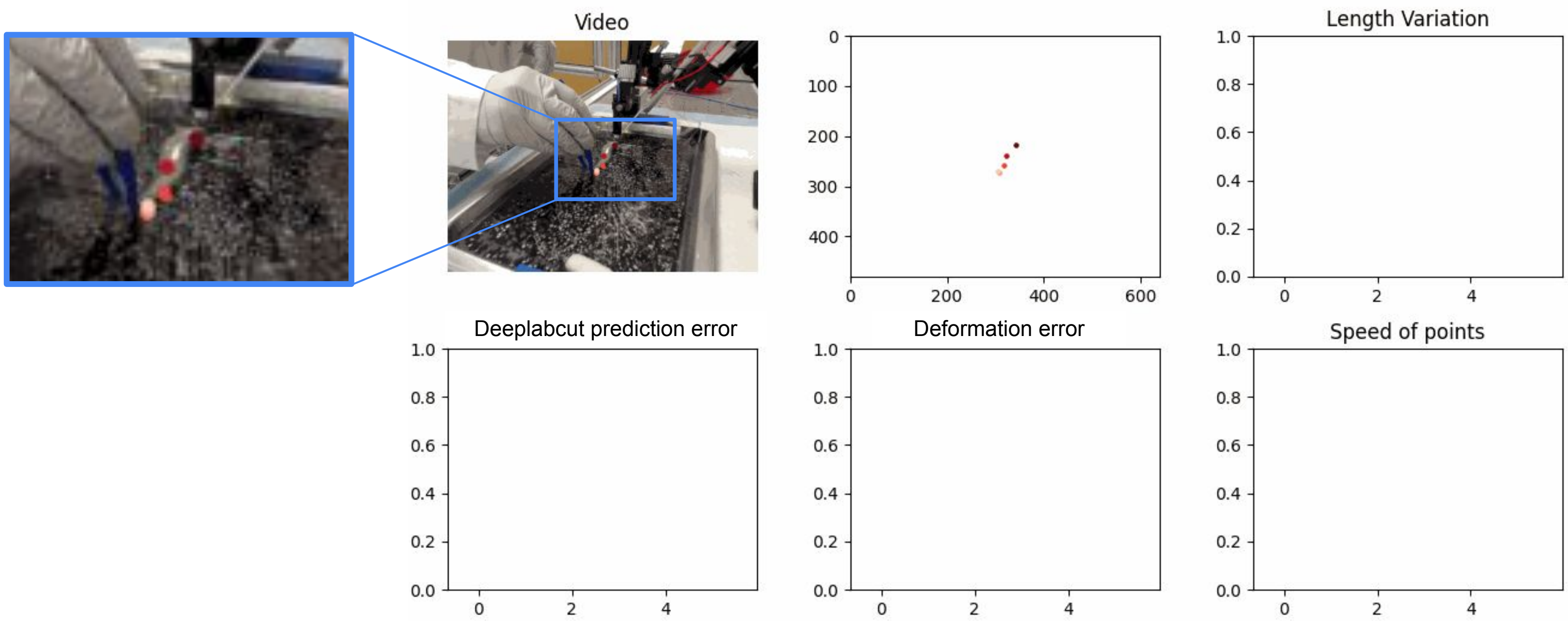


Results


Video
0
100
200
300
400
0
200
400
600


Video
0
100
200
300
400
0
200
400
600

How the quality of the results were verified

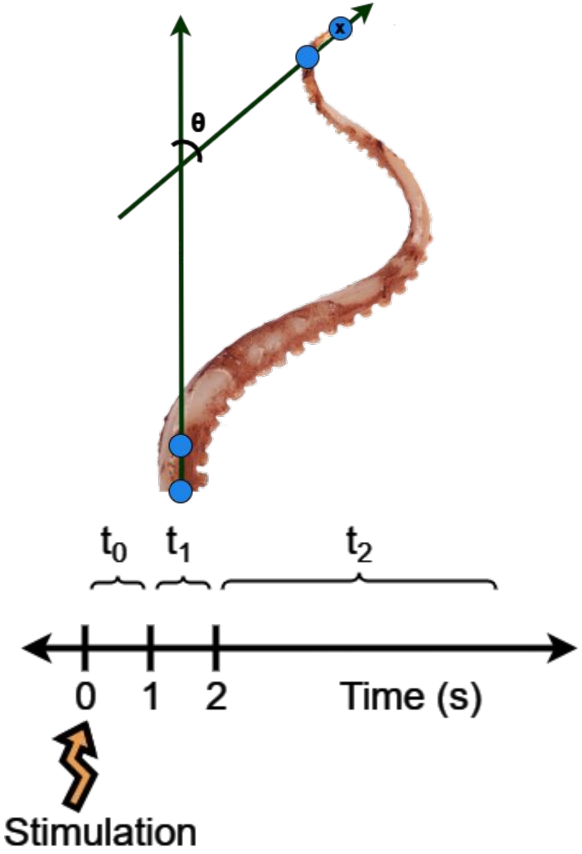


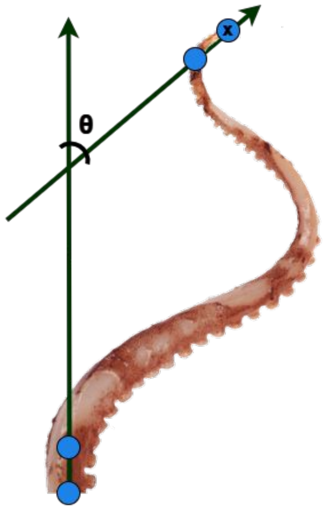
Extracting Kinematic Features

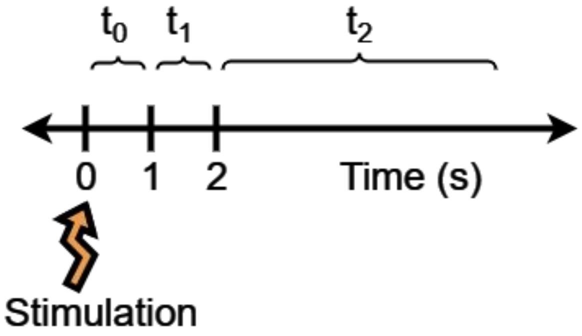
Computed various relevant kinematic features which could potentially describe the entire motion for 3 different time intervals immediately following stimulation.

Feature	Unit
angular position - distal (θ)	° (degree)
angular speed - distal (Δθ)	°/ms
lateral speed (v)	cm/ms
lateral displacement (d)	cm

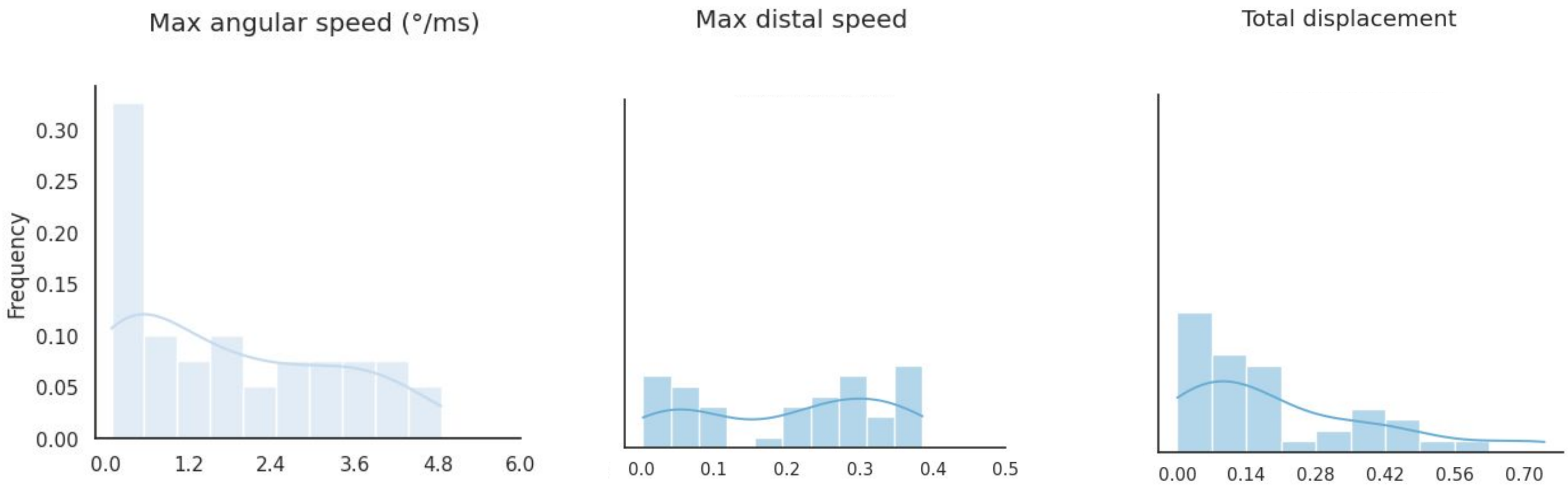
$$\theta = \arccos\left(\frac{\mathbf{A} \cdot \mathbf{B}}{\|\mathbf{A}\|\|\mathbf{B}\|}\right)$$




θ
x


t_0
t_1
t_2
0
1
2
Time (s)
Stimulation

Distribution of Kinematic Features



Can we do more?

- Pose estimation is limited to capture information from tracked keypoints alone
- How to capture information without using any user-specified metrics?

Unsupervised Machine Learning!

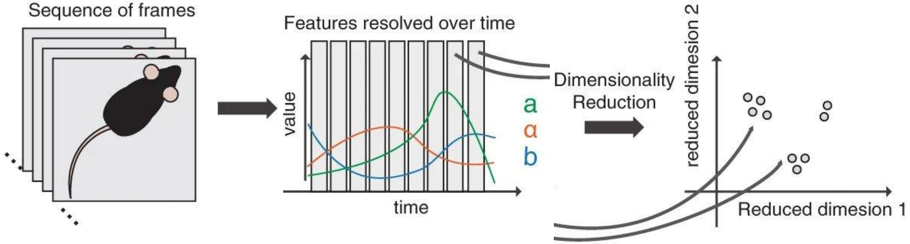


Image Courtesy: https://www.nature.com/articles/s41386-020-0751-7

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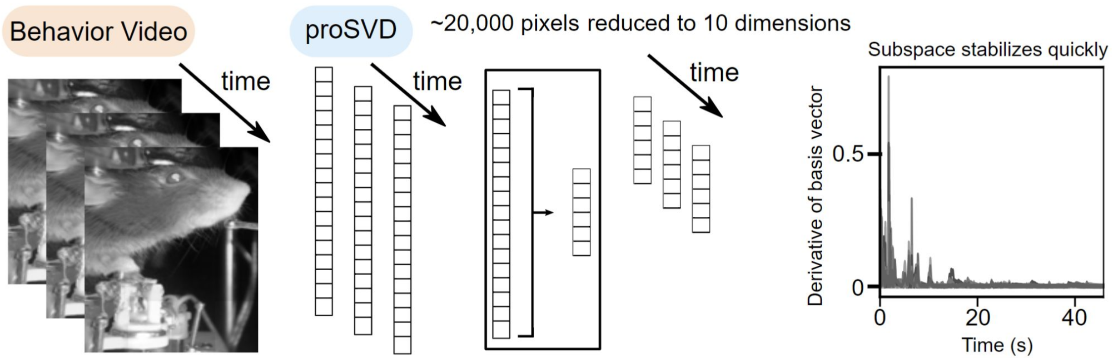
Procrustean SVD

- **for what:** fast streaming dimension reduction of high-dimensional data
- **how:** orthogonal procrustes approach
- **why use this:**
  - unsupervised learning
  - stable representation of the data
  - extremely fast

Algorithm 1 Procrustean SVD (proSVD)

Given: Initial data X_0, decay parameter $\alpha \in (0, 1]$
Initialize: QR Factorization: $X_0 = Q_0 R_0$

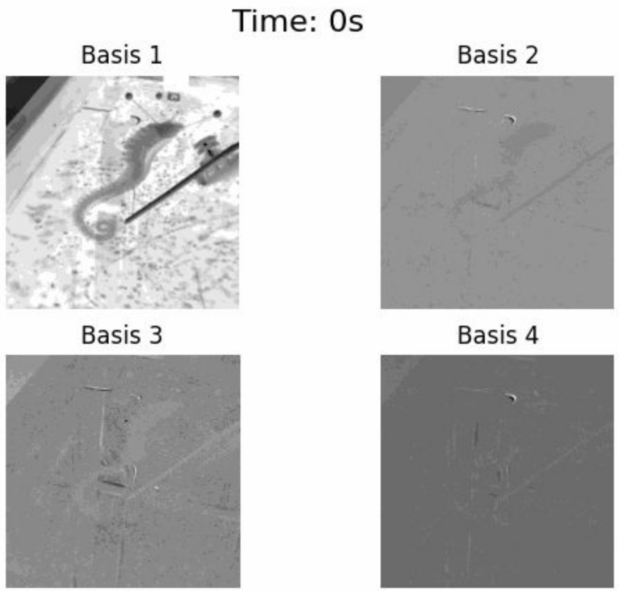
for $t = 1 \dots$ **do**
  Fetch b new columns of data, X_+
  $C \leftarrow Q_{t-1}^\top X_+, \quad X_\perp \leftarrow X_+ - Q_{t-1} C,$
  $\hat{Q} \leftarrow [Q_{t-1} \quad Q_\perp], \quad \hat{R} \leftarrow \begin{bmatrix} R_{t-1} & C \\ 0 & R_\perp \end{bmatrix}$
  $U, \Sigma, V \leftarrow \mathtt{SVD}(\hat{R})$
  $\Sigma \leftarrow \alpha \Sigma$
  $M \leftarrow Q_{t-1}^\top \hat{Q} U_1 = [\mathbb{1}_{k \times k} \quad \mathbf{0}_{k \times b}] U_1$
  $\tilde{U}, \tilde{\Sigma}, \tilde{V} \leftarrow \mathtt{SVD}(M), \quad T \leftarrow \tilde{U} \tilde{V}^\top$
  $Q_t \leftarrow \hat{Q} U_1 T^\top$
  $Q_v, R_v \leftarrow \mathtt{QR}(V), \quad R_t \leftarrow T \Sigma_1 Q_v^\top$
end for



Bubblewrap: Online tiling and real-time flow prediction on neural manifolds
Anne Draelos et al.

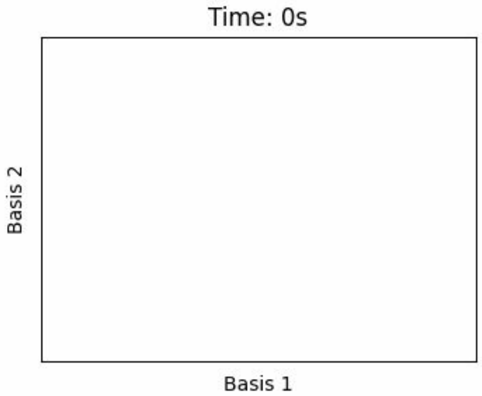
Procrustean SVD

Basis Frames



Original Video

Basis Loadings



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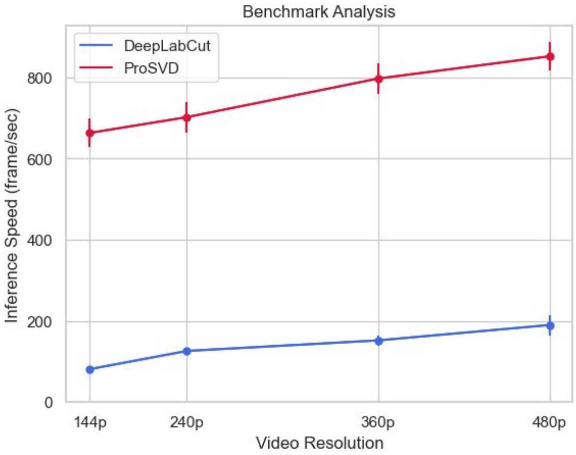
Comparison of Inference Speed



- **Memory**: 128 GB
- **CPU**: 32 core
  - Clock speed: 5.8GHz
  - Model name: 13th Gen Intel(R) Core(TM) i9-13900KF
- **GPU**: 12 GB
  - NVIDIA GeForce RTX 4070 Ti GPU

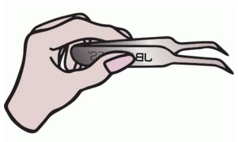
- ProSVD is a much faster algorithm and does not require training
- There is bandwidth to perform pre-processing and post-processing with proSVD to observe more predictive features
- For motions in the order of 50-100ms, both these algorithms are quite effective to perform real-time low-latency closed loop experiments

Does the Octopus elicit distinguishable behavior with varying stimuli?

Experiment - stimulation elicits behavior

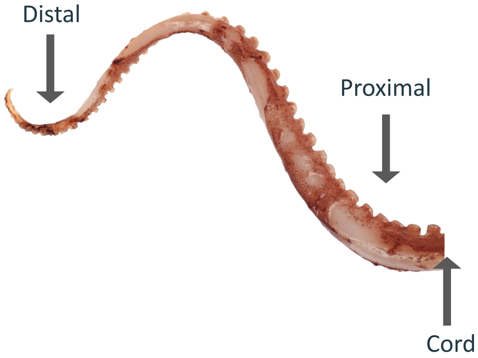
Stimulation

Electrical
100Hz/5mA/50ms



Mechanical
Pinch/touch

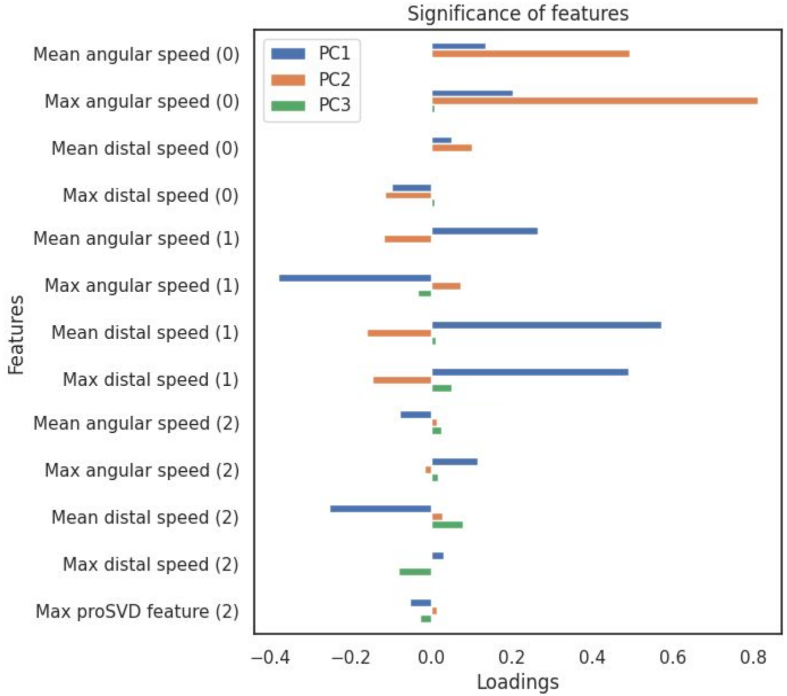
Stimulus Locations



Motion Behavior

Image Courtesy: Pelled Lab, MSU

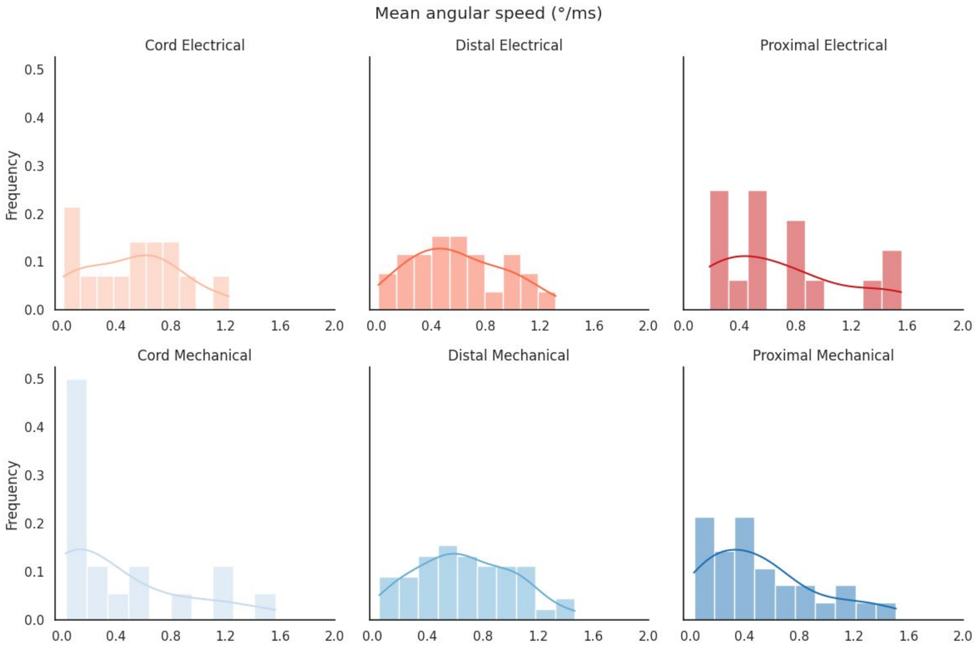
Significance of features

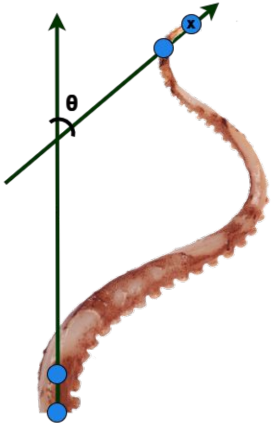


- To estimate which features are more significant, PCA was performed and the loadings of these features in the first three principal components were visualized
- **Important features**:
  - Translational speed of the distal part during 1-2 seconds
  - Angular speed of the distal part immediately following stimulation

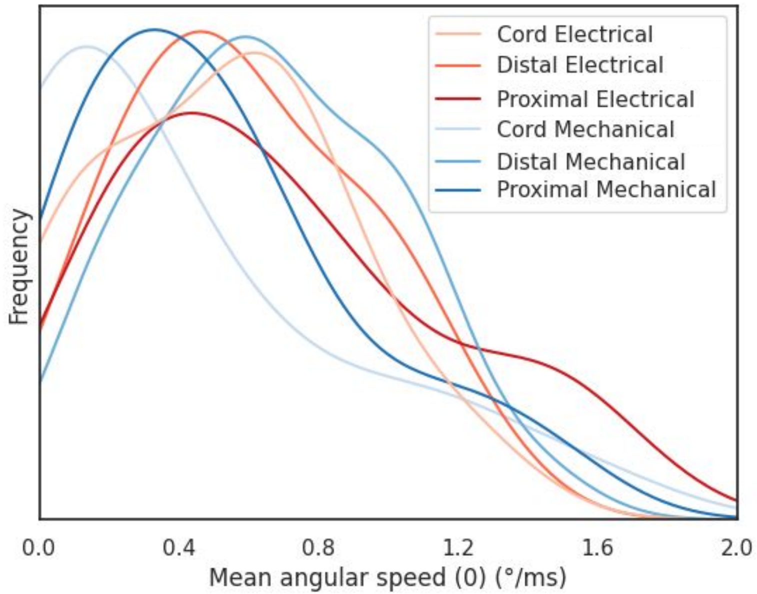
Does angular speed explains stimulation?

Histogram distribution of angular speed with different stimulus parameters





Visual analysis: Kernel Density Estimation (KDE)



Quantitative Analysis: Kolmogorov-Smirnov (K-S) test

Two-Sample K-S test was performed to determine if these features are statistically distinguishable

Electrical v/s Mechanical

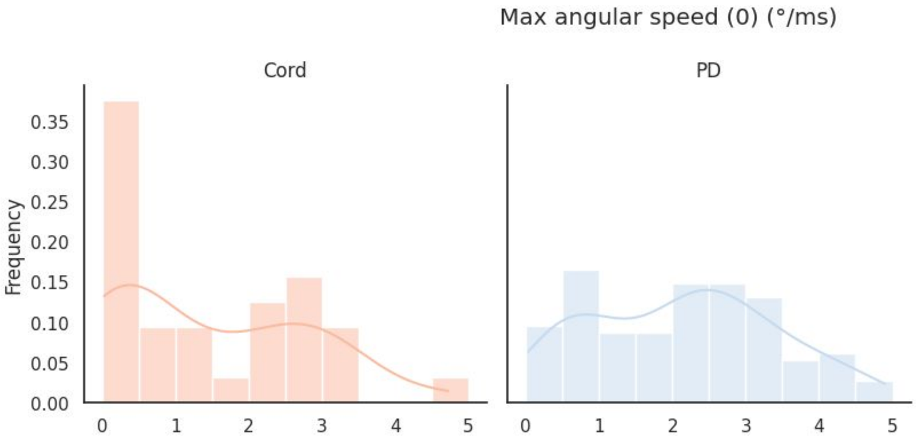
	Cord	Distal	Proximal
p-value	0.12	0.07	0.25
distribution	same	same	same

Between Stimulus locations

Cord v/s Distal	Cord v/s Proximal	Distal v/s Proximal
0.003	0.007	0.082
different	different	same

Cord v/s Others (PD)

- **Cord:** the nerve fibers that communicate with the central brain
- **Other locations:** more peripheral



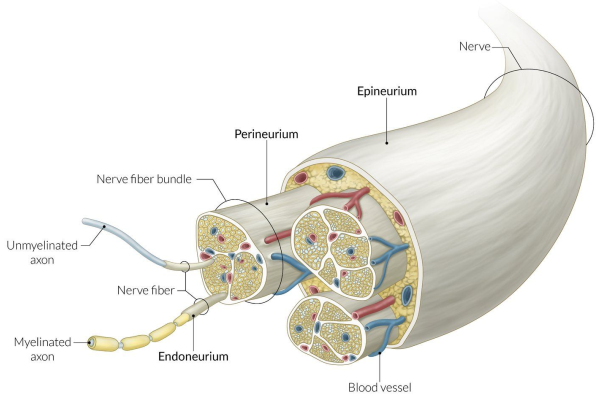
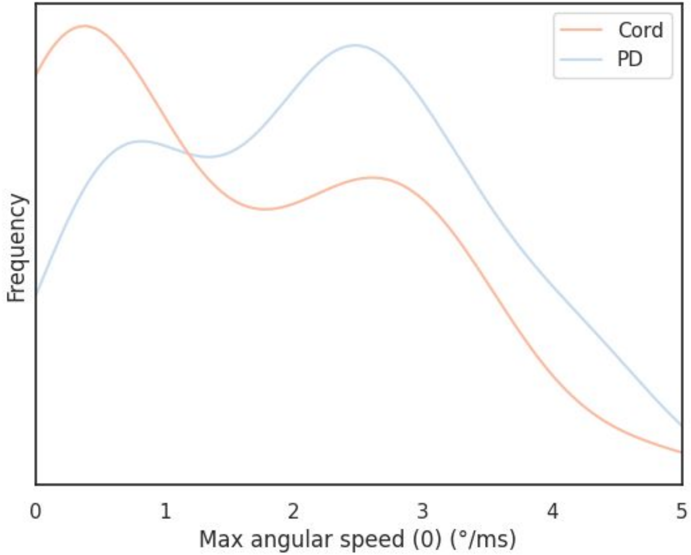


Image Courtesy: https://www.amboss.com/us/knowledge/nerve-tissue-synapses-and-neurotransmitters

Cord v/s Others (PD)

Visual analysis: KDE plot

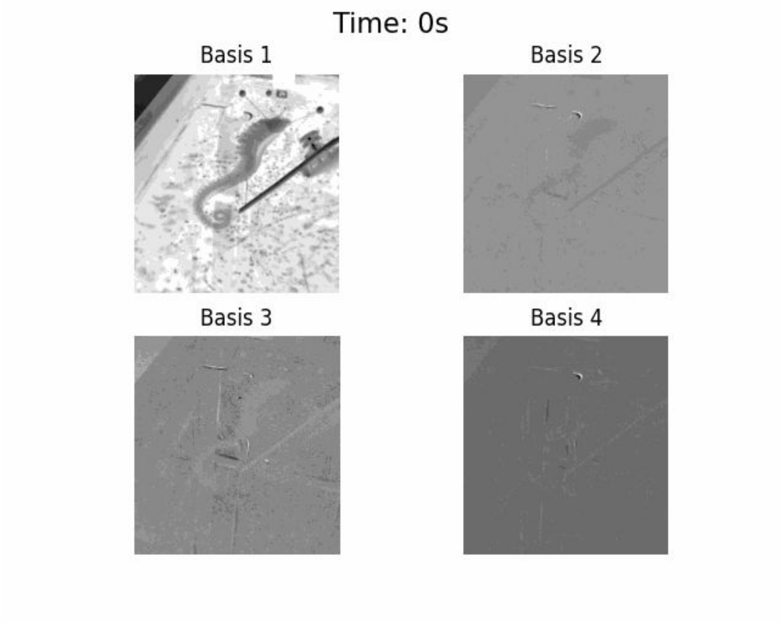


Quantitative Analysis: K-S test

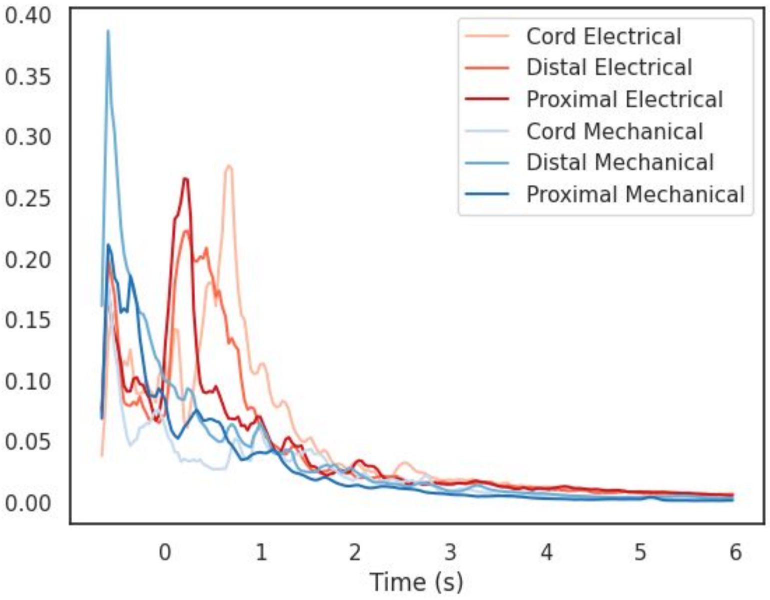
		PD v/s Cord
t_0	Mean angular speed (0)	different-0.010
	Max angular speed (0)	different-0.014
	Mean distal speed (0)	same-0.257
	Max distal speed (0)	different-0.016
t_1	Mean angular speed (1)	different-0.001
	Max angular speed (1)	different-0.001
	Mean distal speed (1)	different-0.029
	Max distal speed (1)	different-0.012
t_2	Mean angular speed (2)	different-0.003
	Max angular speed (2)	different-0.004
	Mean distal speed (2)	same-0.085
	Max distal speed (2)	same-0.051

Are proSVD features distinguishable?

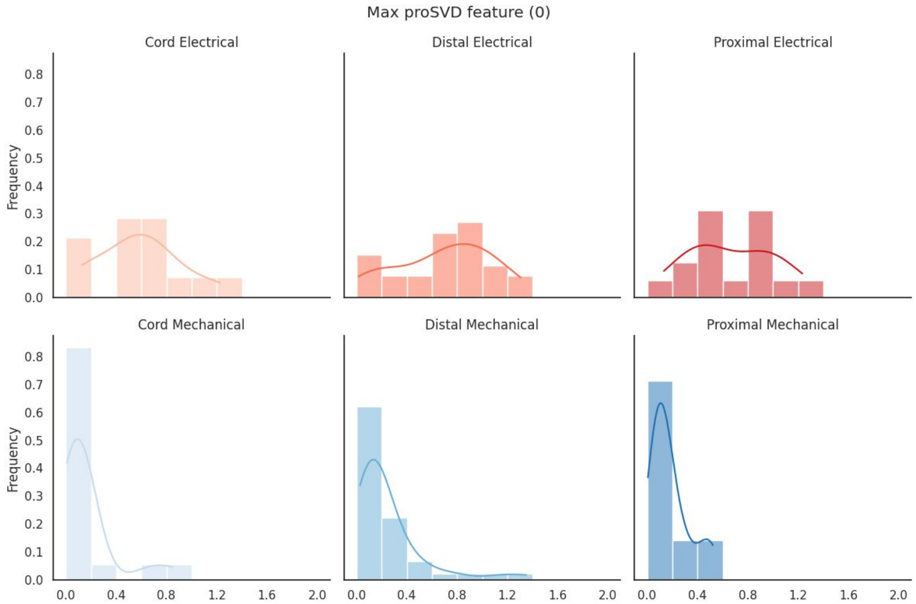
Basis Frames (Q)

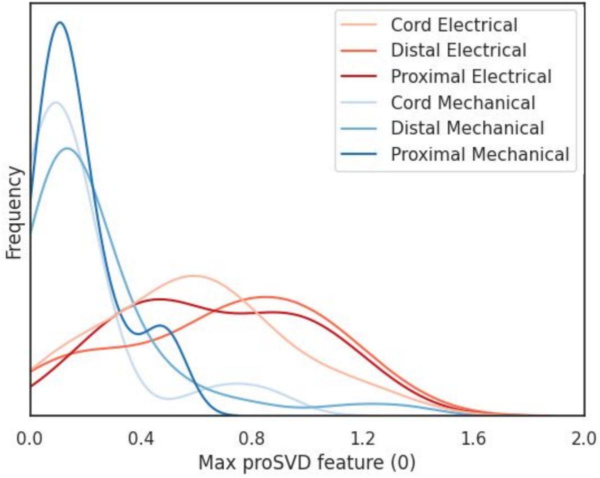


Feature dQ: norm of diff of basis Q across time (plotted for basis 1)



Are proSVD features distinguishable?



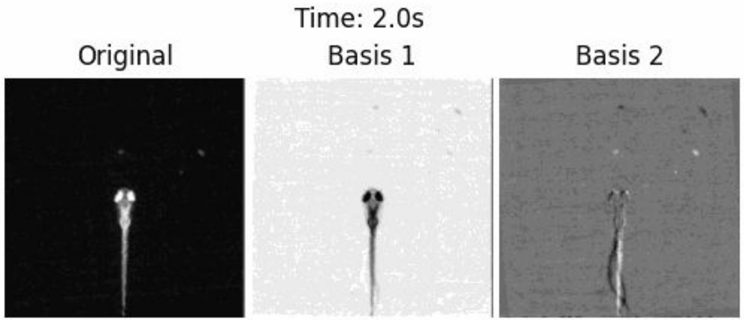


Cord	Distal	Proximal
0.0012	0.0011	0.0011
different	different	different

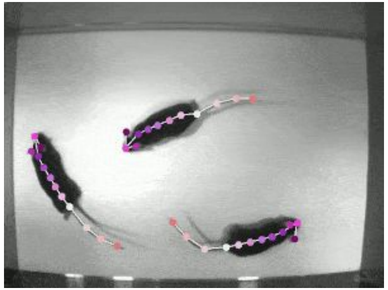
Observation: Separation of electrical and mechanical stimulation!

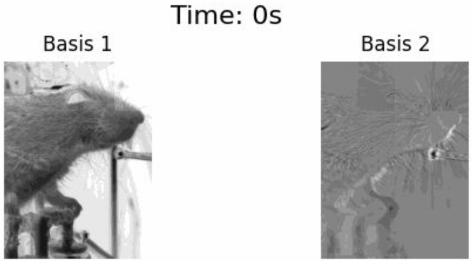
Future Directions

- These analysis are **species-agnostic!**
- Currently working on extending to other experiments/datasets such as mice and zebrafish.



Data Courtesy: https://pubmed.ncbi.nlm.nih.gov/29307558/


Media courtesy: https://www.mackenziemathislab.org/deeplabcut



Data Courtesy: https://repository.cshl.edu/id/eprint/38599/

Followup? Reach out!

- Lab website: https://draeloslab.org/
- PI: Dr. Anne Draelos, BME
- : draeloslab/stim_behavior
- Sachin: sachinks@umich.edu