EPFL

NeuroMechFly, a neuromechanical model of adult Drosophila melanogaster

Controlling behavior in animals and robots

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Introduction

NeuroMechFly, a neuromechanical model of adult *Drosophila melanogaster*

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Animal behavior emerges from an interaction between neural network dynamics, musculoskeletal properties and the physical environment. Accessing and understanding the interplay between these elements requires the development of integrative and morphologically realistic neuromechanical simulations. Here we present NeuroMechFly, a data-driven model of the widely studied organism, *Drosophila melanogaster*. NeuroMechFly combines four independent computational modules: a physics-based simulation environment, a biomechanical exoskeleton, muscle models and neural network controllers. To enable use cases, we first define the minimum degrees of freedom of the leg from real three-dimensional kinematic measurements during walking and grooming. Then, we show how, by replaying these behaviors in the simulator, one can predict otherwise unmeasured torques and contact forces. Finally, we leverage NeuroMechFly's full neuromechanical capacity to discover neural networks and muscle parameters that drive locomotor gaits optimized for speed and stability. Thus, NeuroMechFly can increase our understanding of how behaviors emerge from interactions between complex neuromechanical systems and their physical surroundings.

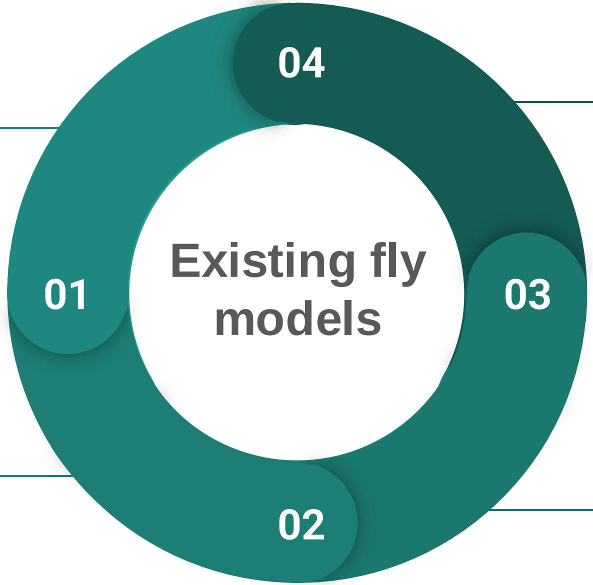
NeuroMechFly

- Neuromechanical model of the Drosophila
- Open-source computational framework
- 4 independent computational modules :
  - Physics-based simulation environment
  - Biomechanical exoskeleton
  - Muscle models
  - Neural network controllers

Scientific Background

Neuromechanical models

Quantification of behaviour kinematics



Connectomics data

Genetic targeting of neurons for recordings and perturbations

Scientific Background :

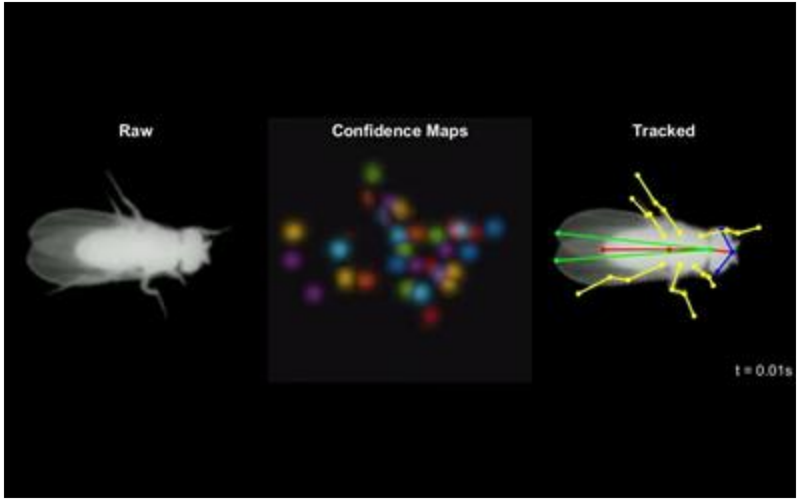
OpenWorm

Szigeti, B. et al. Openworm: an open-science approach to modeling *Caenorhabditis elegans*. *Front. Comput. Neurosci.* 8, 137 (2014)

Scientific Background :

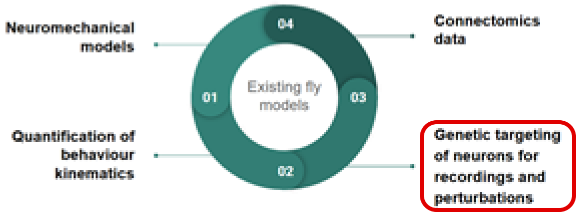
LEAP

- Deep-learning-based method for predicting the positions of animal body parts
- Graphical interface for labeling of body parts and training the network
- Offers fast predictions on new data

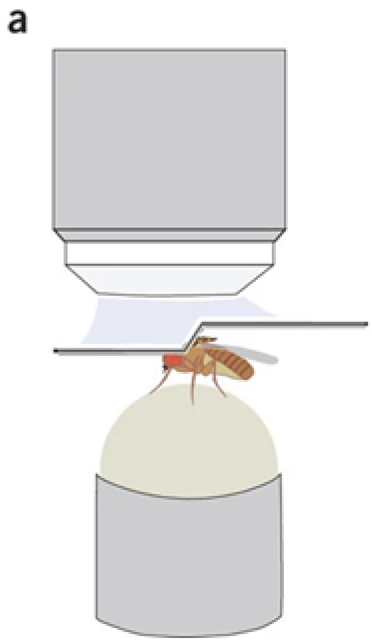


Pereira, T. D. et al. Fast animal pose estimation using deep neural networks. *Nat. Methods* 16, 117–125 (2019)

Scientific Background :

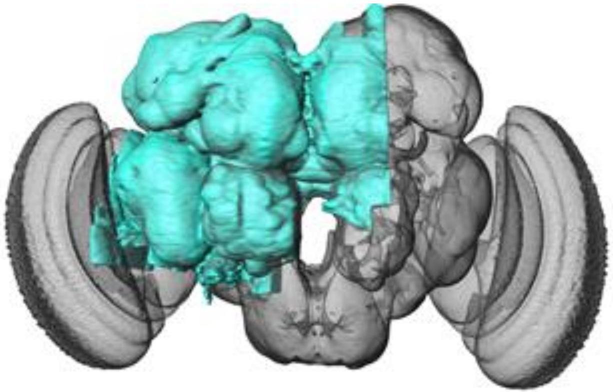


- Two-photon calcium imaging
- Genetically encoded calcium sensor
- Monitor behaviour and physiology



Seelig, J. D. et al. Two-photon calcium imaging from head-fixed *Drosophila* during optomotor walking behavior. *Nat. Methods* 7, 535–540 (2010)

Scientific Background :



- Present the circuitry of a large fraction of the brain of the fruit fly *Drosophila melanogaster*
- Provide detailed circuits consisting of neurons and their chemical synapses

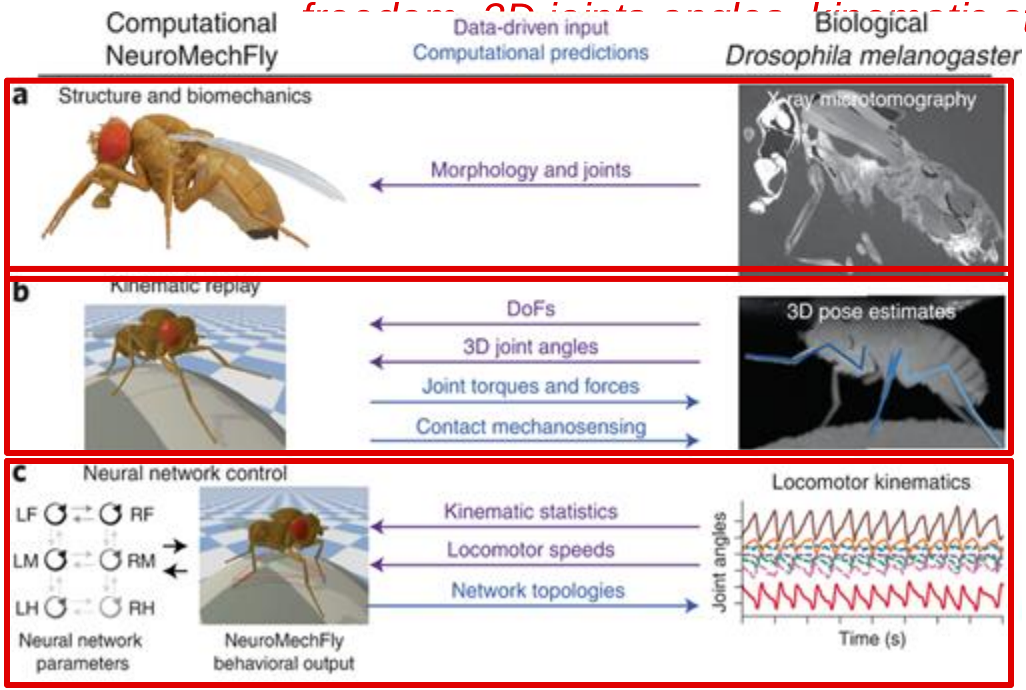
Scheffer, L. K. et al. A connectome and analysis of the adult *Drosophila* central brain. *eLife* 9, e57443 (2020)

Limitations of Previous Models

- Lack morphological accuracy, needed for mass distribution, compliance and physical constraints
- Lack muscle models and their associated passive dynamical properties
- Lack neural networks or other control architectures

Methods

Goal : Obtained the model's *biomechanical exoskeleton* and defined the *degrees of freedom, 3D joints angles, kinematic statistics* and *locomotor speeds*

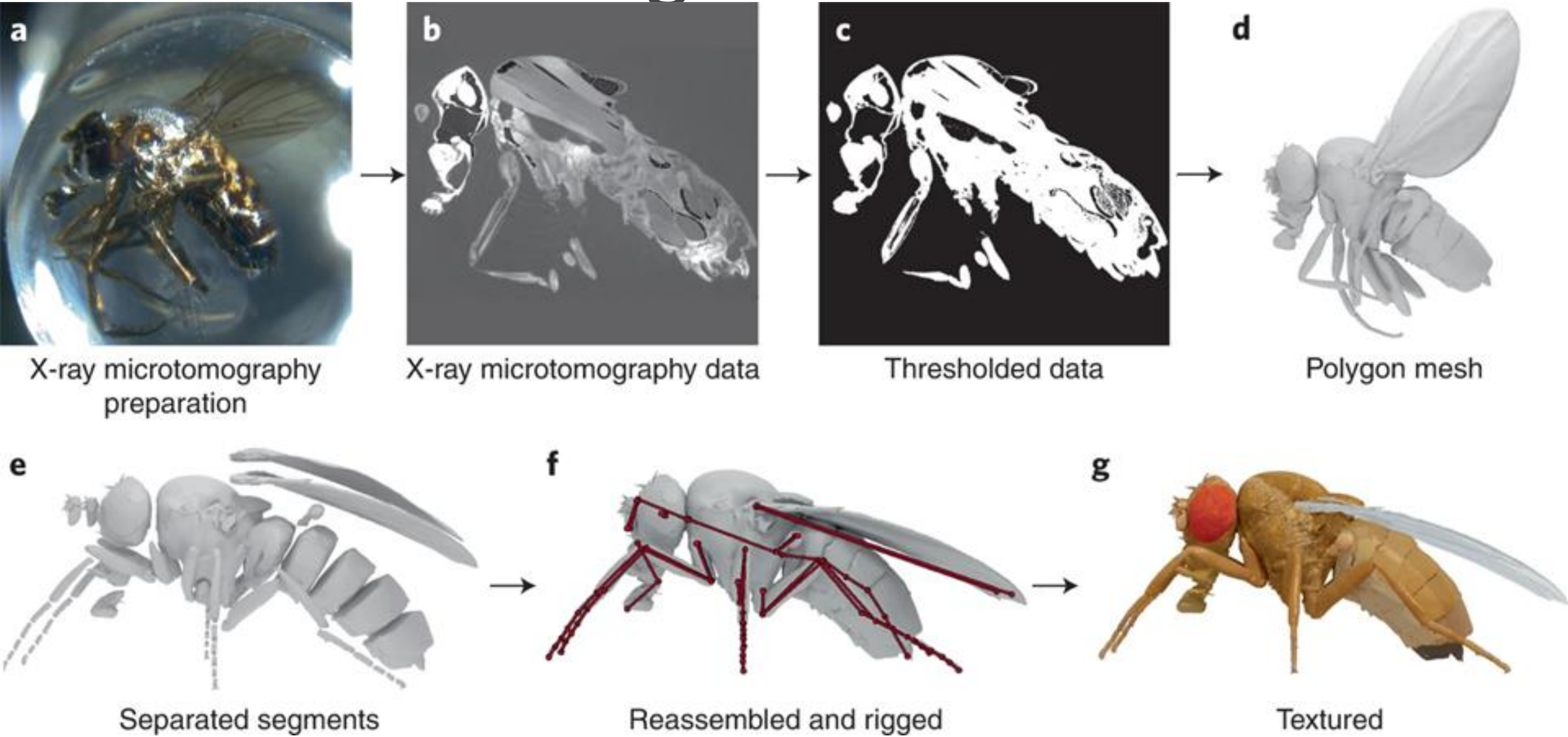


a. Obtained model's exoskeleton and joints

b. Inferred **ground reaction forces**, **joint torques**, and **tactile contacts** by replaying measured leg kinematics in a biomechanical simulation.

c. Real limb kinematics guided evolutionary optimization of neuromuscular parameters.

Constructing the Biomechanical Model



Identification of the minimum DoFs

Goal : Have a *minimum number* of DoF because we want to build the *simplest* possible model.

To **construct the leg's kinematics**, they focused on **two** main movements :

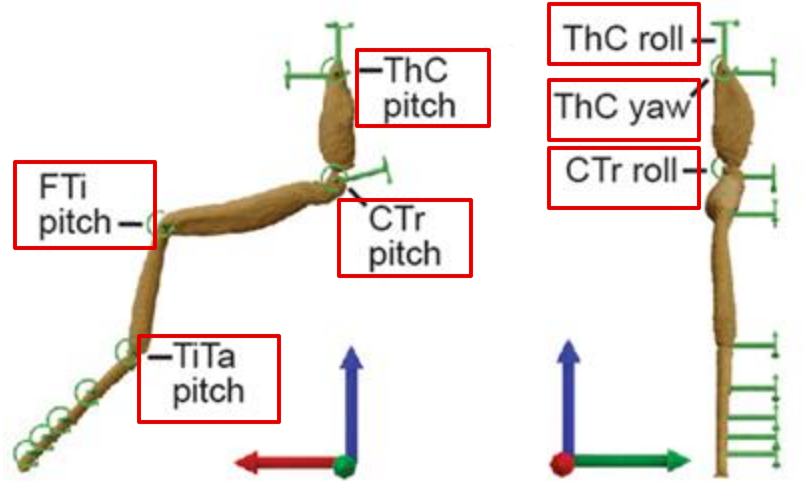
Forward walking	**Grooming**
	

Identification of the minimum DoFs

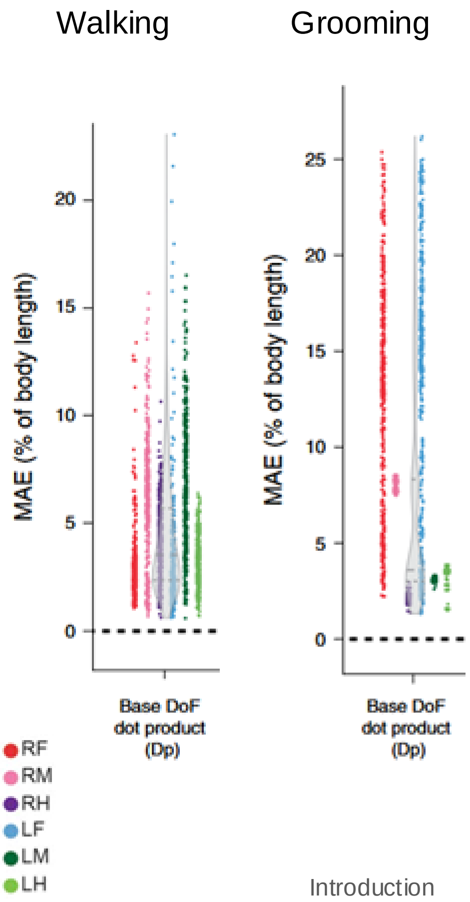
6 base DoFs …

- Thorax–coxa (ThC): *Elevation–Depression, Protraction–Retraction, Rotation*.
- Coxa–trochanter (CTr): *Flexion–Extension*
- Femur–tibia (FTi): *Flexion–Extension*
- Tibia–tarsus (TiTa): *Flexion–Extension*
- Coxa-trochanter (CTr): *Rotation*

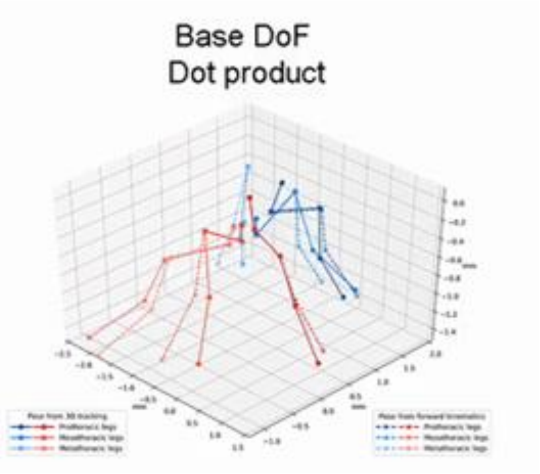
… +1

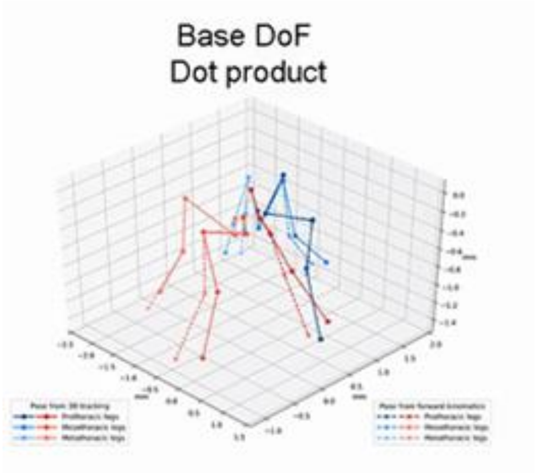


Identification of the minimum DoFs



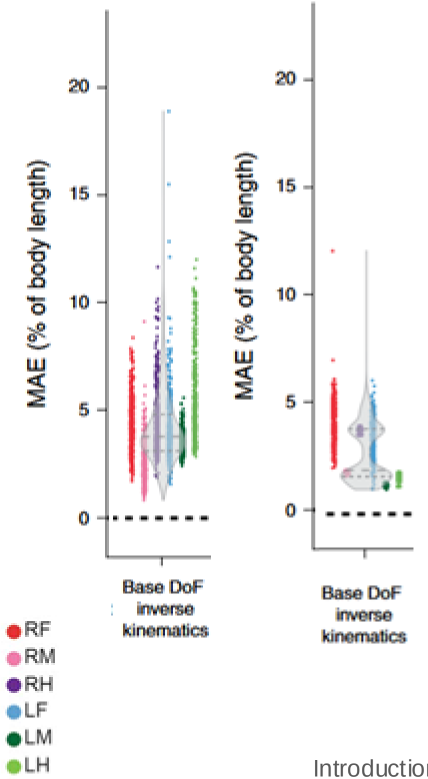
- Only 6 DoFs used to replay walking and grooming.
- Problem : Observed consistent *out-of-plane* leg movements



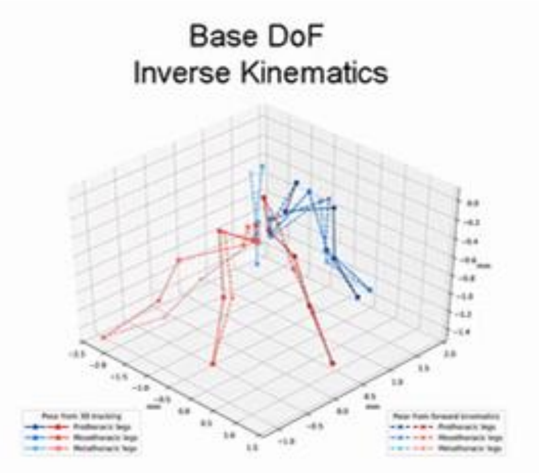


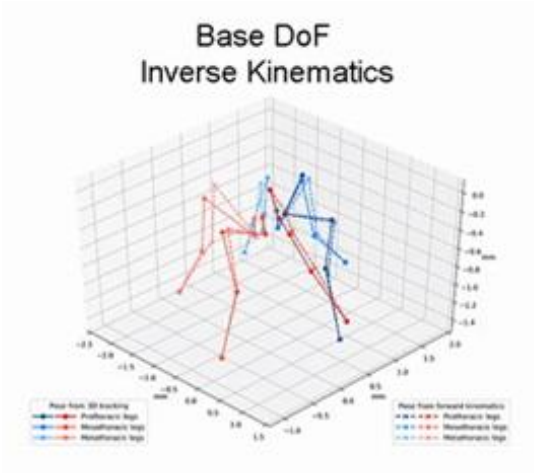
Identification of the minimum DoFs

Walking Grooming



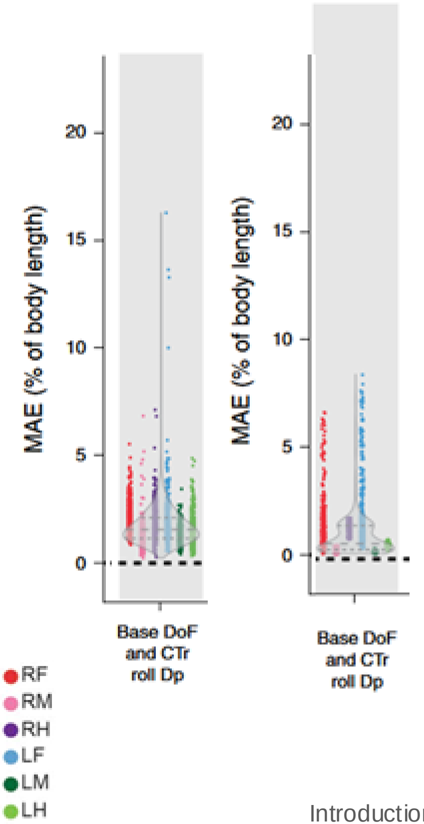
- Inverse kinematics optimization of joint angles
- Problem : Still observed consistent *out-of-plane* leg movements



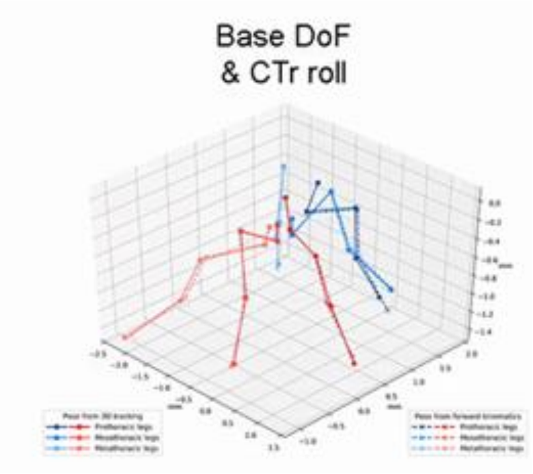


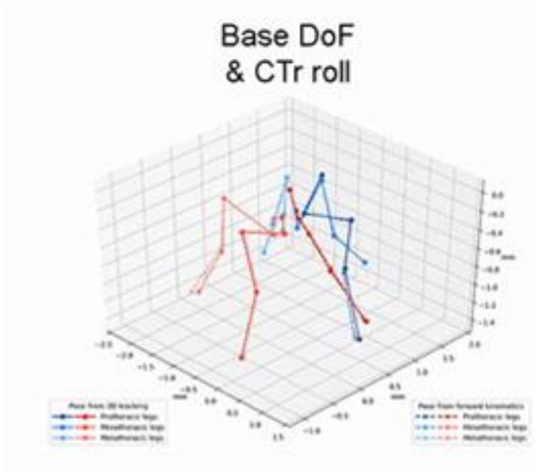
Identification of the minimum DoFs

Walking Grooming

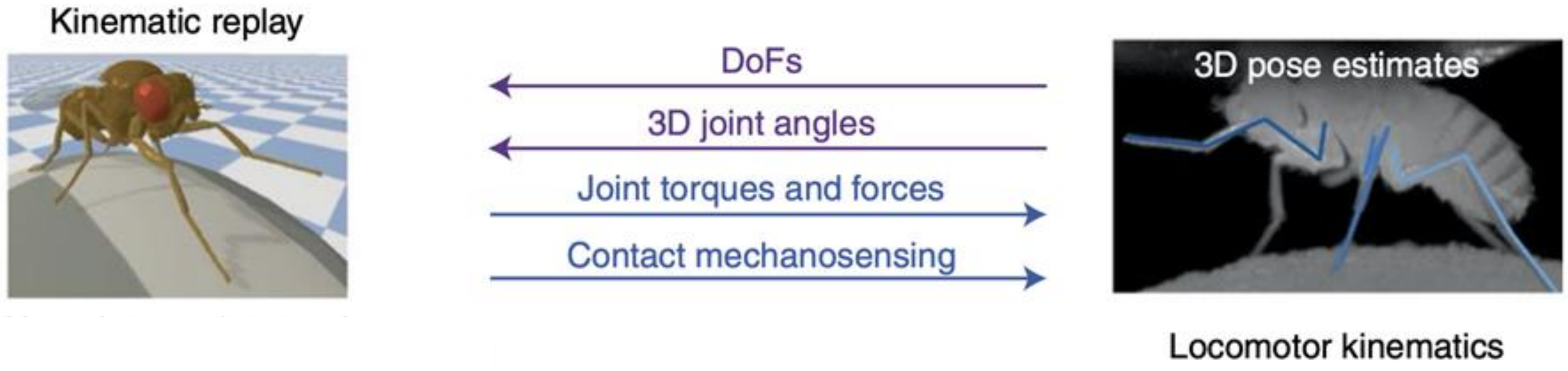


- *Extra DoF* might be needed at the CTr joint to accurately replicate real fly leg movements.





Inferring Joint Torques & Contact Forces



- Kinematic Replay
- PD Controller
- Morphological Accuracy

Inferring Joint Torques & Contact Forces

Kinematic Replay for Forward Walking

Raw data