BIOENG-456

Controlling Behavior in Animals and Robots

Week 2: Embodiment and motor control

Animal agility is unmatched in robotics

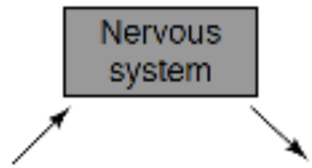
National Geographic

Animal agility is unmatched in robotics

National Geographic

Where does behavior come from?

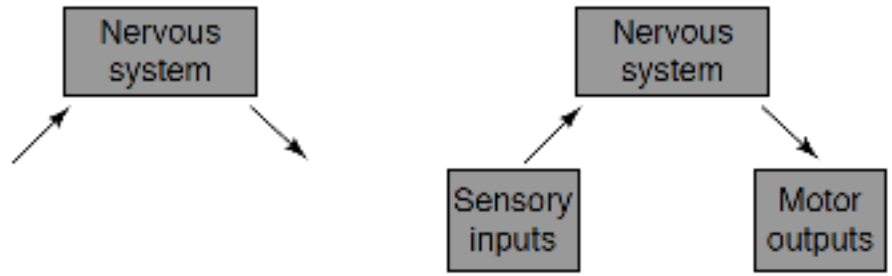
A view from studying neurons in a dish



Chiel & Beer, *TINS*, 1997

Where does behavior come from?

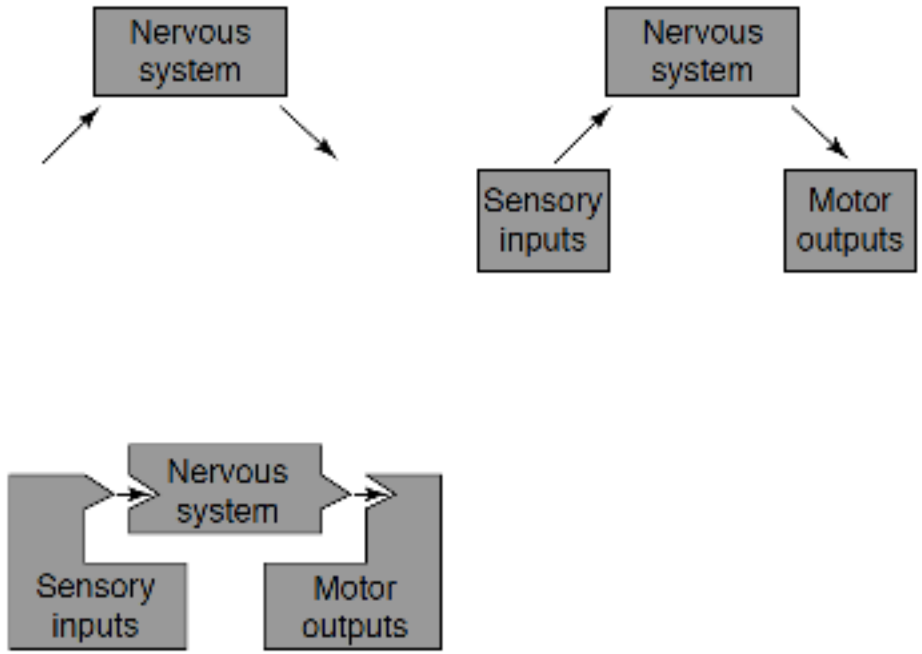
A view from studying neurons in an animal



Chiel & Beer, *TINS*, 1997

Where does behavior come from?

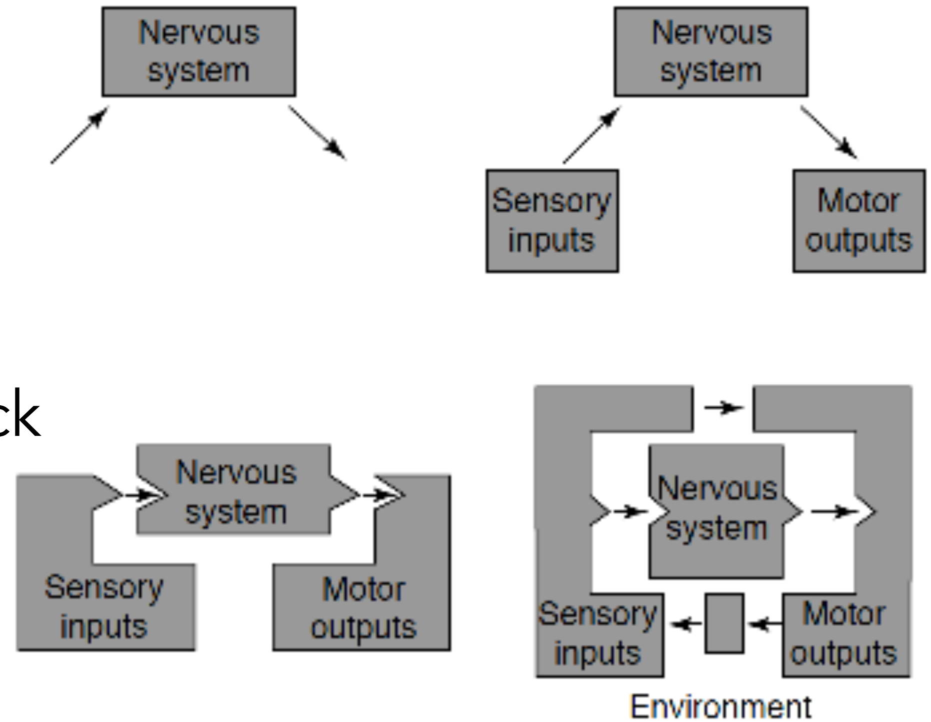
A view from studying neurons in an animal keeping in mind the co-evolution of body and brain



Chiel & Beer, *TINS*, 1997

Where does behavior come from?

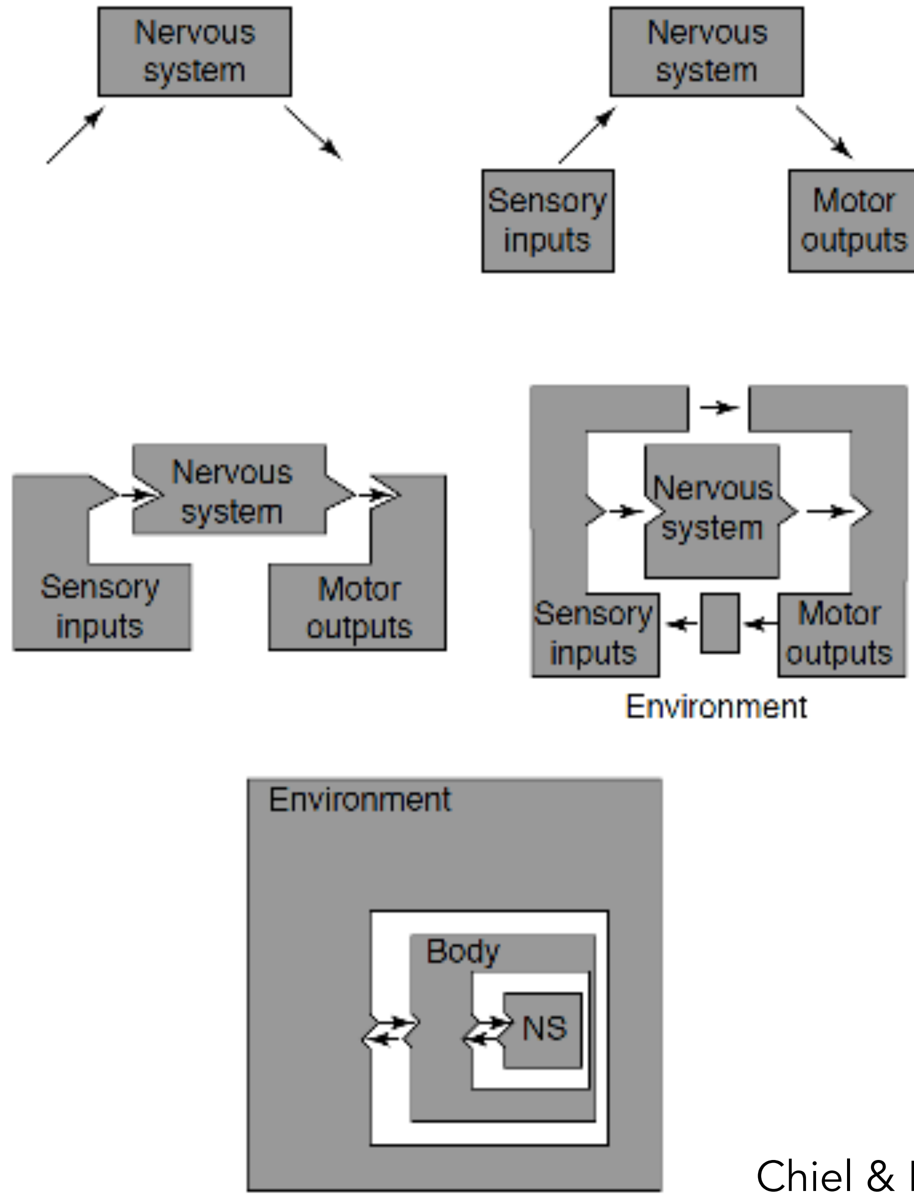
A view from studying neurons in an animal and acknowledging the importance of environmental feedback



Chiel & Beer, *TINS*, 1997

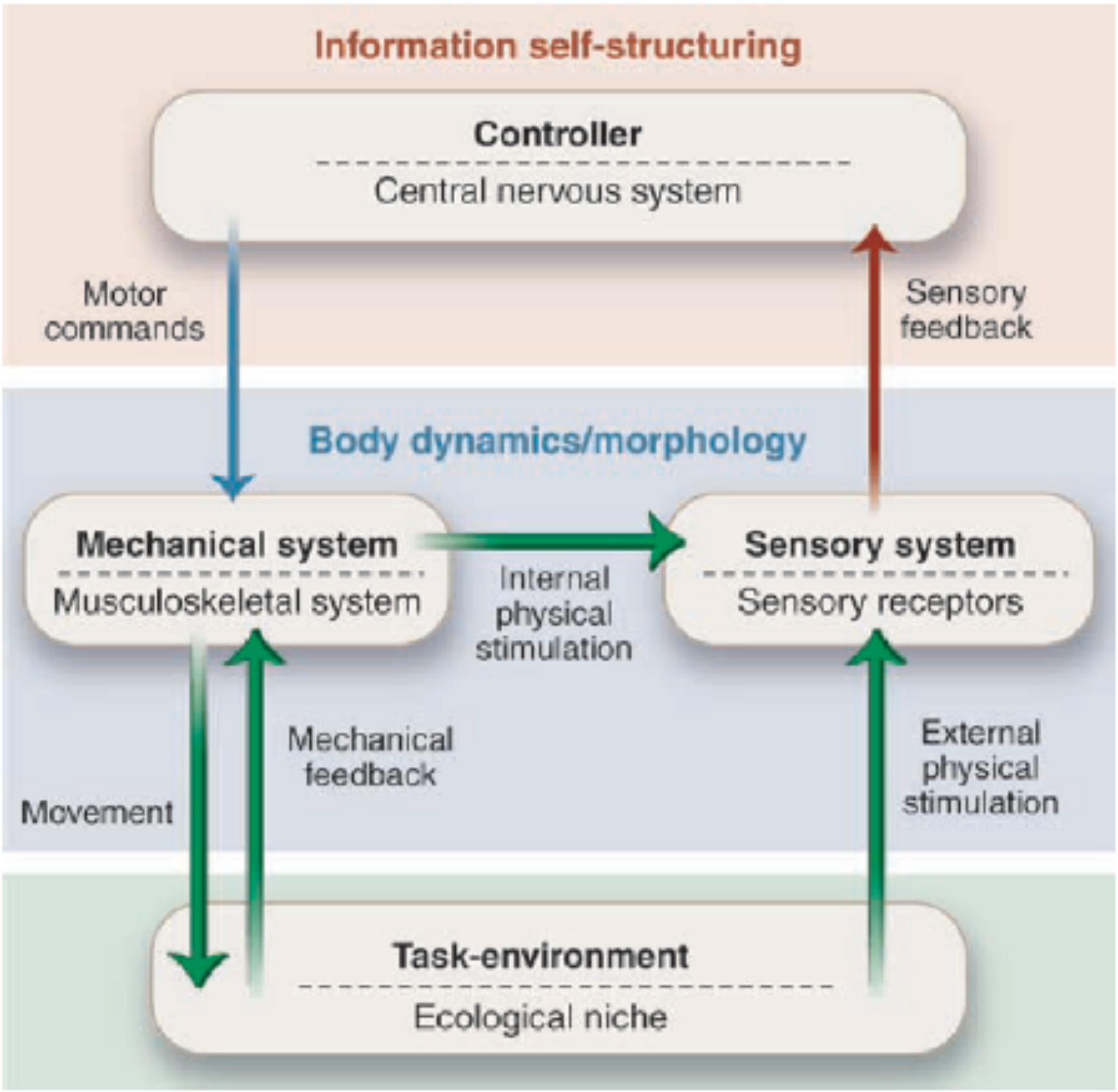
Where does behavior come from?

A full view of the brain, body, and environment



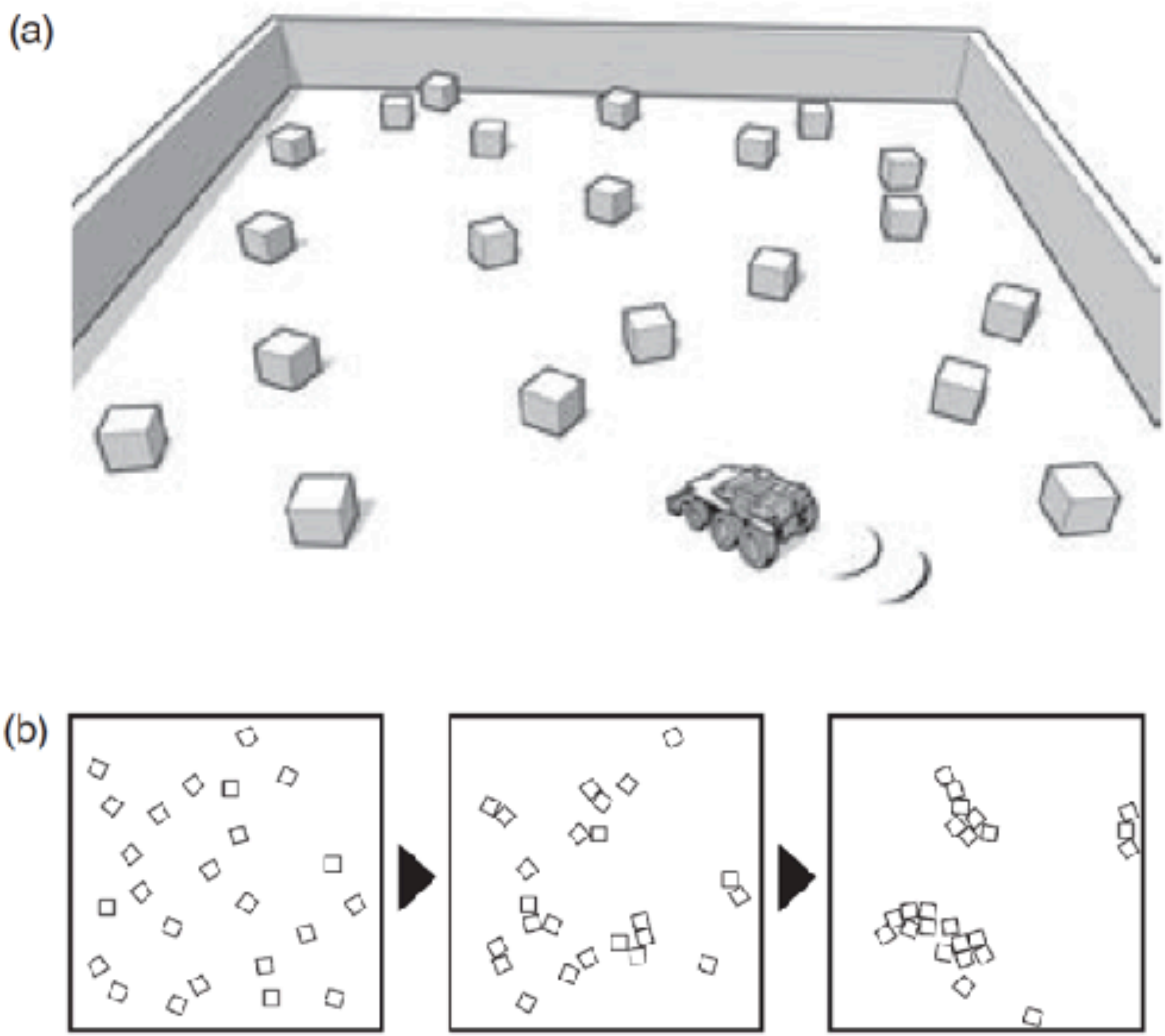
Chiel & Beer, *TINS*, 1997

The controller, embodiment, and environment



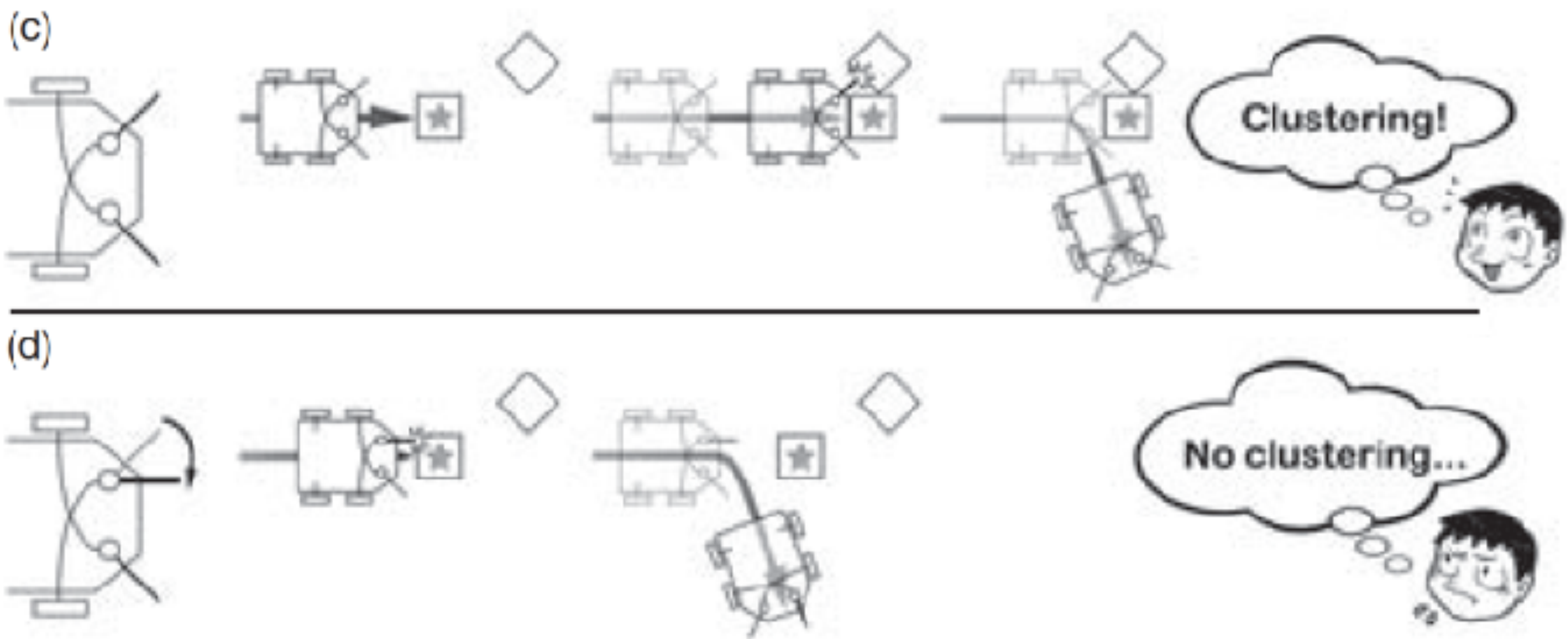
Pfeifer et al., *Science*, 2007

Maris Robots: an example of embodiment at work



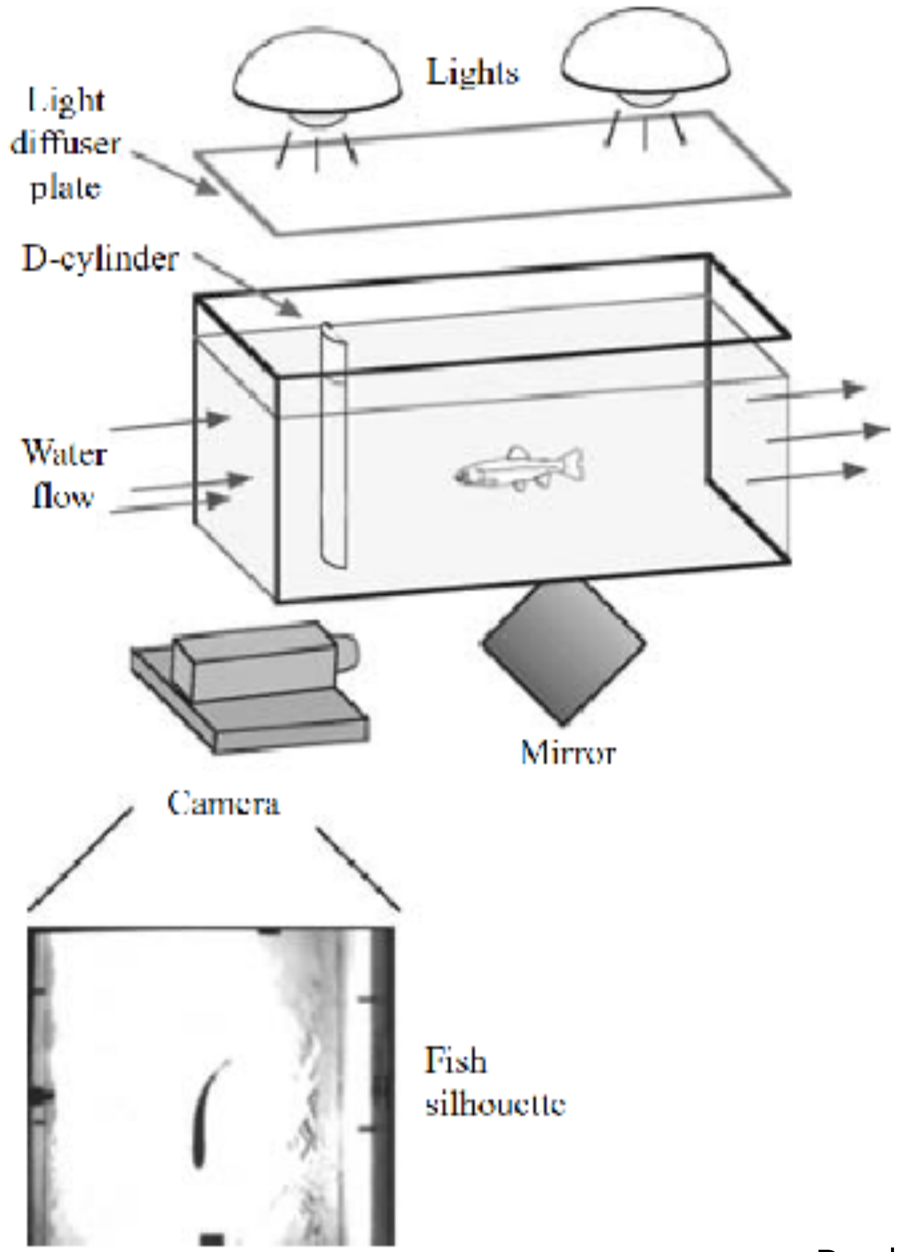
Pfeifer & Bongard, "How the Body Shapes the Way We Think", pgs 72-75

Maris Robots: an example of embodiment at work



Pfeifer & Bongard, "How the Body Shapes the Way We Think", pgs 72-75

Another example of embodiment



Beal et al., *J. Fluid Mech*, 2006

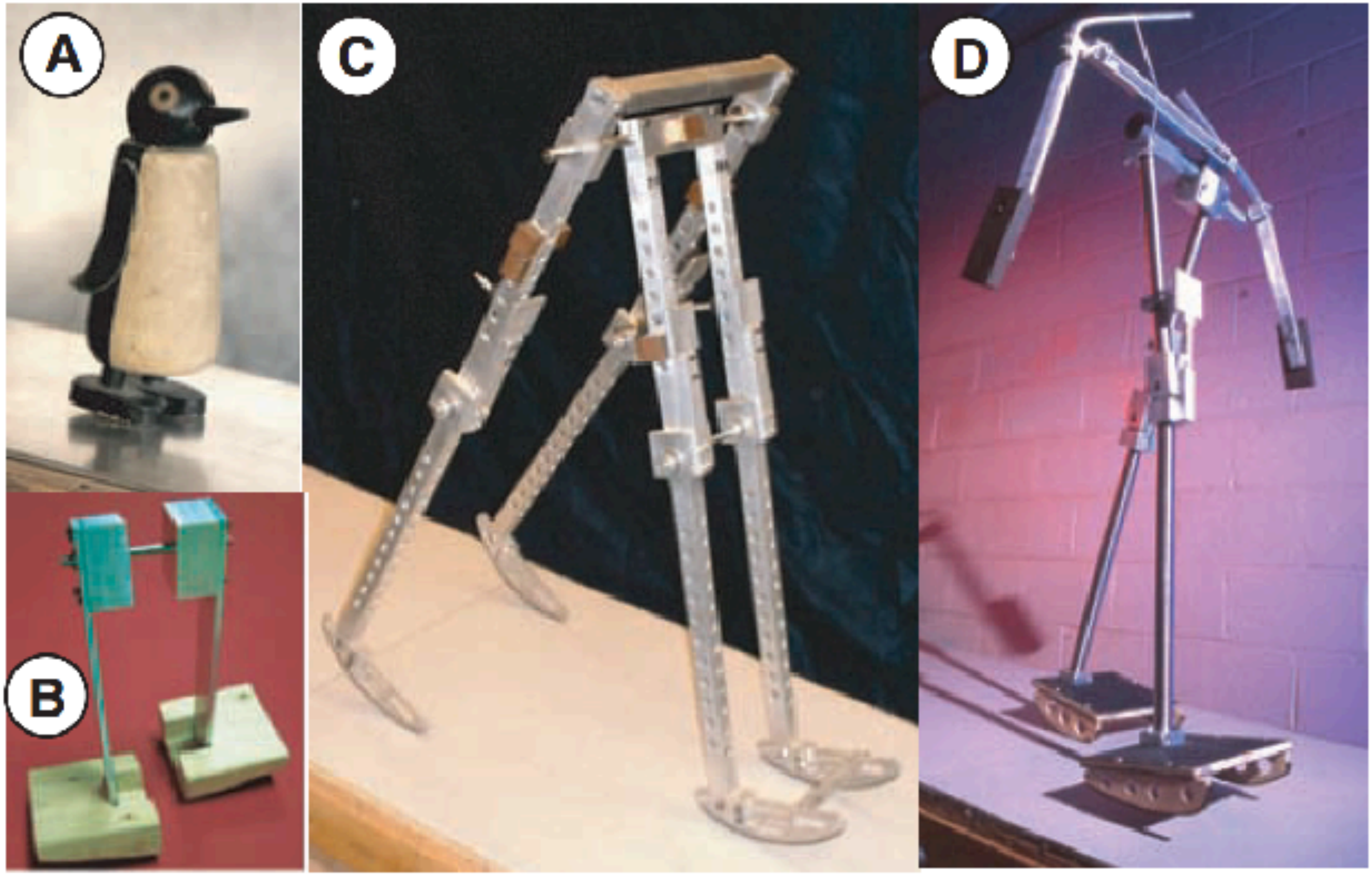
Another example of embodiment

Beal et al., *J. Fluid Mech*, 2006

Passive propulsion in vortex waves

Beal et al., *J. Fluid Mech*, 2006

Efficient Bipedal Robots Based on Passive-Dynamic Walkers



Collins et al., *Science*, 2005

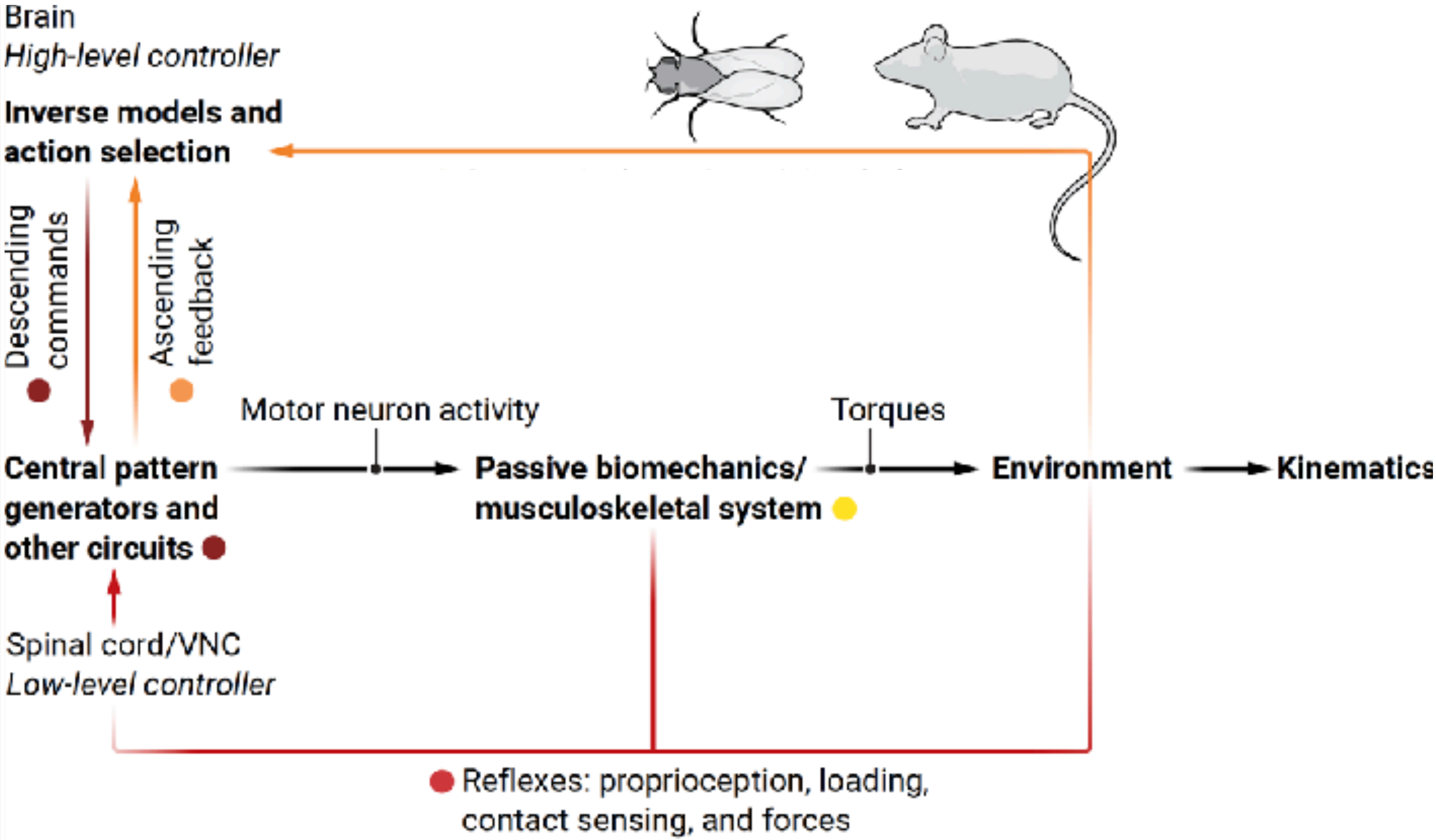
Efficient Bipedal Robots Based on Passive-Dynamic Walkers

Collins et al., *Science*, 2005

Any questions?

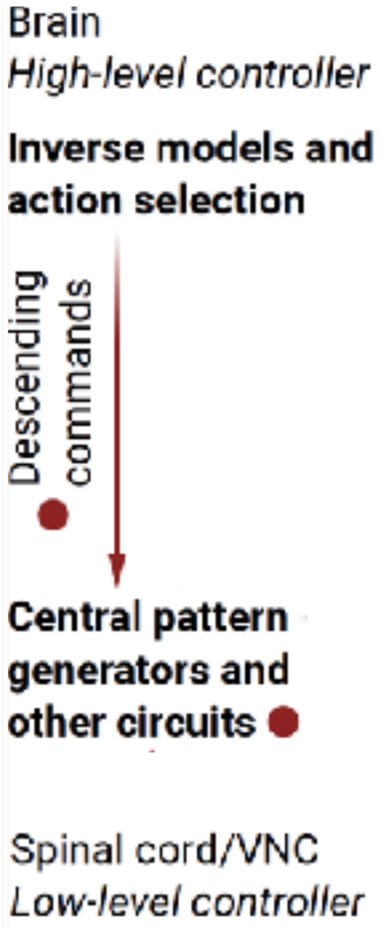
What about the controller…

A simplified schema of biological motor control

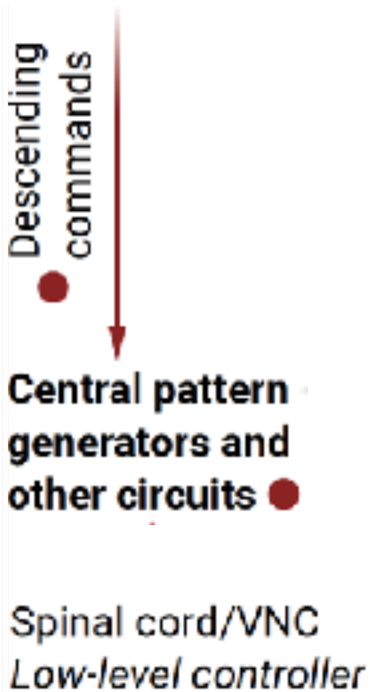


Ramdya & Ijspeert, *Science Robotics*, 2023

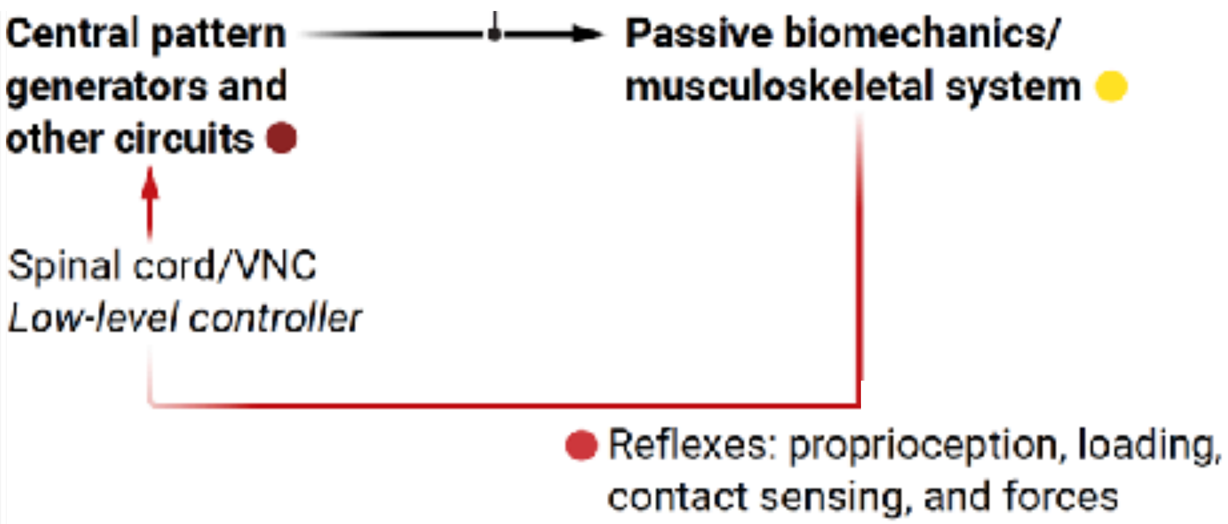
Descending drive



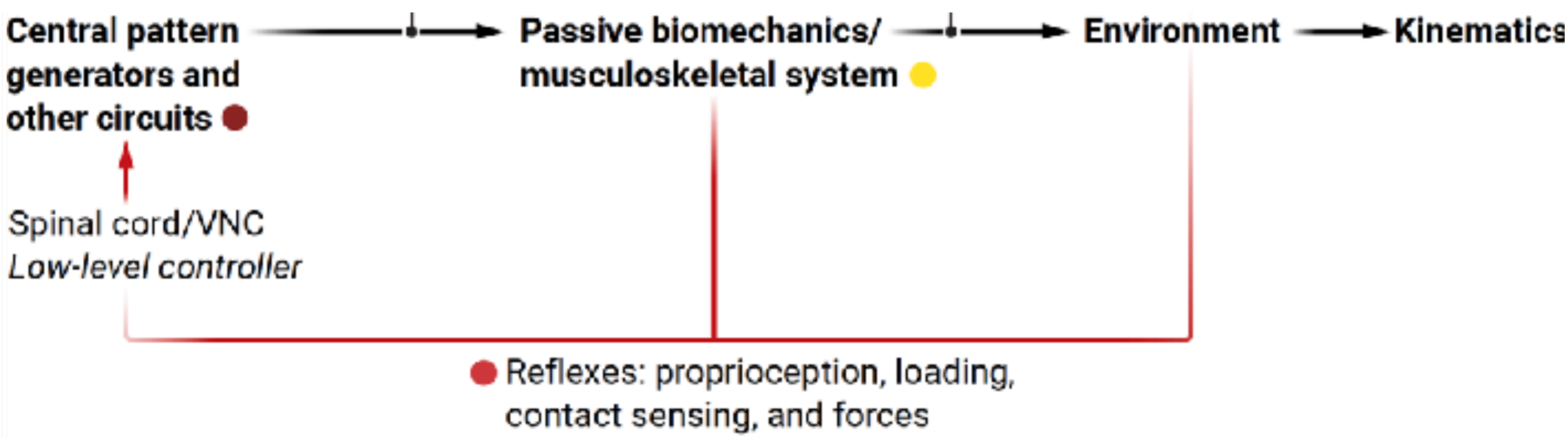
Motor system (spinal/ventral nerve cord)



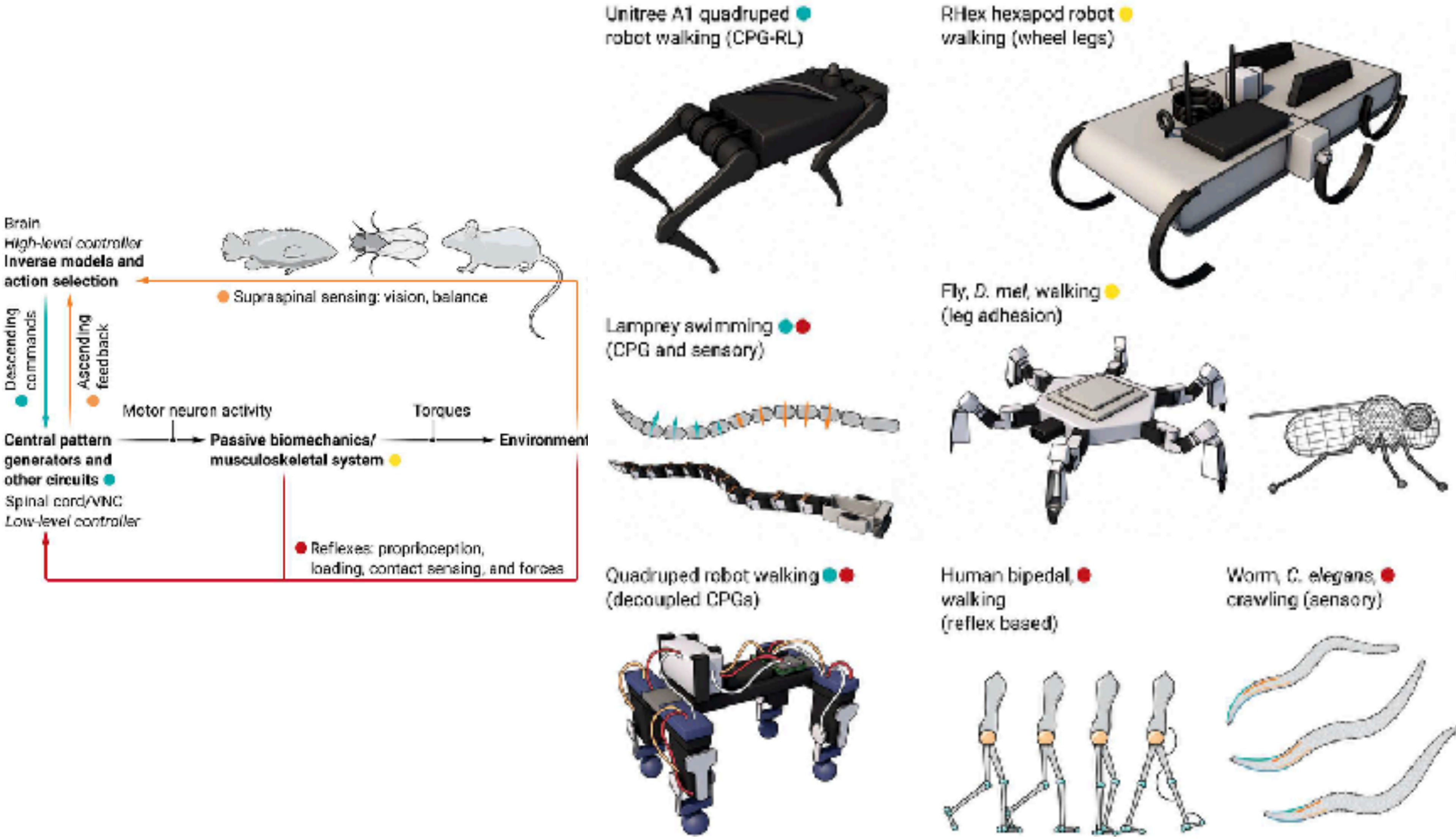
Sensory feedback from limbs



Musculoskeletal biomechanics



These elements have been used in robotics



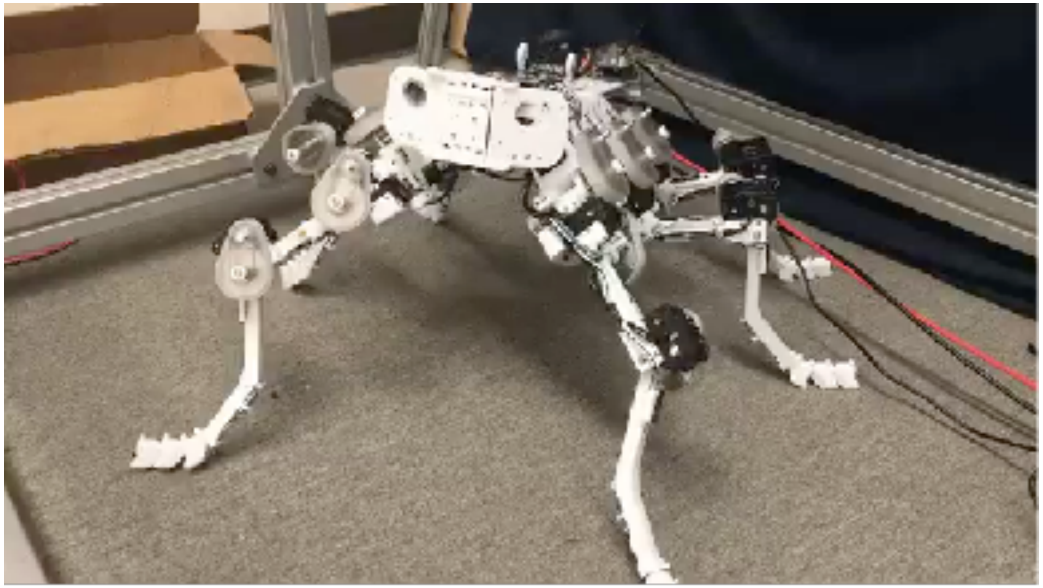
Any questions?

The mechanics of limb motor control in the fly…

Flies use their legs for complex behaviors

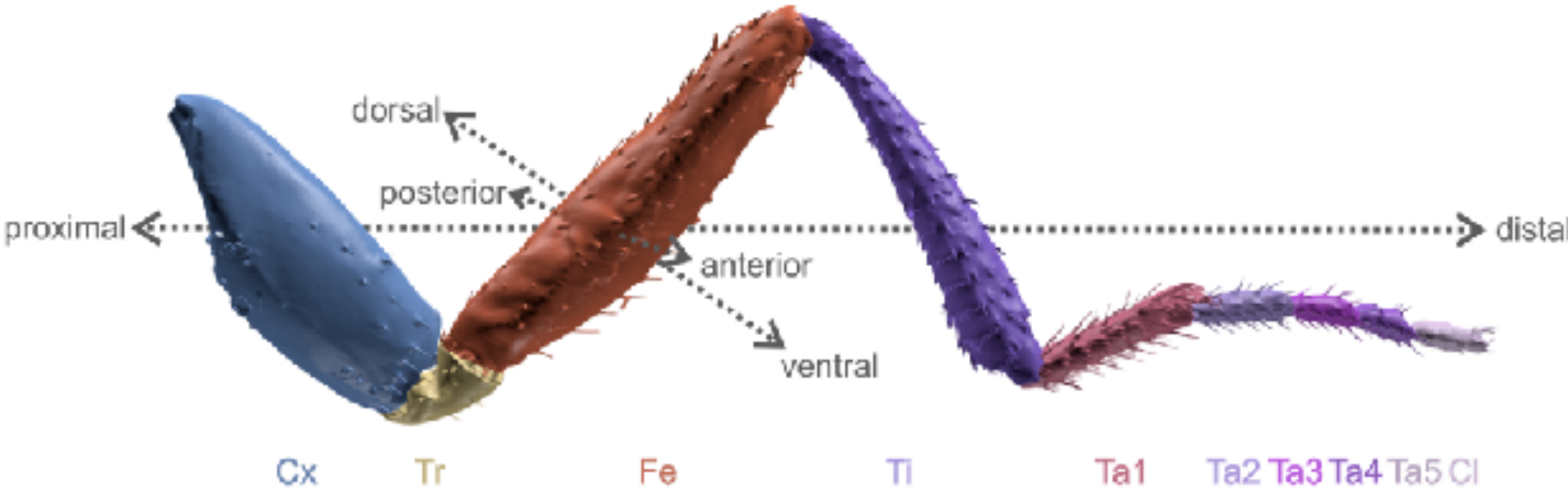
Gap crossing - Triphan et al. 2016

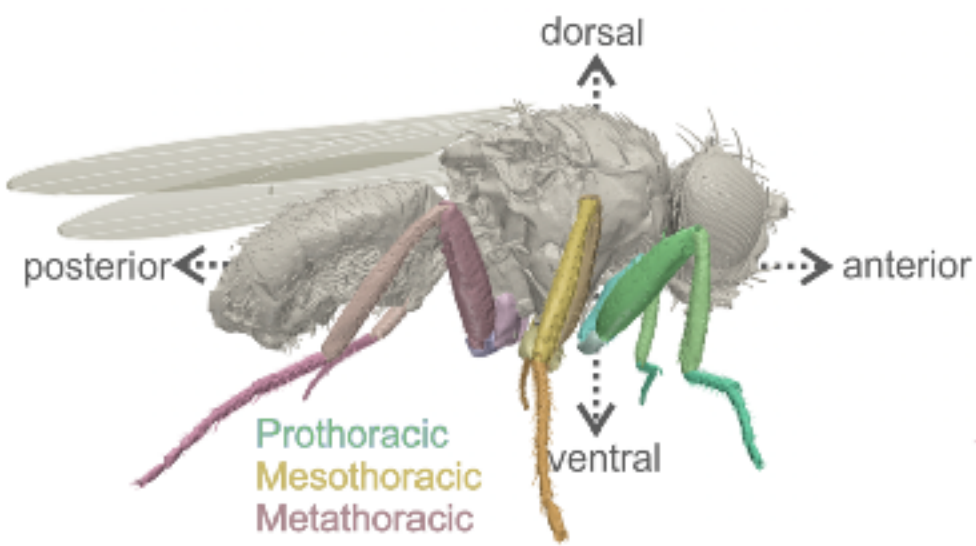
Male aggression - Hoopfer & Anderson



“Drosophibot” Goldsmith et al.,. *Bioinspir. Biomim.* 2020

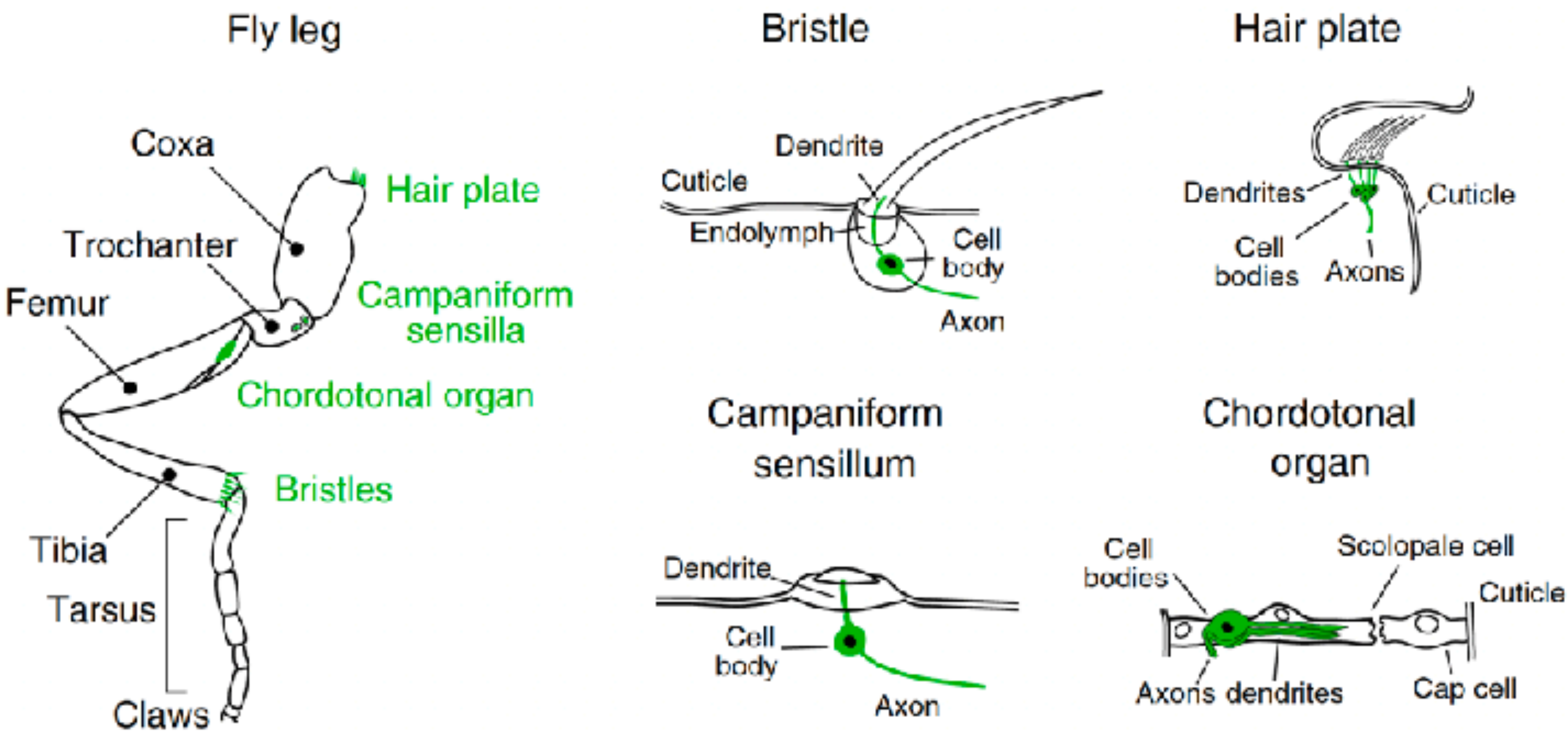
The *Drosophila* leg





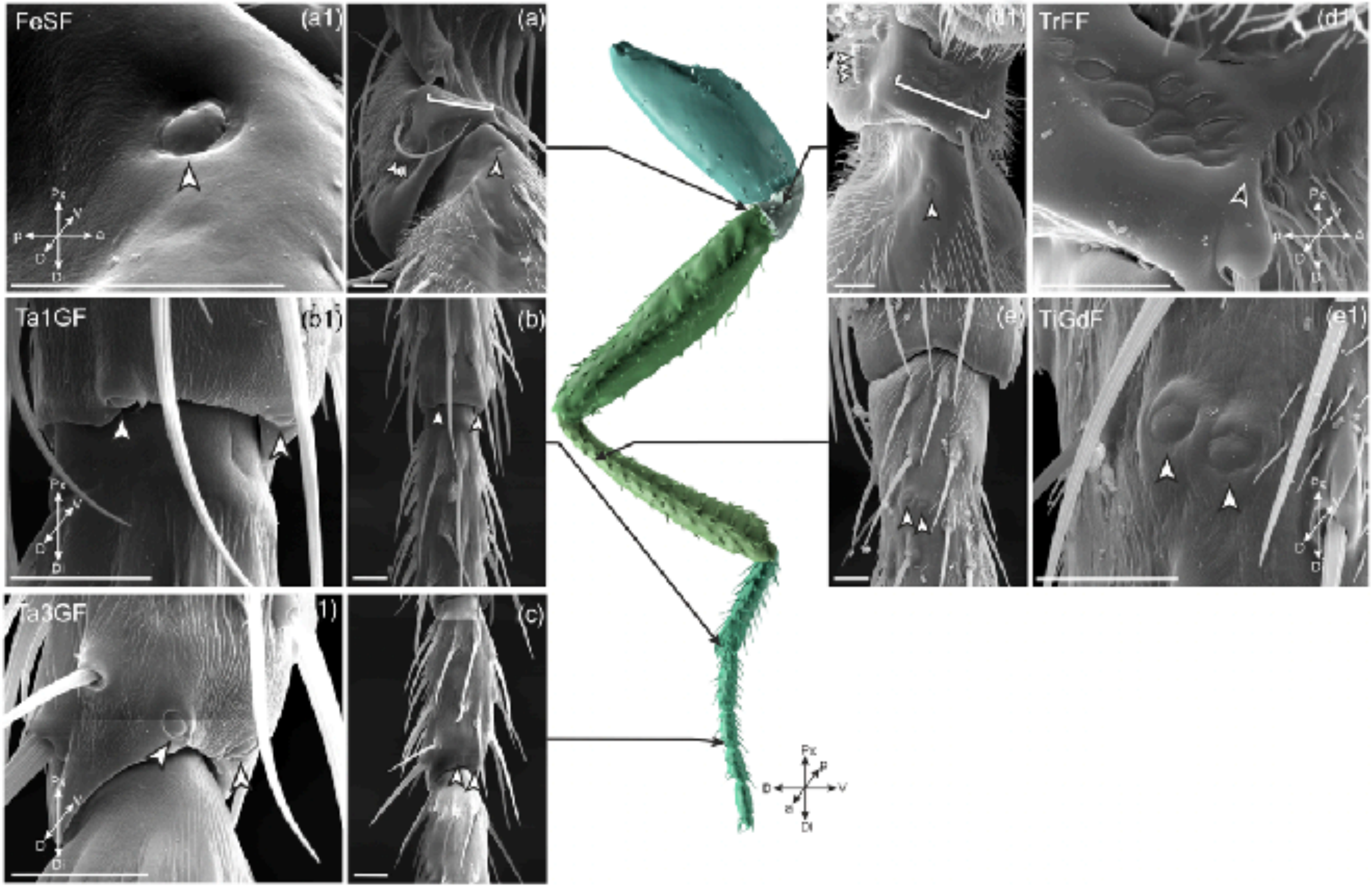
Dinges et al. *J Comp Neurol* 2020

The legs are covered with diverse mechanosensors



Tuthill & Wilson. *Current Biology* 2016

Example mechanosensor: Campaniform sensillae



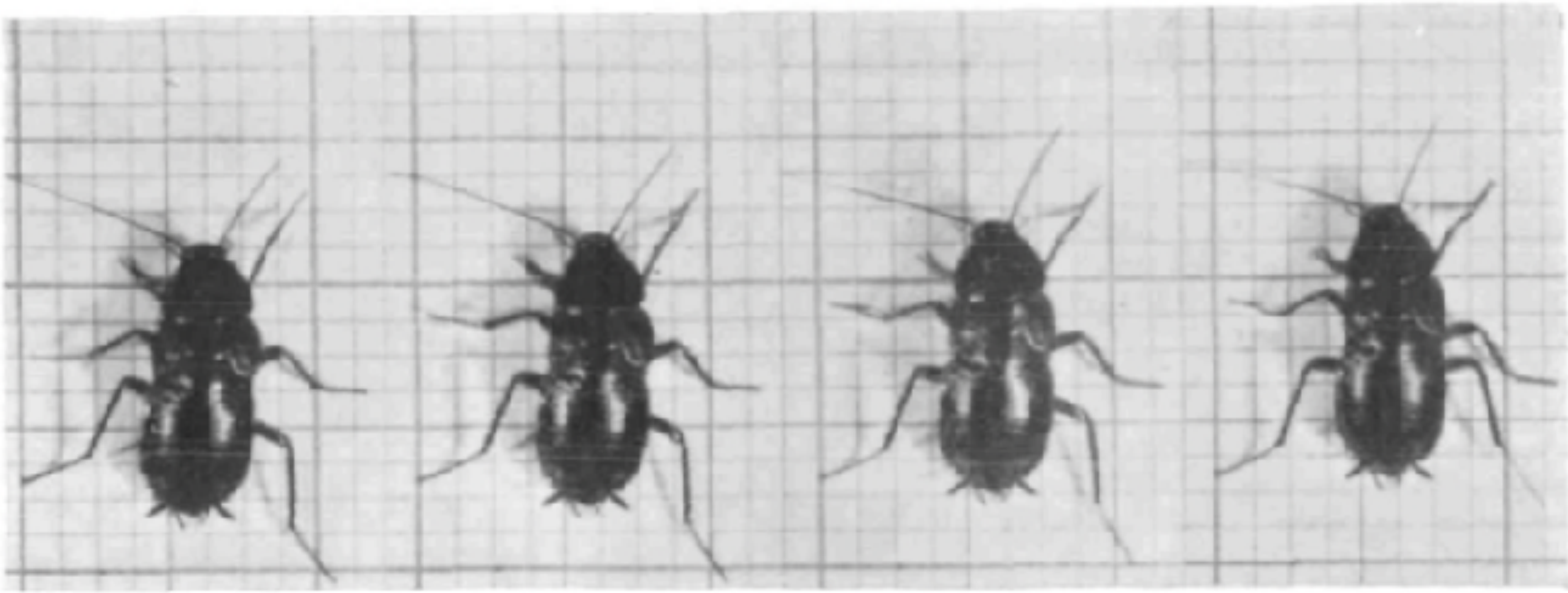
Dinges et al. *J Comp Neurol* 2020

Any questions?

Insect locomotor gaits…

Early account of insect leg coordination

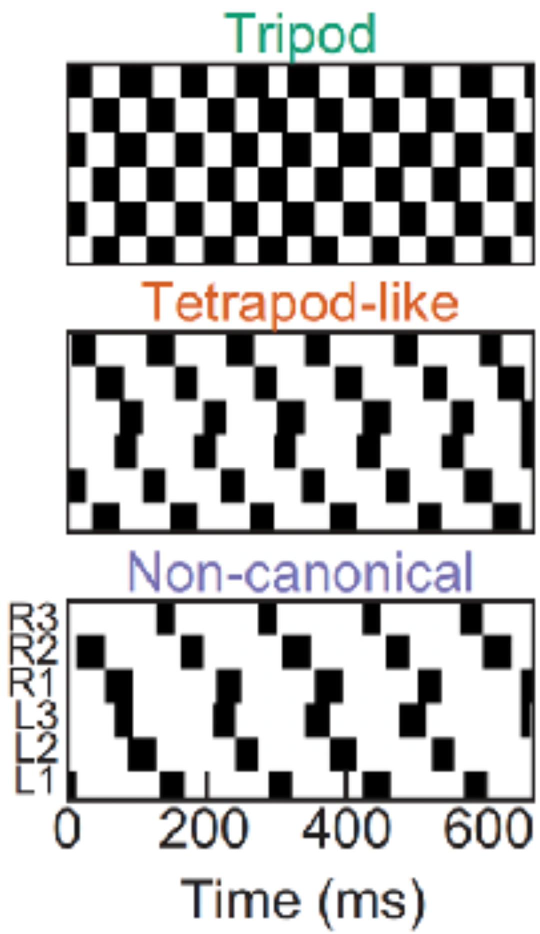
JOURNAL OF EXPERIMENTAL BIOLOGY, 29, 2 PLATE 12

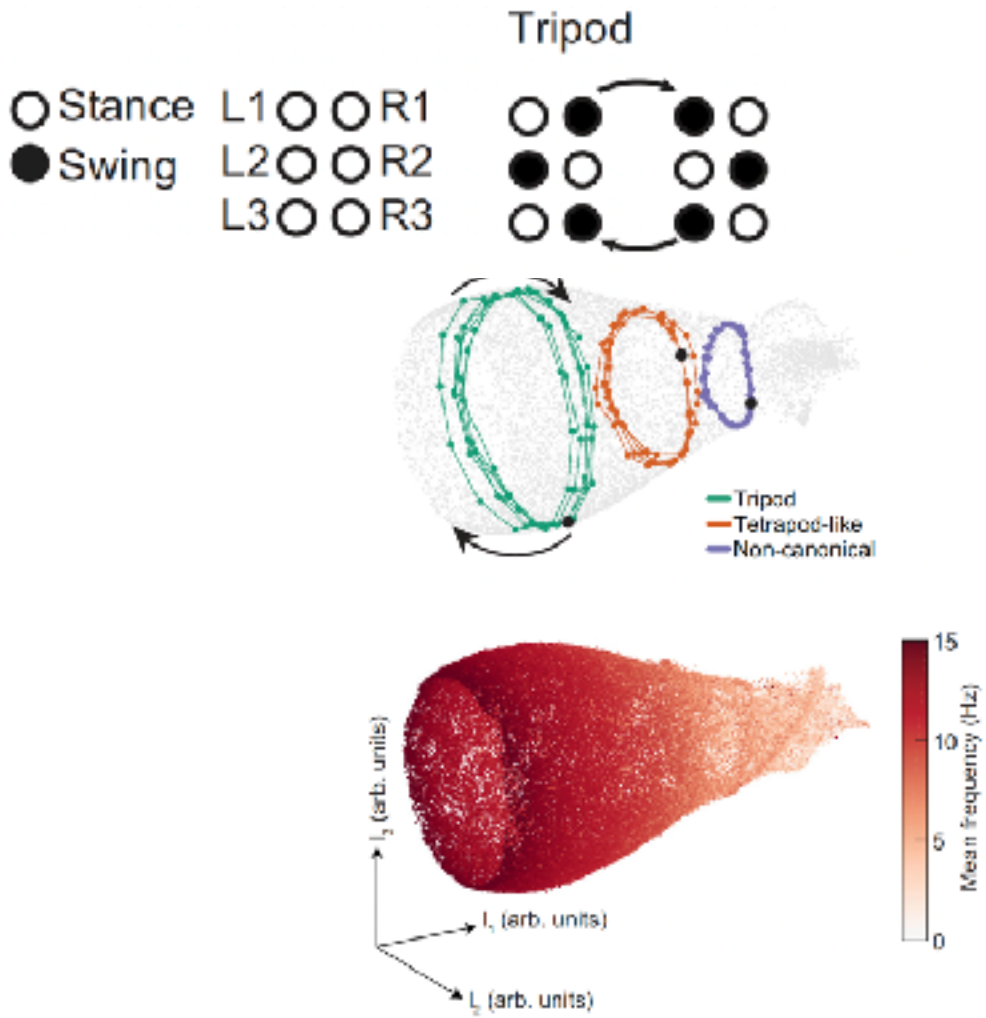


5. Several gaits have been observed, the most common order of protraction being R1, L2, R3, L1, R2, L3, R1, etc., but these grade into one another if the ratio p/r is altered and the two rules obeyed. A system of rigidly alternating tripods would result if the ratio p/r was unity, but this is never quite realized as there is always a delay, sometimes extremely short, between the protraction of the three legs of a triangle. At very slow speeds the rhythm R3, R2, R1, L3, L2, L1, R3, etc., may be present.

Hughes. *JEB* 1951

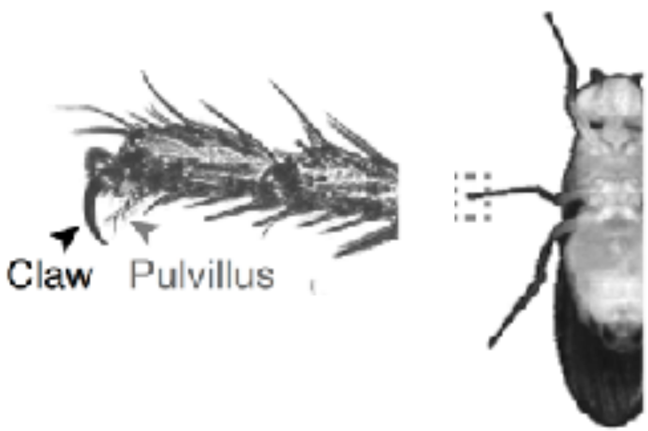
A continuum of interleg coordination

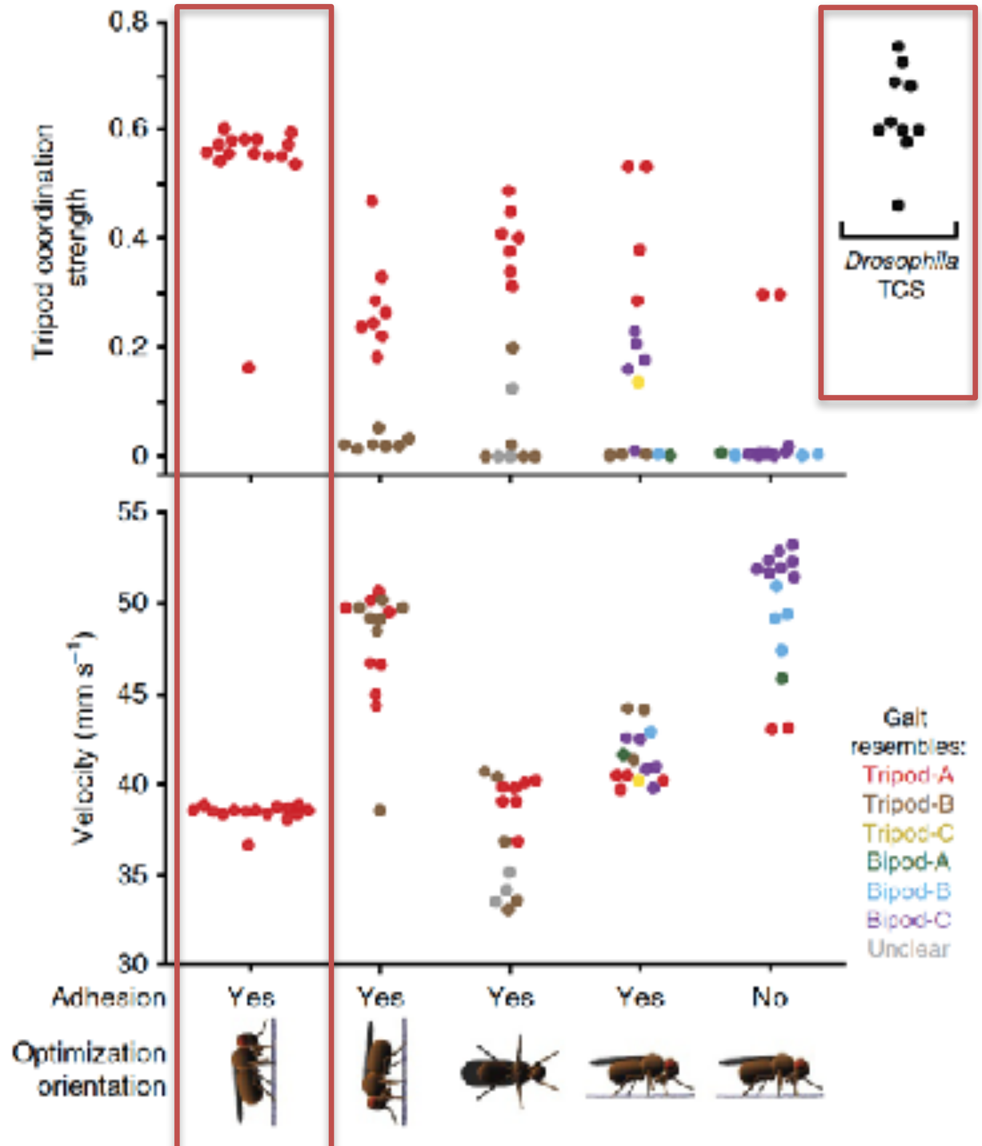




DeAngelis et al. *Elife* 2019

Climbing with leg adhesion favors the tripod gait



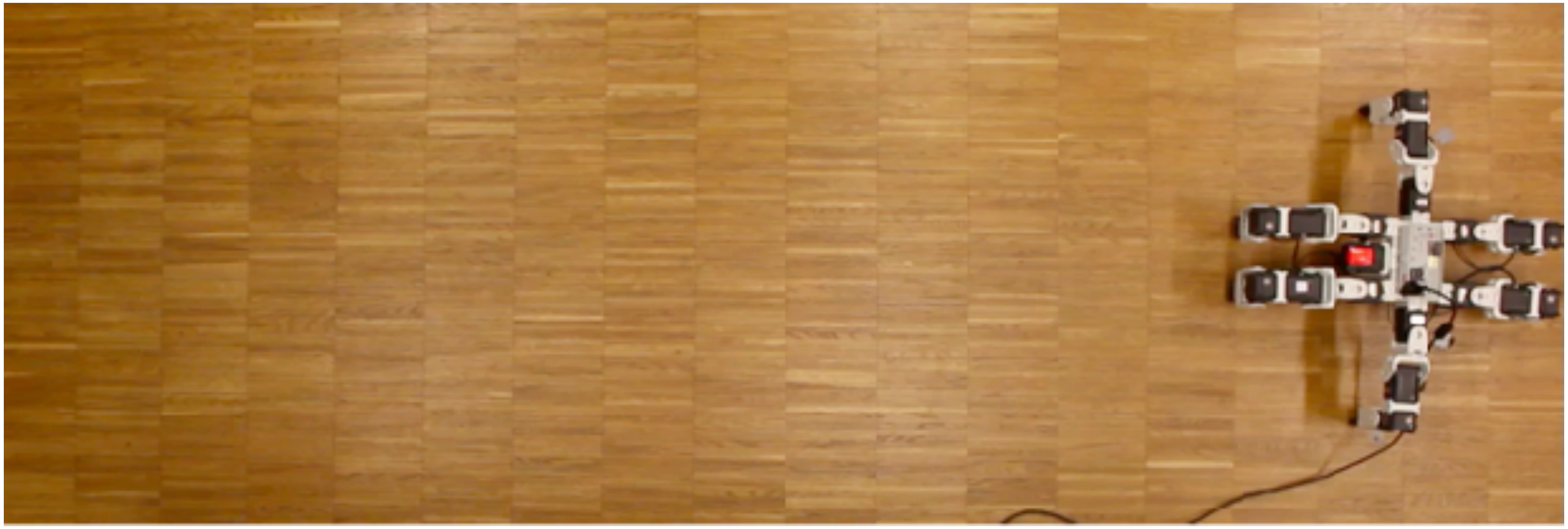


Ramdya, Thandiackal et al. *Nature Communications*, 2017

Bipod gaits are fastest in a robot without adhesion

Tripod

Bipod

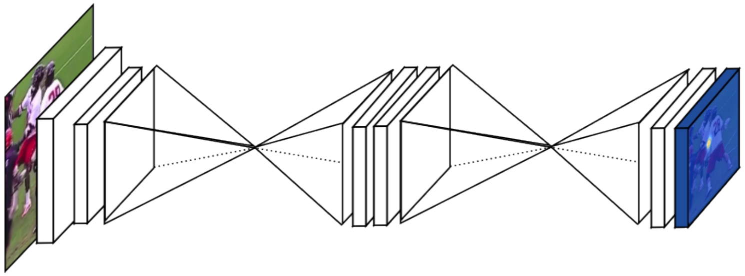


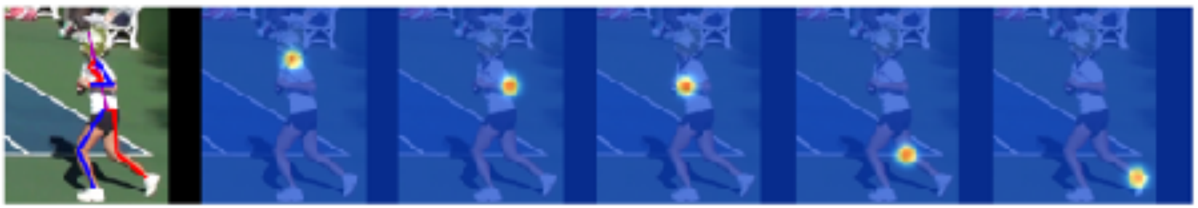
Ramdya, Thandiackal et al. *Nature Communications*, 2017

Any questions?

How do we study motor control in *Drosophila*…

Stacked hourglass deep network for pose estimation





Newell et al. *CVPR*, 2016

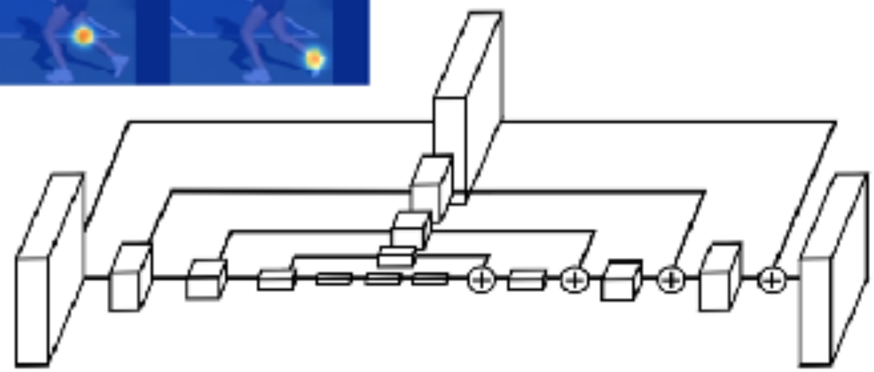


Fig. 3. An illustration of a single "hourglass" module. Each box in the figure corresponds to a residual module as seen in Figure 4. The number of features is consistent across the whole hourglass.

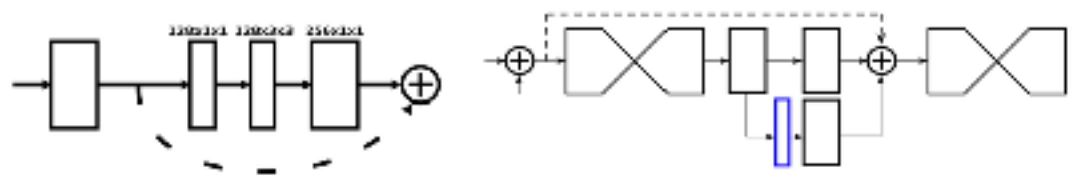
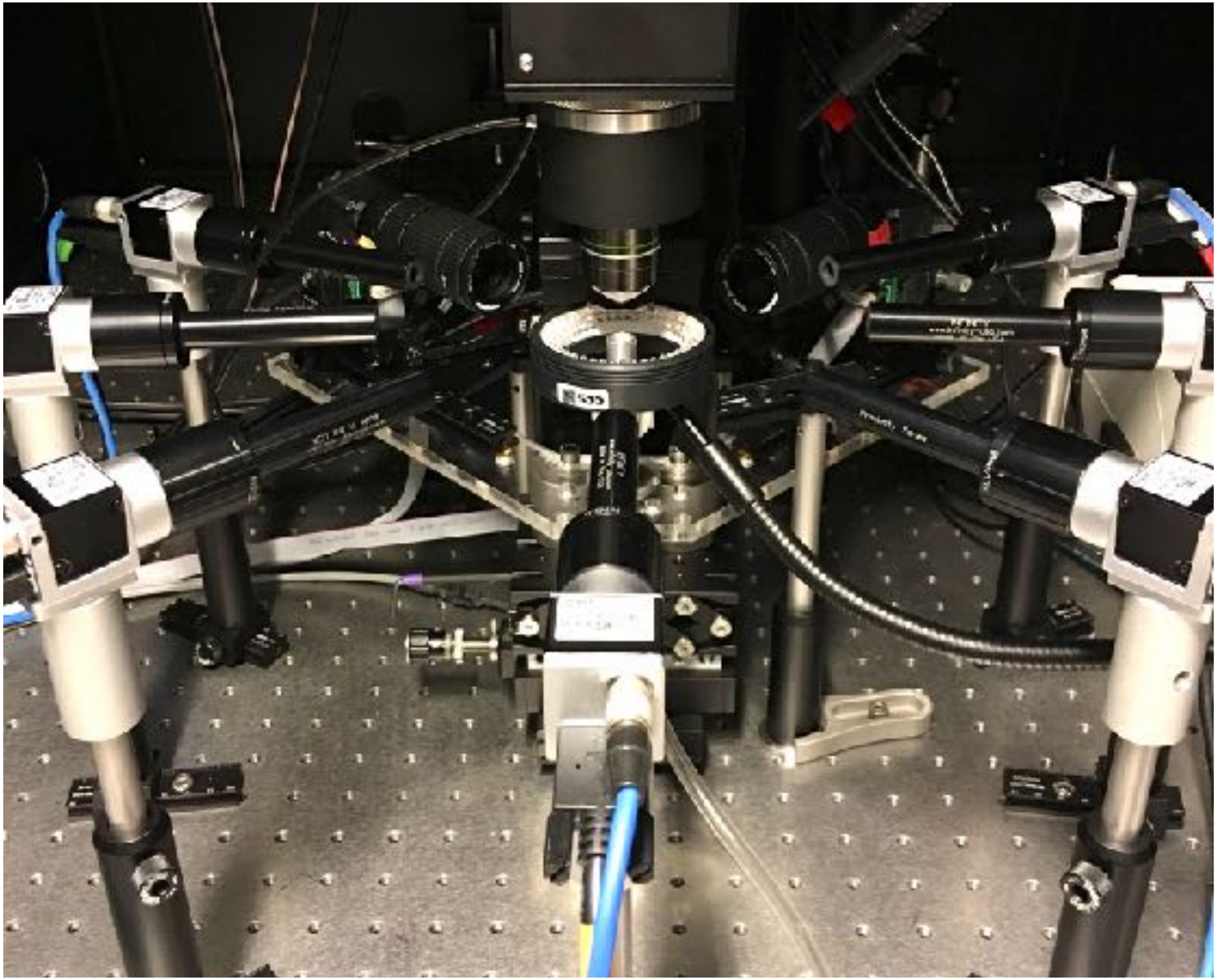


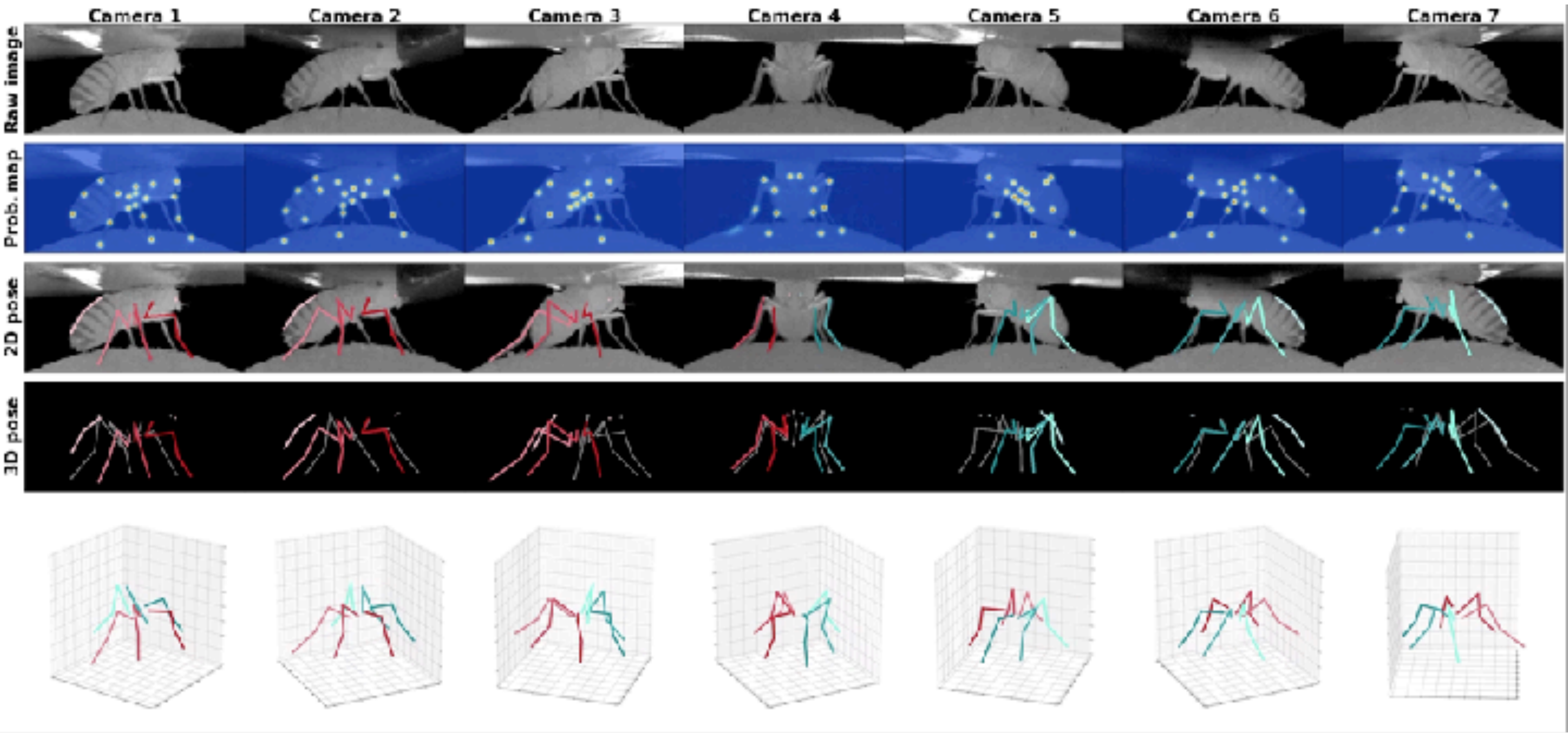
Fig. 4. Left: Residual Module [14] that we use throughout our network. **Right:** Illustration of the intermediate supervision process. The network splits and produces a set of heatmaps (outlined in blue) where a loss can be applied. A 1x1 convolution remaps the heatmaps to match the number of channels of the intermediate features. These are added together along with the features from the preceding hourglass.

DeepFly3D: Deep network-based 3D pose estimation



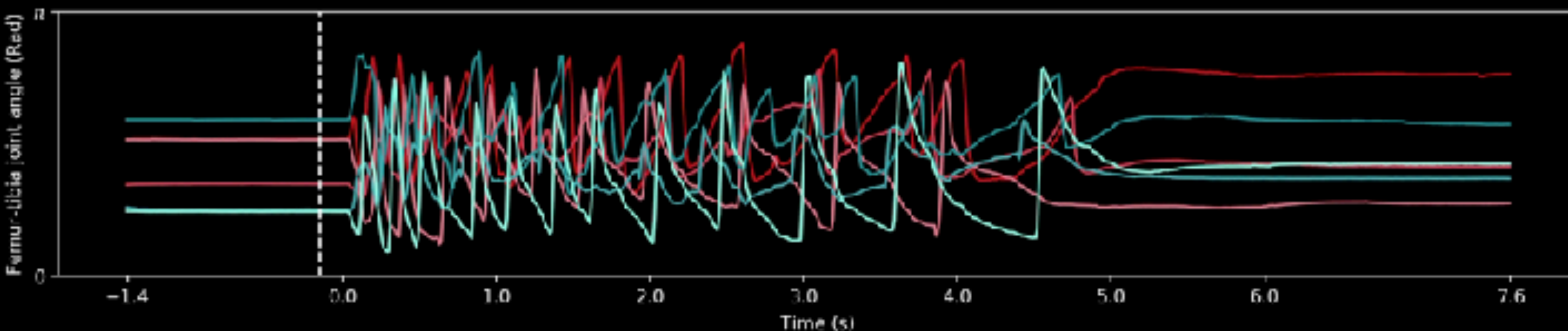
Günel et al. *Elife*, 2019

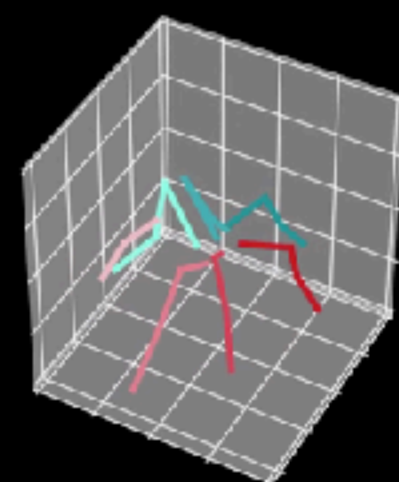
DeepFly3D: Deep network-based 3D pose estimation



Günel et al. *Elife*, 2019

DeepFly3D: Deep network-based 3D pose estimation

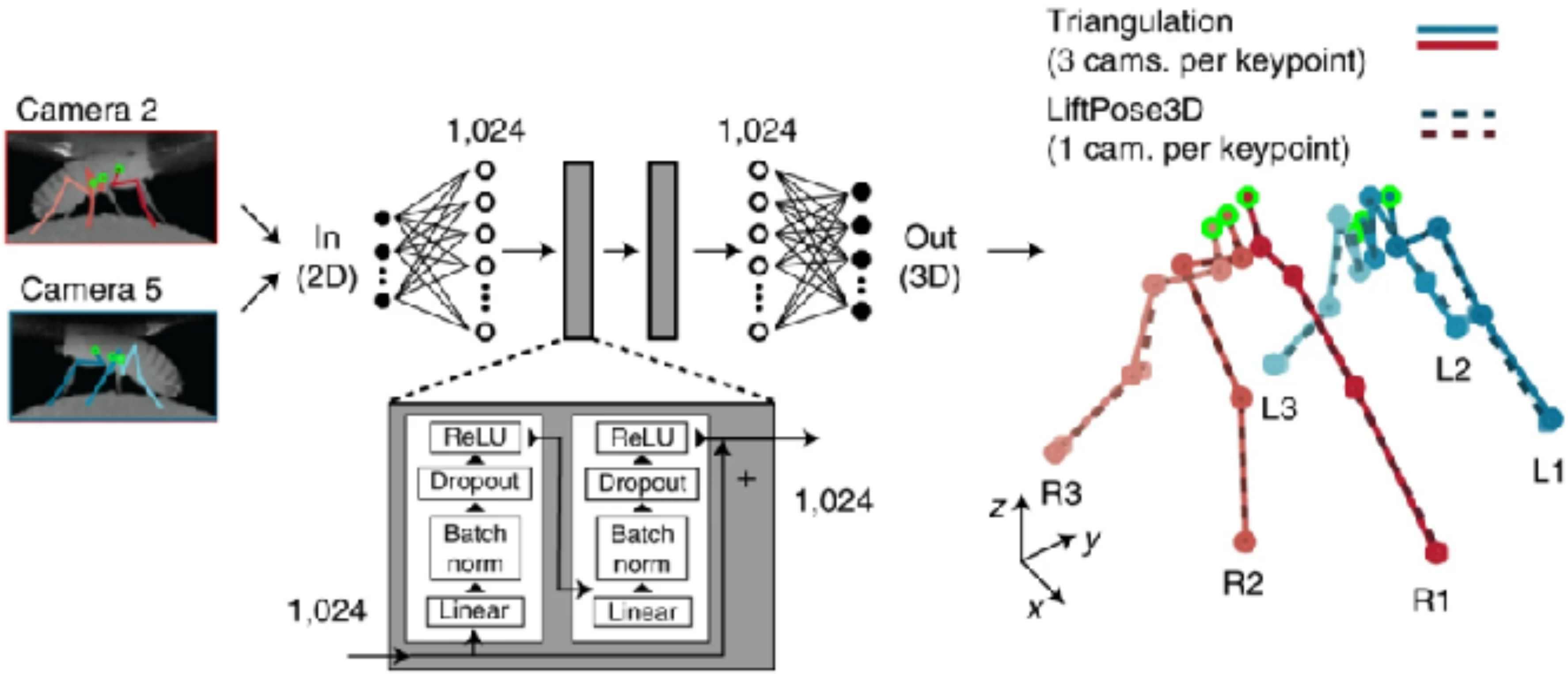




~0.3x real-time

Günel et al. *Elife*, 2019

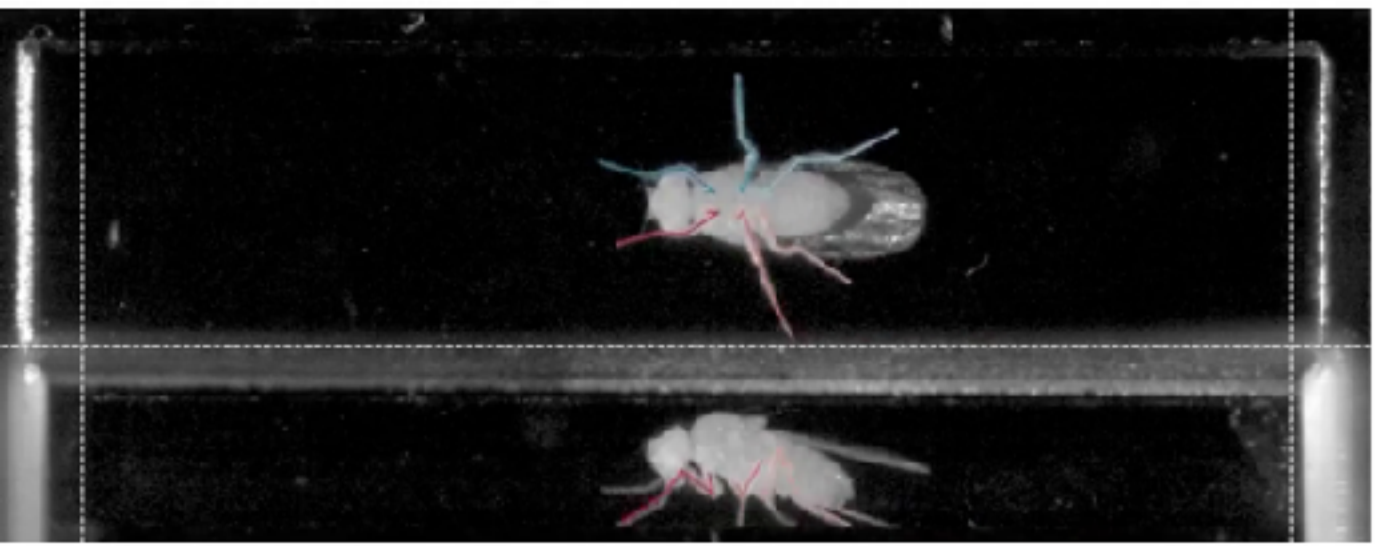
LiftPose3D: lifting 2D pose to 3D pose

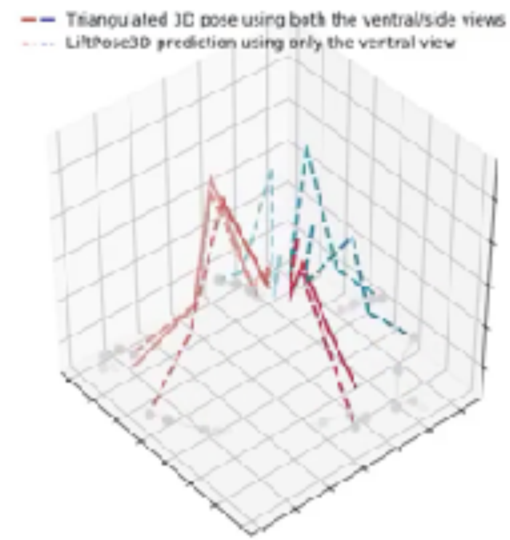


adapted from Martinez et al. *ICCV 2017*

Gosztolai, Günel et al. *Nature Methods* 2021

LiftPose3D: obtaining 3D poses for obscured, or partially triangulated keypoints





Gosztolai, Günel et al. *Nature Methods* 2021

More pose estimation tools

ELSEVIER

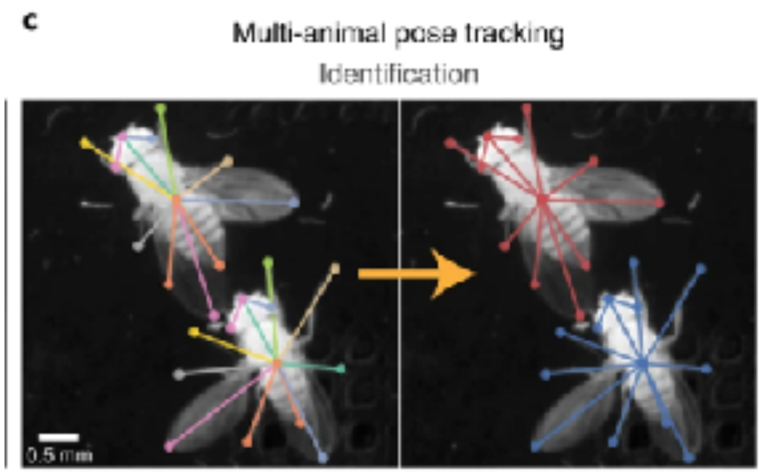
Current Opinion in Neurobiology
Volume 73, April 2022, 102522

Perspective

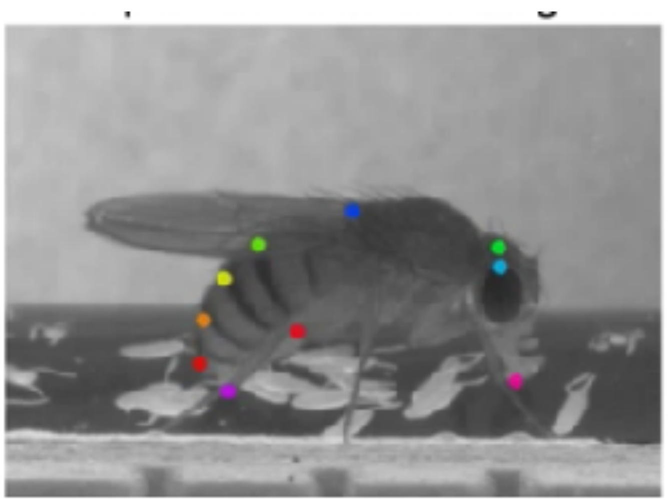
Leaving flatland: Advances in 3D behavioral measurement

Jesse D. Marshall[1], Tianqing Li[2], Joshua H. Wu[2], Timothy W. Dunn[2]

SLEAP



Pereira et al., 2022 *Nature Methods* 2022



DeepLabCut

Mathis et al. *Nature Neuro.* 2018

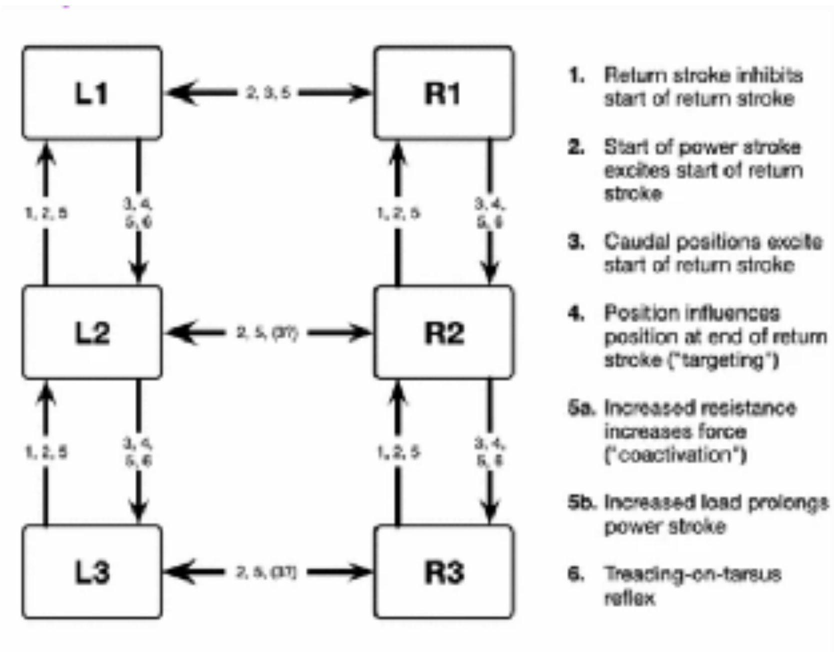
Any questions?

What can we decipher underlying locomotor algorithms in *Drosophila*?

Prominent algorithms for interleg coordination

(Decentralized)

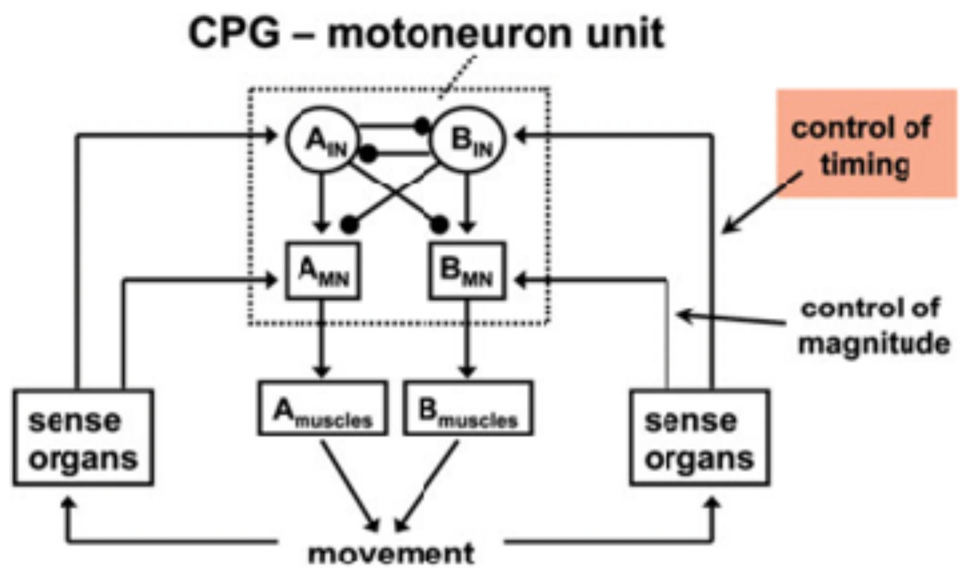
Rule-based controller



Schilling et al. *Biol Cyber.* 2013

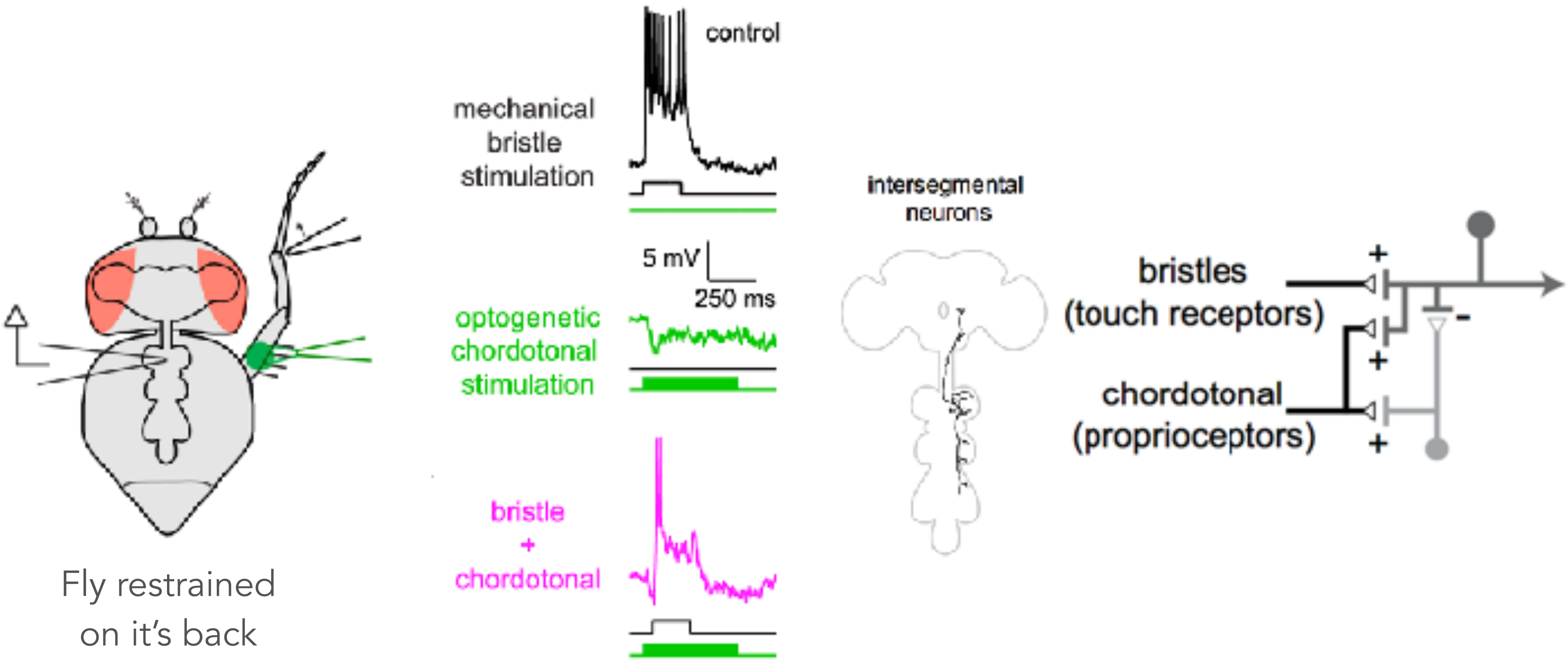
(Centralized)

CPG network-based controller



Daun-Gruhn. *J Comput Neurosci.* 2011

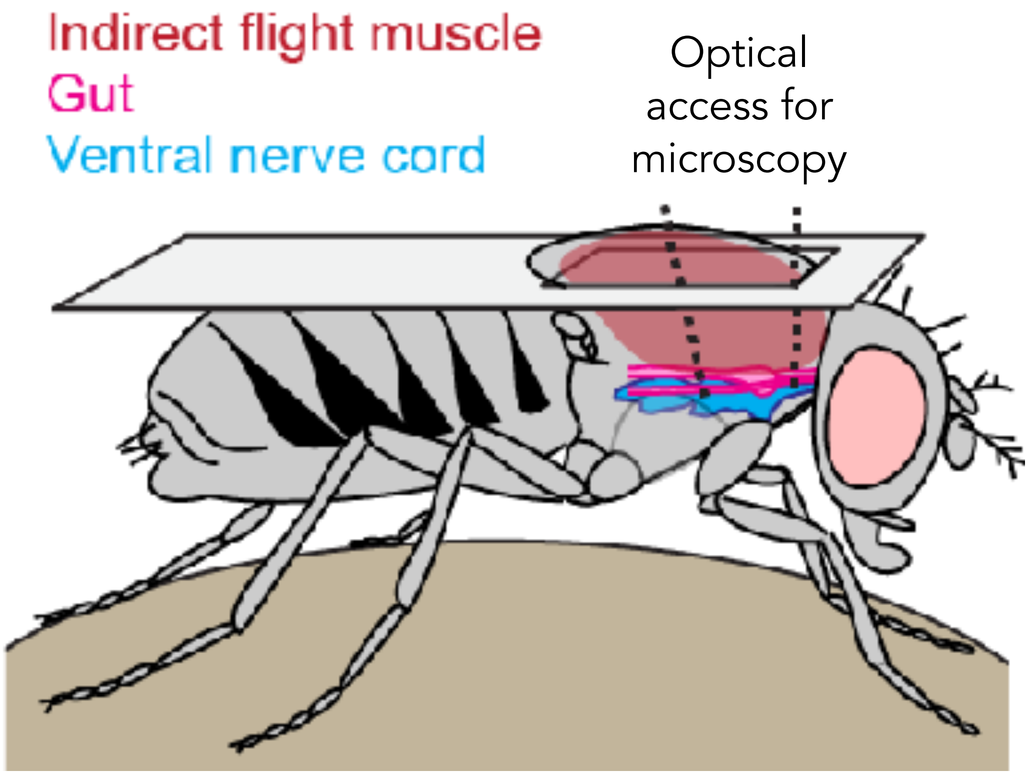
Recording motor circuits in restrained animals



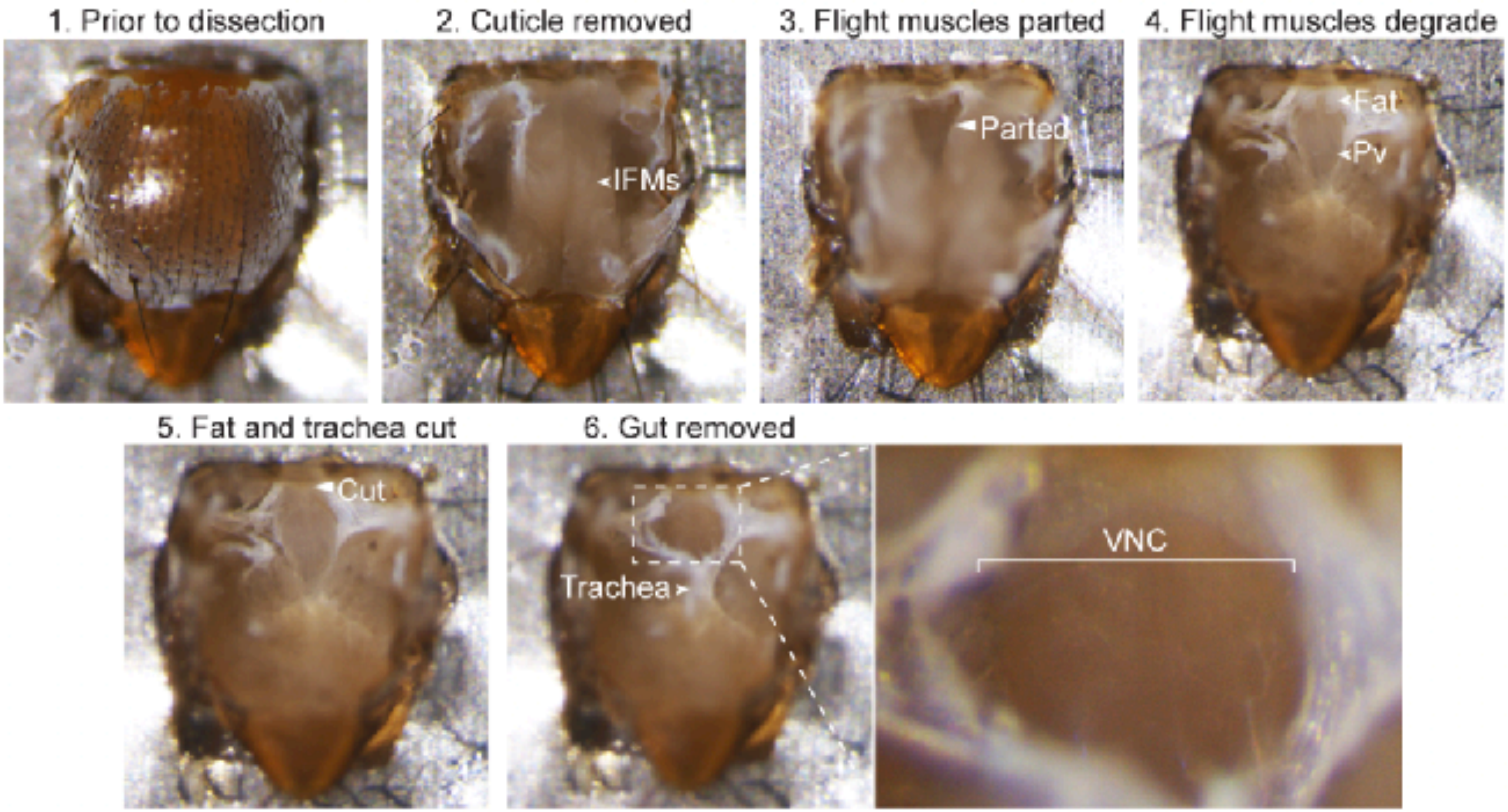
Fly restrained on it's back

Tuthill & Wilson, *Cell* 2016

Recording motor circuits in *behaving* animals

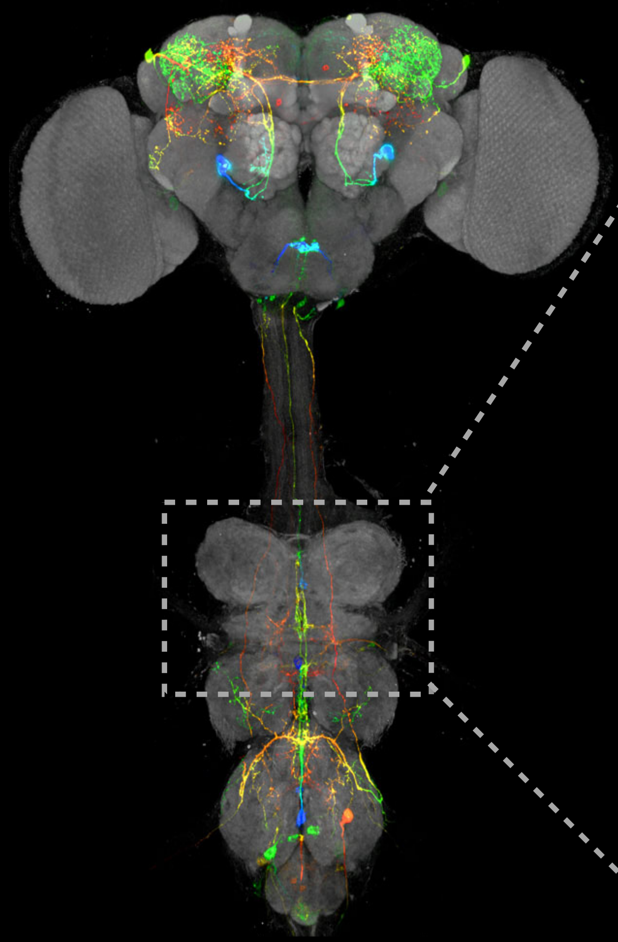


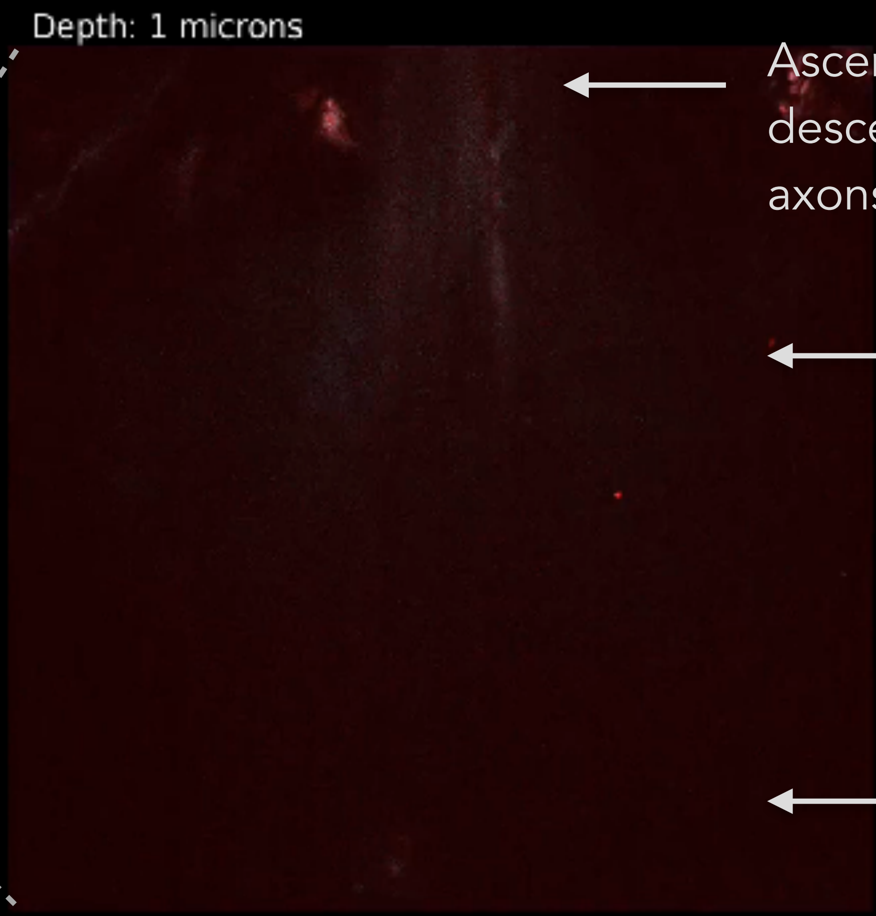
Recording motor circuits in *behaving* animals



Chen, Hermans et al., *Nature Communications*, 2018

Recording motor circuits in *behaving* animals



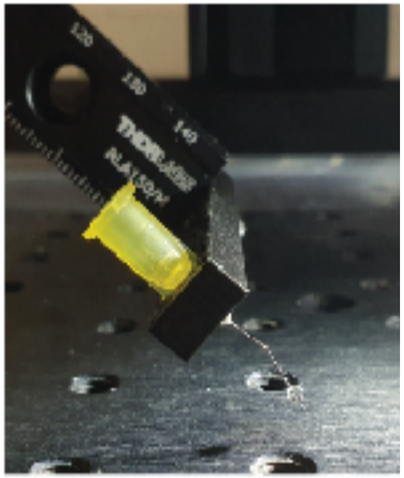


Functional responses (GCaMP6s)
Anatomical marker (tdTomato)

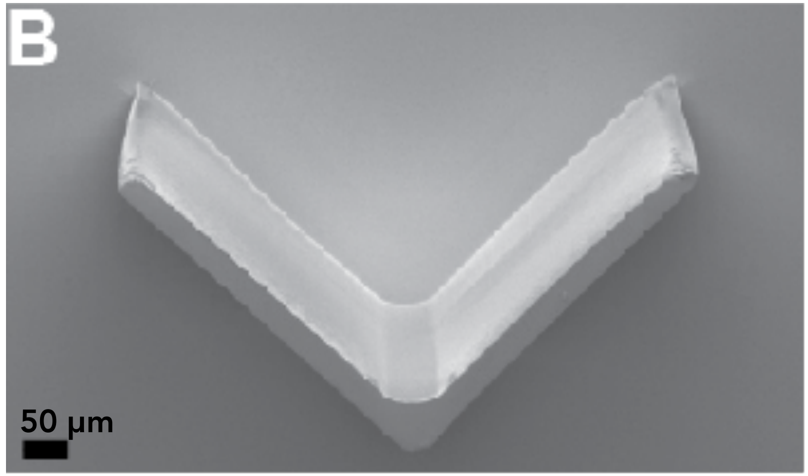
Chen, Hermans et al., *Nature Communications*, 2018

Recording motor circuits across a lifetime

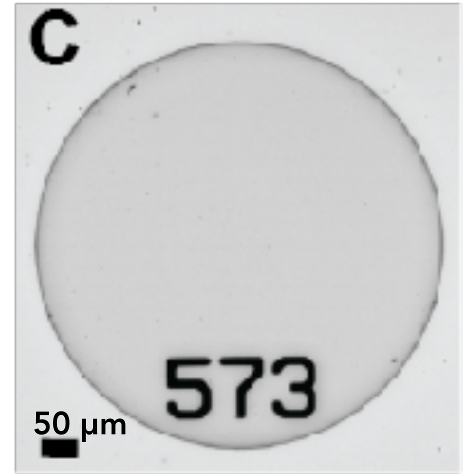
Dissection arm

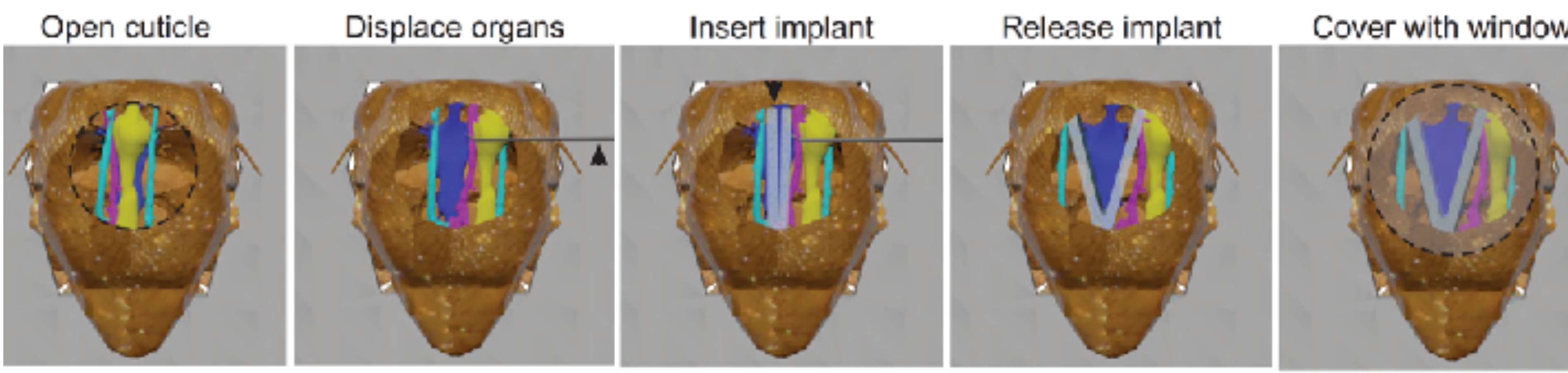


Thoracic implant



Thoracic window





Opening the cuticle

10x real-time

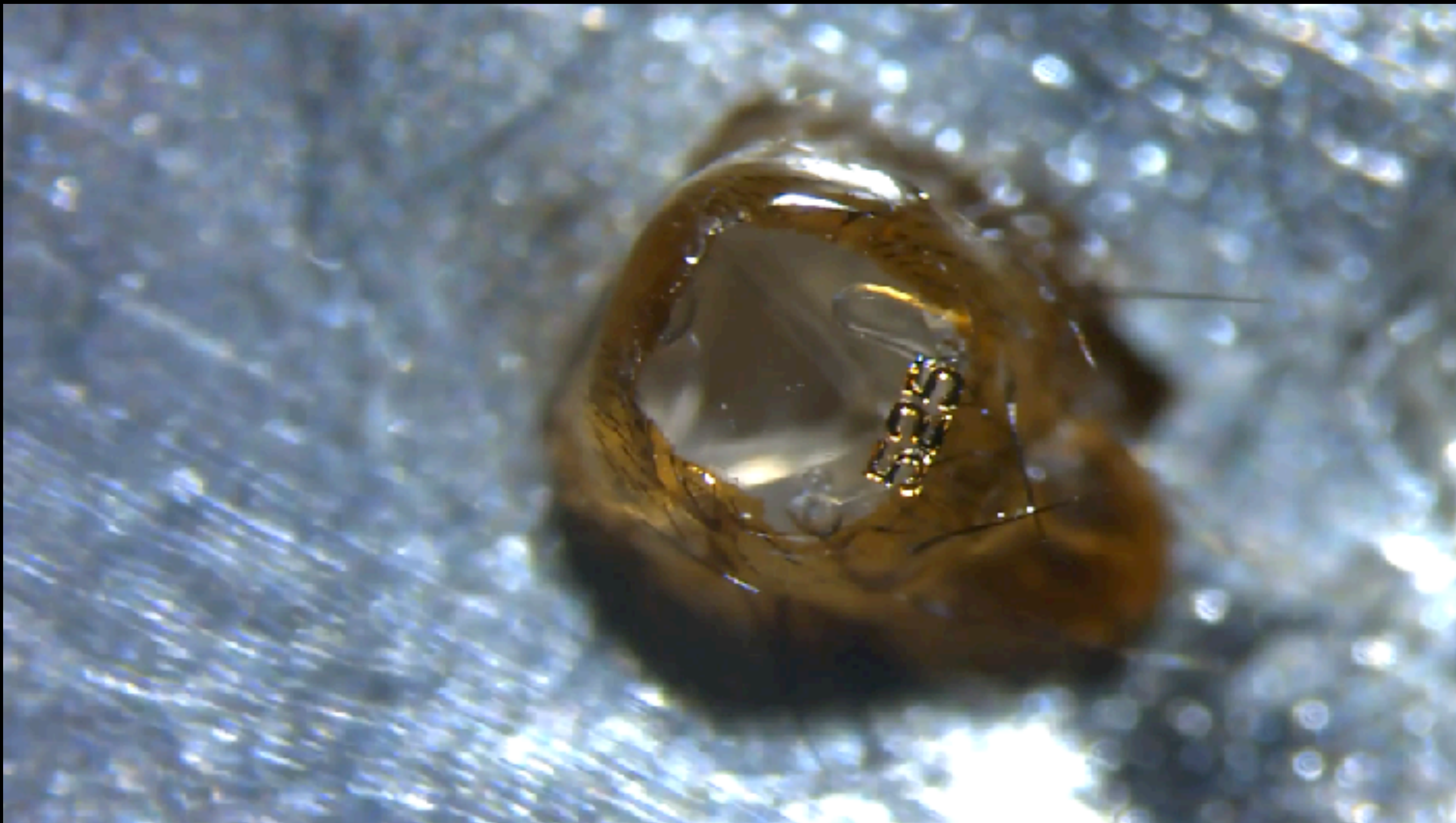
Inserting and positioning an Ostemer implant

40x real-time

Replacing cuticle with a numbered SU-8 window

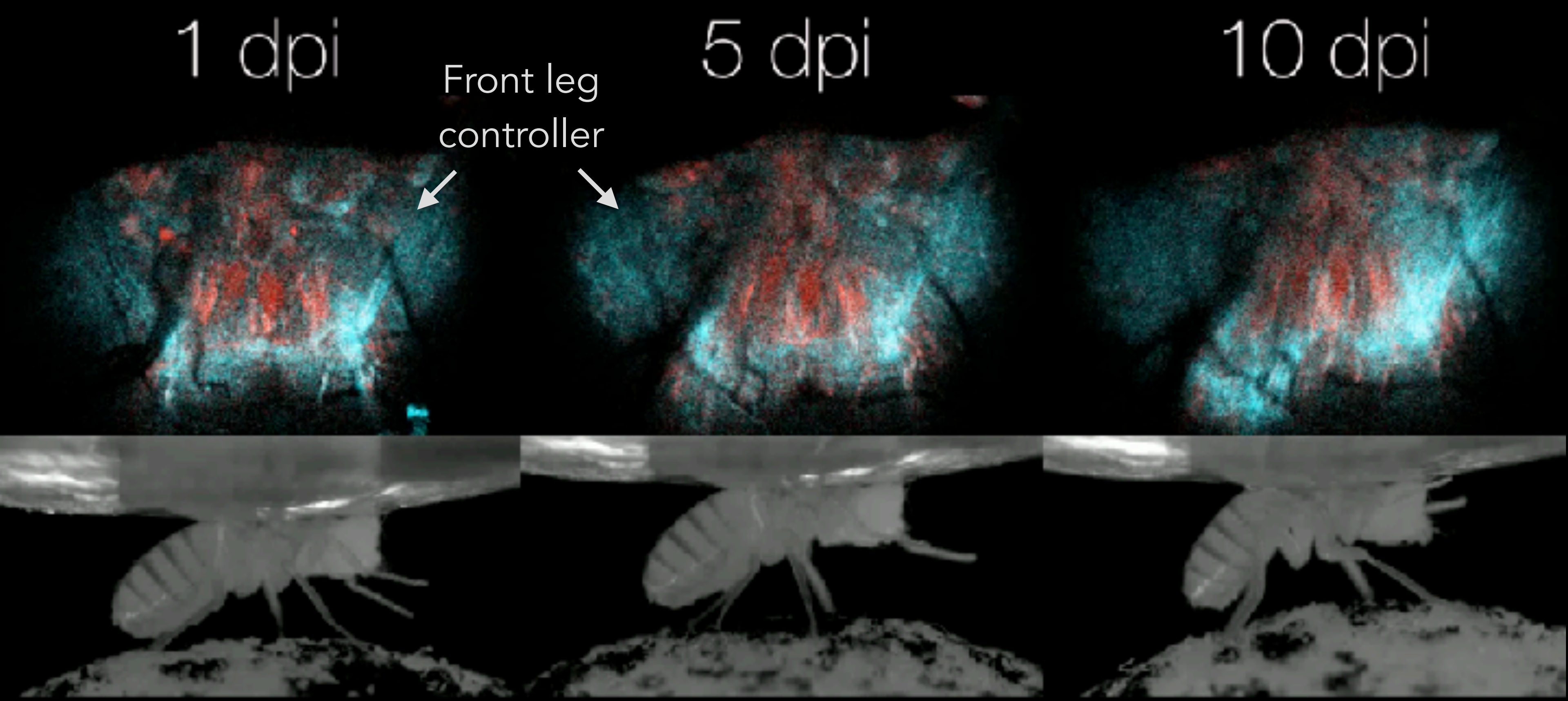
20x real-time

Dismounting after implantation



Hermans, Kaynak et al., *Nature Communications* 2022

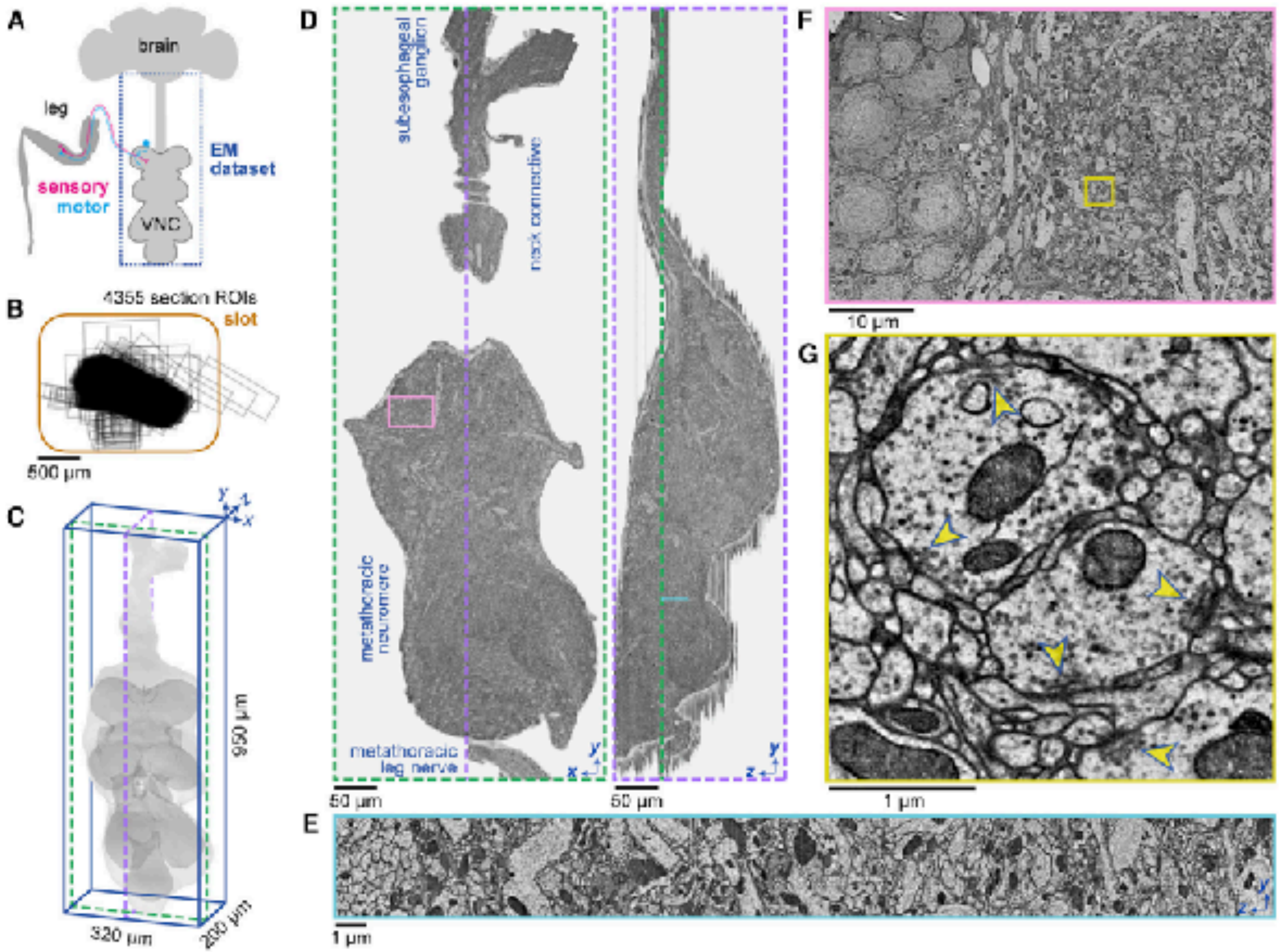
Repeatedly imaging the motor system of one fly



Functional responses (GCaMP6s)
Anatomical marker (tdTomato)
dpi = days post implantation

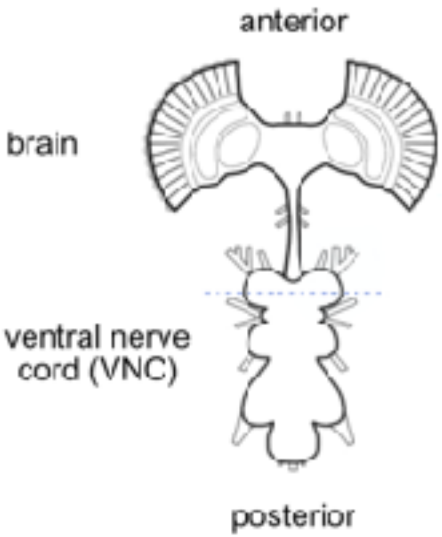
Hermans, Kaynak et al., *Nature Communications* 2022

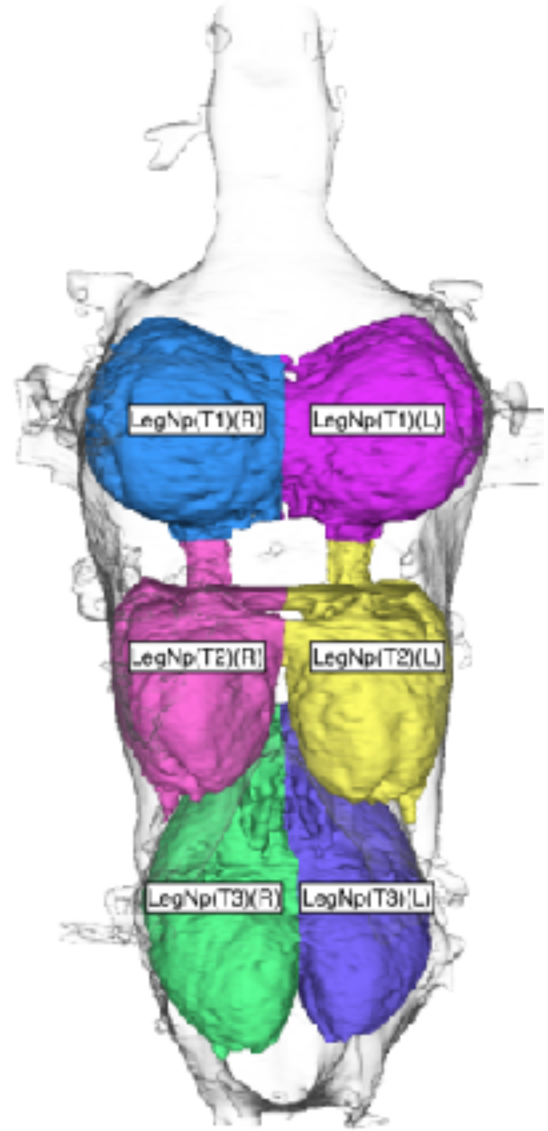
Obtaining a motor system (VNC) connectome



Phelps et al. *Cell* 2021

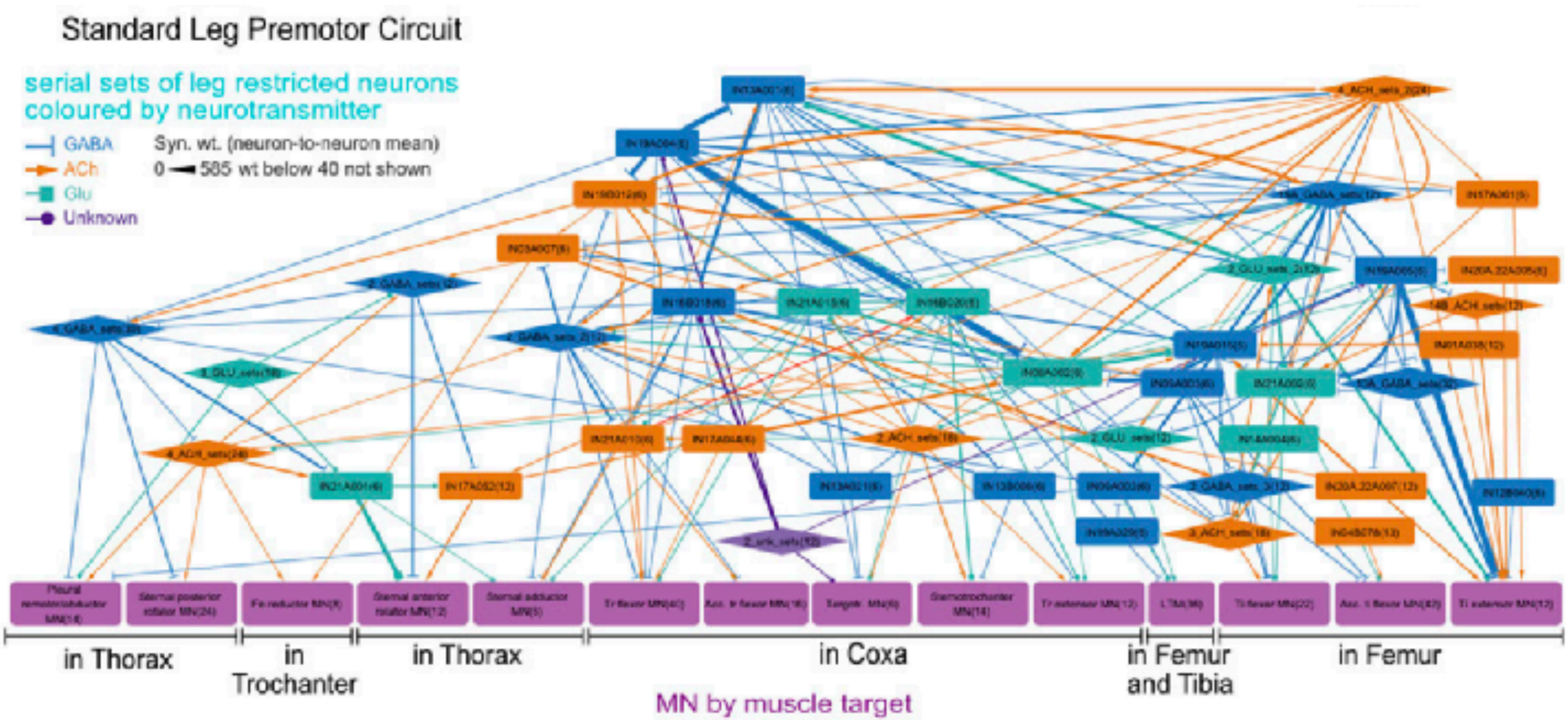
A male *Drosophila* motor system (VNC) connectome





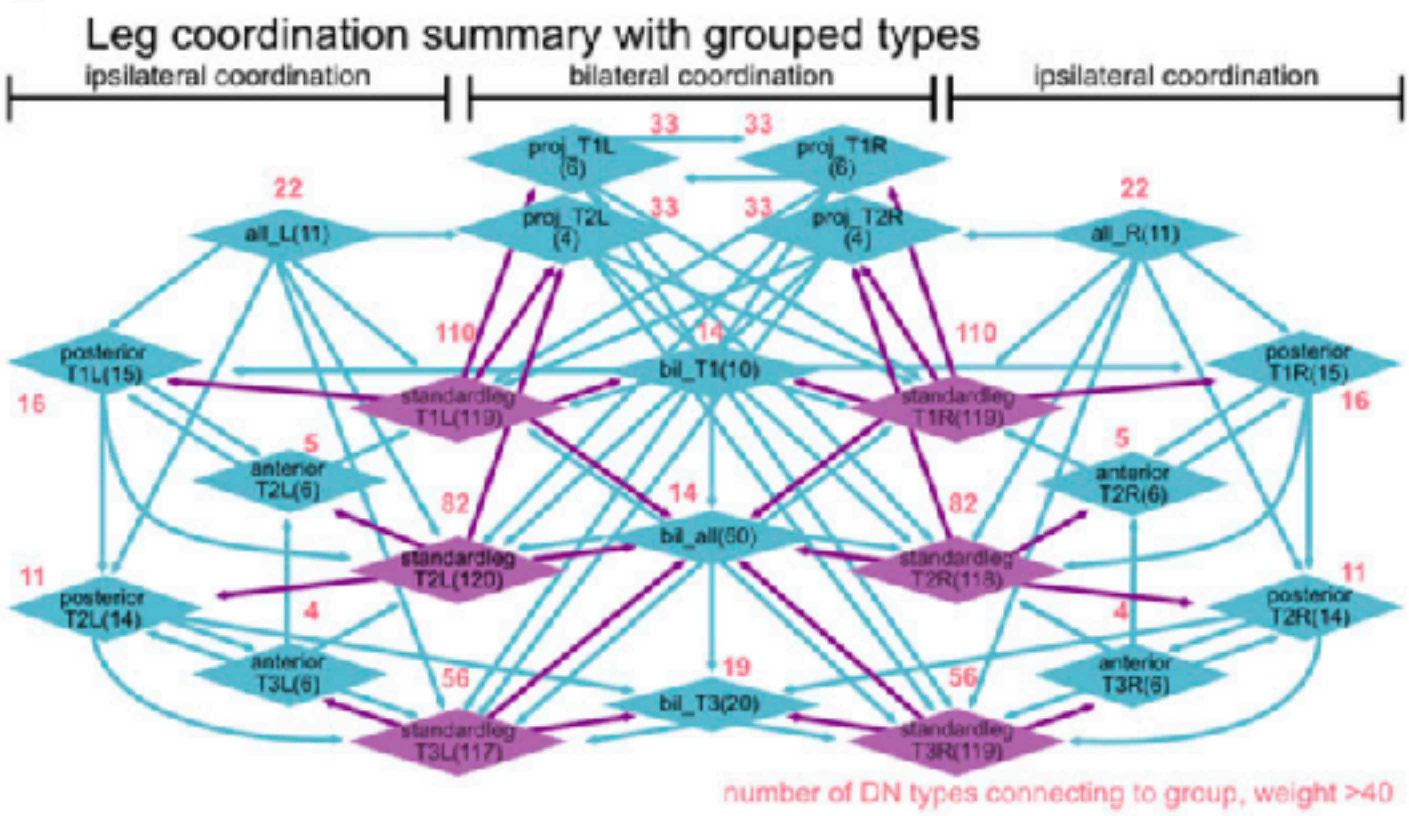
Takemura et al. *bioRxiv* 2023

A repeated graph for each leg



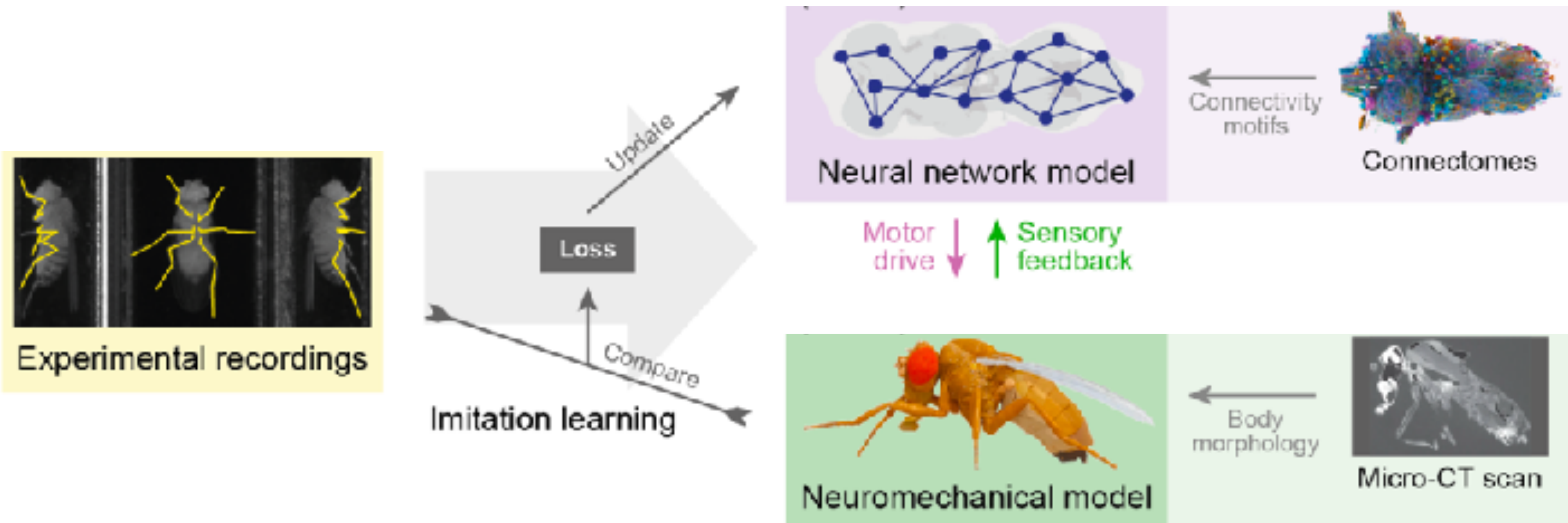
Cheong et al. *bioRxiv* 2023

A graph for gait coordination between legs



Cheong et al. *bioRxiv* 2023

An approach for linking networks to behavior



Sibo Wang

Any questions?

Today's papers:

How can we use simulations to investigate *Drosophila* locomotion and sensorimotor neuroscience?