EPFL

Implementing adhesion for NeuroMechFly – Neuromechanical model of Drosophila Melanogaster

Bachelor Project Final Presentation by:

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Introduction

- Aim: Set the groundworks for adhesion in simulating D. Melanogaster to bring the model closer to reality using MuJoCo
  - Add adhesion to the model
  - Study relationship contact forces with adhesion
  - Test different adhesion rules to allow walking with adhesion

State of the art – Adhesion in D. Melanogaster

- Adhesive Structures:
  - Claw: for rough ground
  - Pulvillus (Setae): for climbing
- Experiments with adhesion [2]:
  - Increasing speed (continuous gait changes):
    - Slow wave -> Tetrapod -> **Tripod gait** [2 ,3]
  - Stance duration affects walking speed
- Experiments without adhesion:
  - Covering only pretarsus [3] :
    - A-typical Bipod gait
  - Shorter setae [9]:
    - Cannot climb but can still walk

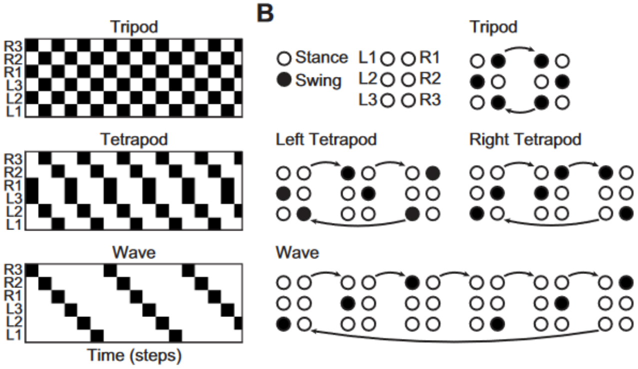
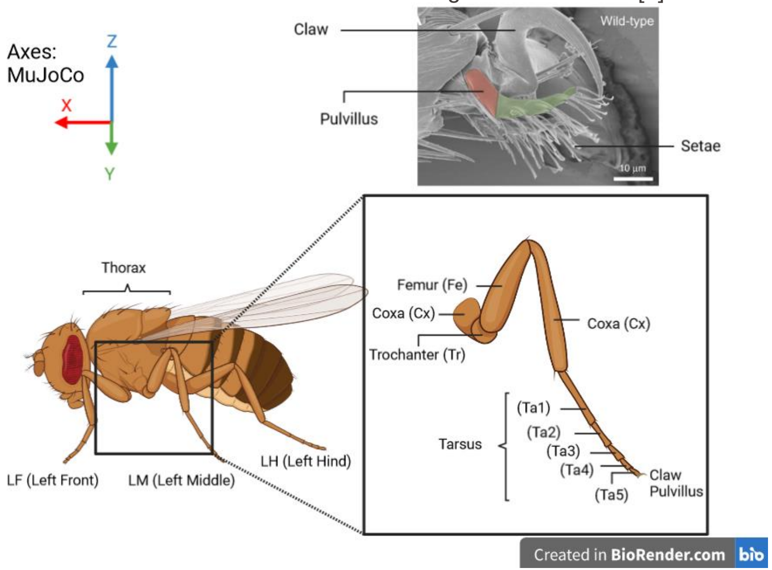


Figure from: [2]

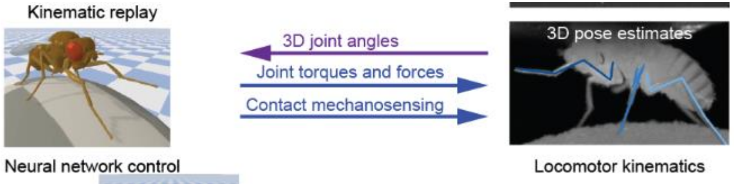
Image labelled from : [9]



State of the art – Simulation of D. Melanogaster

- NMF does not include Pretarsus [6]
- MuJoCo:
  - Adhesion actuators applied on « bodies »
  - Adhesion forces are added linearly to the normal component of the contact [4]
- FlyGym [7]:
  - For reinforcement learning:
    - At each timestep : action fed into nmf.step() function
- Existing Joint angle data:
  - Tethered Fly walking on ball
- Scaling units:
  - Gravity scaled by 1E5: (0,0,-9.81E5)[$\frac{m}{s^2}$]
  - Mass and time unchanged (1kg = 1kg, 1s = 1s)
  - Length scaled by $1^{E}6$ (1m = 1um in reality)
  - Therefore the scaling is not consistent

Image labelled from : [1]



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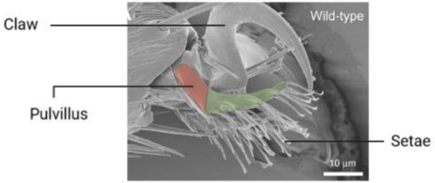
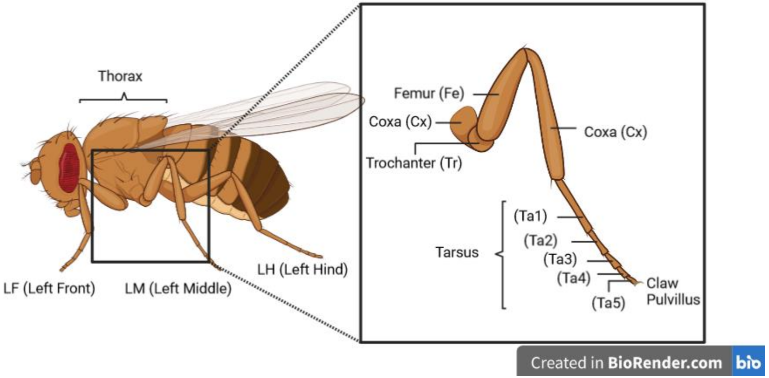


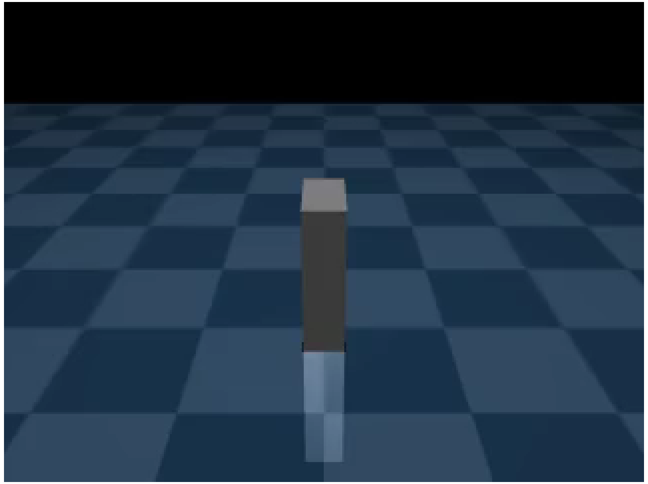


Project Timeline– Overview

- Part 1: Adhesion on a simple block
- Part 2.1: Static Fly: adhesion on FlyGym
  - Add adhesion actuators on Tarsi 5
  - Gain grid search : Single Leg adhesion
    - **Aim:** Find gain at which a single leg adheres to ground at inverted gravity
  - Study Contact forces vs Adhesion:
    - **Aim:** Study reactability of the simulation to the addition of the contact forces
- Part 2.2: Walking Fly: adhesion on FlyGym
  - Definition adhesion rules
  - Adhesion vector calculations versions:
    - Prerun adhesion: simple method
    - Prerun adhesion: iterative method
    - Dynamic adhesion

Part 1 : Adhesion on simple block

- Learn how to add adhesion actuators in XML file and during initialization
- Access / change gravity
- Change adhesion control value



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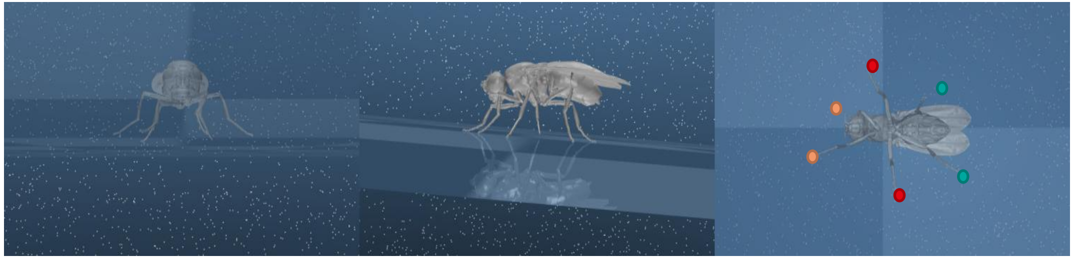
Part 2.1: Static Fly: adhesion on FlyGym

- Gain grid search : Single Leg adhesion
  - Inverted gravity
  - Asymmetric initial pose

Leg	Critical Gain
LF Tarsus 5	1930
LM Tarsus 5	3373
LH Tarsus 5	3364
RF Tarsus 5	2264
RM Tarsus 5	2078
RH Tarsus 5	4016



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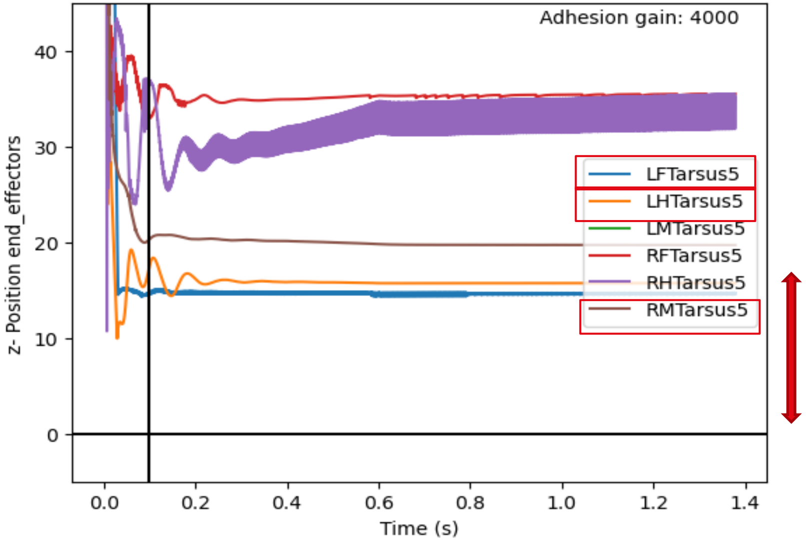
Part 2.1: Static Fly: adhesion on FlyGym

- **Dichotomous gain grid search : Single Leg adhesion**
  - Validate by adding adhesion to LF, LH, and RM Tarsus 5 (Tripod)
    - Legs dont pierce the floor
    - Legs dont fly away



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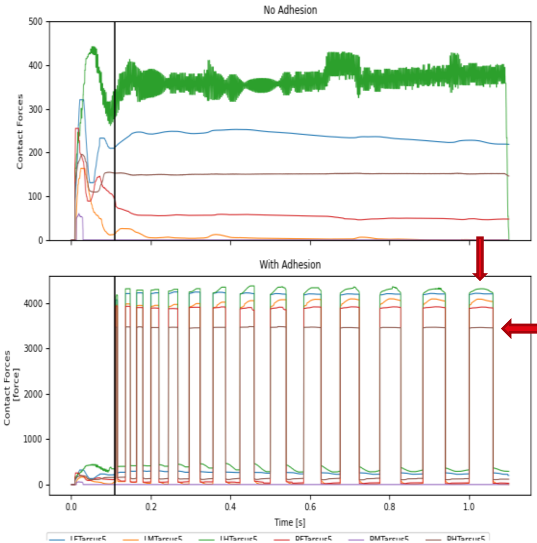
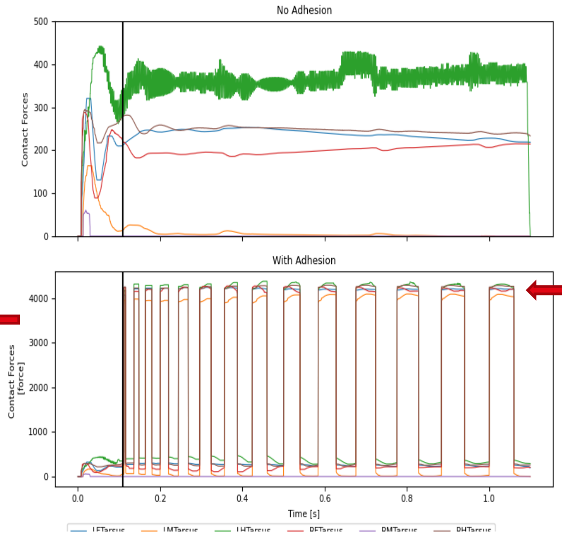
Part 2.1: Static Fly: adhesion on FlyGym

- Study Contact forces vs Adhesion:
  - **Aim:** Study reactability of the simulation to the addition of the contact forces
  - Linear relationship

Only Tarsus 5 (median filtered):



Sum of all Tarsus (median filtered):



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Part 2.2: Walking Fly: adhesion on FlyGym

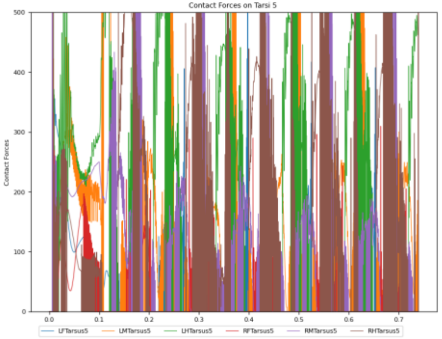
- Adhesion rules to calculate adhesion vectors

  1. $$\frac{dF_{contact}}{dt} \geq 0$$
  2. $$\frac{dF_{contact}}{dt} > 0$$

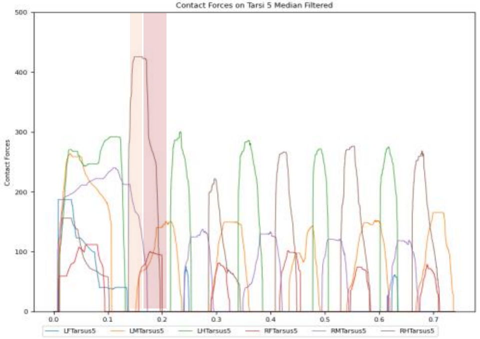
  NB: Are applied on smoothed contact forces

  Window size for the filter: 501 timesteps

Contact forces: NO Filter



Contact forces: Median Filter



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Part 2.2: Walking Fly: adhesion on FlyGym

- Adhesion vector calculations versions:

  N adhesion strengths are tested

  The adhesion strength increases with each simulation

  Median filter window size: 501

  - Prerun adhesion: simple method

    Step 1: Run without adhesion: calculate adhesion vector

    Step 2: Run all N simulations using that adhesion vector from step 1)

  - Prerun adhesion: iterative method

    Step 1: Run without adhesion: calculate adhesion vector

    Step 2*: Run N-simulations that each use the adhesion vector from the N-1 simulation

  - Dynamic adhesion:

    Step 1*: Calculate the adhesion vector by filtering the contact forces during the simulation

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    - **Dynamic adhesion**

Part 2.2: Walking Fly: adhesion on FlyGym

Reference distance:
distance without adhesion: 4436

Vector Calculation Method	AdhesionRule	Gravity	How many fell?	Did it fly away?	Max. Distance [length]	Gain (of max distance)
Simple	**>**	**Normal**	**1/8**	**-**	**4396**	**2290**
Simple	>=	Normal	5/8	-	4438.1	400
Iterative	**>**	**Normal**	**2/8**	**-**	**(5370)** **4356**	**(400)** **3236**
Iterative	>=	Normal	5/8	-	768	400
Simple AND Iterative	>= AND >	Inverted	-	ALL	-	-
InLine	>	Normal	7/10	-	2277.6	400
InLine	>=	Normal	9/10	-	2277.6	400
InLine	>= AND >	Inverted	-	ALL	-	-

General Conclusion

- Relationship of contact forces and adhesion is linear, but requires stabilization period
- The « > » - adhesion rule works best
- No flies were able to walk with inverted gravity but finetuning the iterative method might be a good idea

Further Interesting Approaches

- Improve data set for walking on ground
- Use the sum of all contact forces of the tarsi instead of only forces on tarsus 5
- Finetune filtering: windowsize, different filters (median, mean, etc.)
- Study contact forces for the different adhesion vector methods
- Adapt gains of single legs with respect to the distance of the center of gravity
- Possible Adhesion Rules:
  - ON: when a threshold in contact forces is attained

Gantt Chart – Until week 6

MuJoCo

Project Modification

Project Start Date:

Bachelor Project: Implement adhesion forces in a neuromechanical model of adult Drosophila melanogaster

		Feb		Mar			
		20-Feb	27-Feb	06-Mar	13-Mar	20-Mar	27-Mar
Activity	**Status**	**WEEK 1**	**WEEK 2**	**WEEK 3**	**WEEK 4**	**WEEK 5**	**WEEK 6**
Project	In progress						
SetUp/ Administration	Completed						
Literature introduction	Completed						
Install Softwares	Completed						
Part 1: Tune parameters for Ball locomotion	In progress						
Verify correct 3D collision implementation in MuJoCo	In progress						
Contacts tuning in MuJoCo for both floor and ball surface	In progress						
Identify how to trace specific positions on the ball and leg in MuJoCo for calculations	In progress						
Identify necessary ball and fly parameters in PyBullet and how they can be accessed	In progress						
Part 2: SetUp Adhesion Forces	Not started						
Research on adhesion/ friction forces	In progress						
Create a theoretical model for Adhesion forces specific to D. Melanogaster	Not started						
Implement model in code (Adhesion On/ Off switch)	Not started						
Part 3: Validate Adhesion Forces	Not started						
Compare ball displacement in the simulation and in the real fly	Not started						
Adjust Adhesion Forces / Parameters, possibly go back to task #12	Not started						
Part 4: Presentation / Report	Not started						
Write-up Report	Not started						
Prepare Presentation	Not started						

midterm presentation 27 March

Gantt Chart

Start FlyGym

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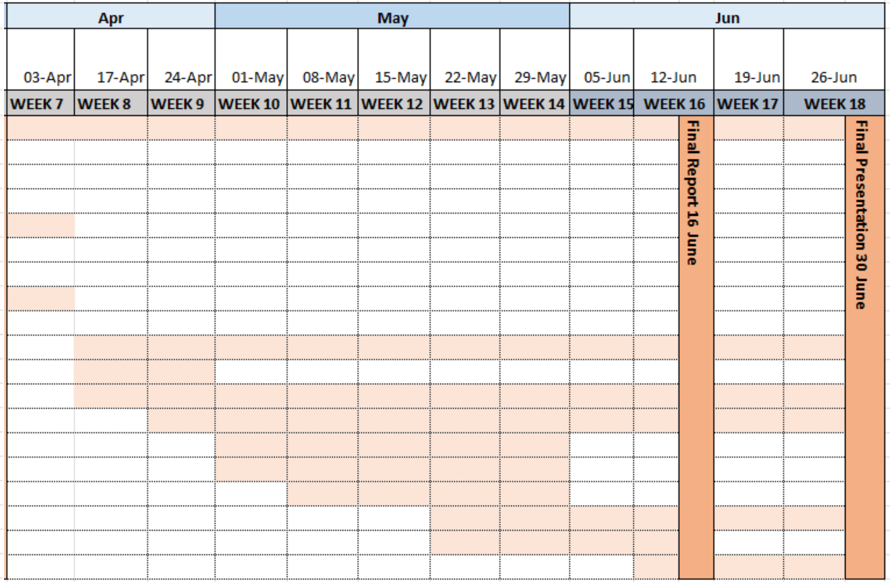

Laetitia Schwitter

Jupyter Notebooks

- ***BrickOnCeiling.ipynb***: Case 1: Adding an adhesion actuator to an XML file. Modify it during the simulation. Case 2: Add adhesion actuator during initialization. Modify it during the simulation. Furthermore find out how to access and modify gravity during the simulation.
- ***mujoco_singleleg_grid.ipynb*****:** Perform grid search to find maximal gain value necessary for a single leg to adhere to the ceiling.
- ***mujoco_contact_forces.ipynb*****:** Analyze the relationship between contact forces and adhesion on a static nonsymmetric fly. The contact forces are filtered with a median filter.
- ***loop_single_step.ipynb*** **:** Use the single step data to create a walking fly that uses a tripod gait for a specified number of steps. Methods to amplify specific angle motion as well as a method to custom generate the number of steps in the simulation wanted.
- ***loop_single_step_bipod.ipynb*****:** Use the single step data to create a walking fly that uses a bipod gait for a specified number of steps
- ***mujoco_prerun_adhesion.ipynb*****:** Offline calculation of adhesion. Computes the derivative of the contact forces of each Tarsus5 / the sum of all Tarsi before any adhesion. Then reruns the simulation once adhesion is applied. Adhesion is on when the derivative is positive or positive and equal.
- ***mujoco_prerun_adhesion_copy.ipynb*****:** Allows to do the grid search for prerun adhesion.

References

[1] V. Lobato-Rios, S. T. Ramalingasetty, P. G. Özdil, J. Arreguit, A. J. Ijspeert, and P. Ramdya, “NeuroMechFly, a neuromechanical model of adult Drosophila melanogaster,” Nat. Methods, vol. 19, no. 5, Art. no. 5, May 2022, doi: 10.1038/s41592-022-01466-7.
[2] B. D. DeAngelis, J. A. Zavatone-Veth, and D. A. Clark, “The manifold structure of limb coordination in walking Drosophila,” eLife, vol. 8, p. e46409, Jun. 2019, doi: 10.7554/eLife.46409.
[3] P. Ramdya et al., “Climbing favours the tripod gait over alternative faster insect gaits,” Nat. Commun., vol. 8, no. 1, Art. no. 1, Feb. 2017, doi: 10.1038/ncomms14494.
[4] “XML Reference - MuJoCo Documentation.” https://mujoco.readthedocs.io/en/stable/XMLreference.html (accessed Jun. 11, 2023).
[5] “Dm_control: Software and Tasks for Continuous Control.” Accessed June 11, 2023. https://www.deepmind.com/publications/dm-control-software-and-tasks-for-continuous-control.
[6] “NeuroMechFly.” Python. 2020. Reprint, Neuroengineering Laboratory @EPFL - Ramdya Lab, March 10, 2023. https://github.com/NeLy-EPFL/NeuroMechFly.
[7] “NeLy-EPFL/flygym.” Neuroengineering Laboratory @EPFL - Ramdya Lab, Apr. 25, 2023. Accessed: Jun. 11, 2023. [Online]. Available: https://github.com/NeLy-EPFL/flygym
[8] Introduction Drosophila - a model system … : Tolwinski, Nicholas. “Introduction: Drosophila—A Model System for Developmental Biology.” Journal of Developmental Biology 5, no. 3 (September 20, 2017): 9. https://doi.org/10.3390/jdb5030009.
[9] Hüsken, Mirko, Kim Hufnagel, Katharina Mende, Esther Appel, Heiko Meyer, Henrik Peisker, Markus Tögel, et al. “Adhesive Pad Differentiation in Drosophila Melanog