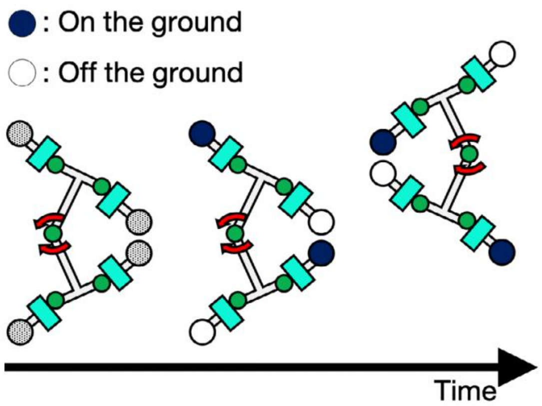
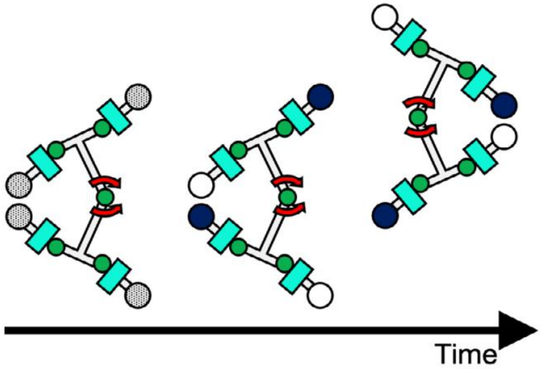




Decentralized Control with Cross-coupled Sensory Feedback Between Body and Limbs in Sprawling locomotion

Shura Suzuki, TakeshiKano, Auke JIjspeert and Akio Ishiguro

Presenter: Boshi An, Di Xiao, Zhuoran Ren

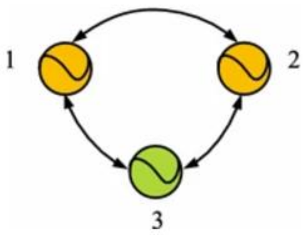
Overview

Quadrupeds achieve rapid and highly adaptive locomotion owing to the coordination between their different body parts.

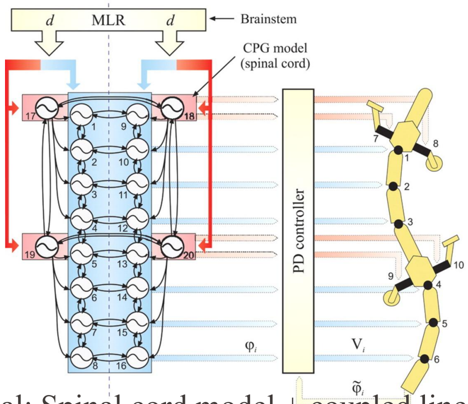
Executive Summary

- Types of robots: quadrupled
- Types of control: Cross-coupled CPG
- Types of design method: Mathematical Modelling and robot simulations
- Type of Gait: Sprawling
- Main content: body-limb coordination, which integrates the cross-coupled sensory feedback to facilitate the understanding and performance of spawling locomotion

Introduction



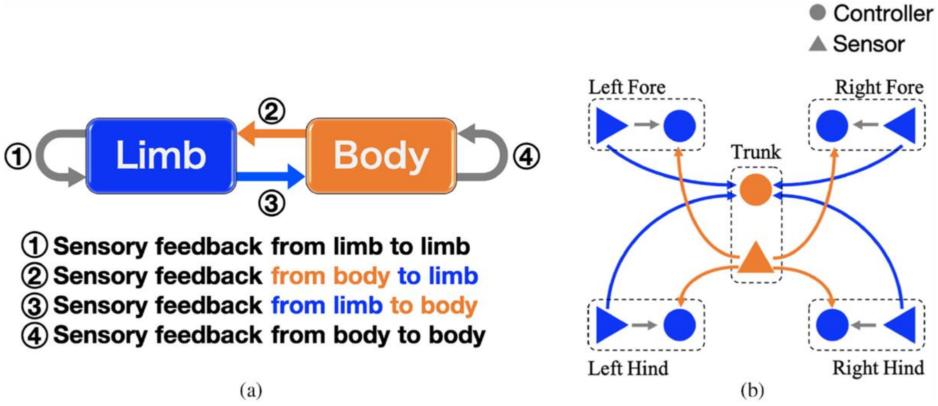
Yin et al: Three pre-defined coupled linear oscillators; 1 represents left front and right hind legs; 2 represents left hind and right front legs; 3 represents waist joint.



Ijspeert et al: Spinal cord model + coupled linear oscillators; Successful real-world deployment of a CPG based salamander robot.

Coordination	Yin *et al*	Ljspeert *et al*	Suzuki *et al (our presentation)*
Body to body	Yes	Yes	Yes
Limb to limb	Yes	Yes	Yes
Body to limb	Yes	No	Yes
Limb to body	Yes	Yes	Yes

Sensory Feedback



Cross-Coupled Sensory Feedback(From the rule 2 and rule 3)

- Body to limb feedback

The trunk sensors detect the torque and angle of the trunk's joint. This information is used to adjust the leg actuators.

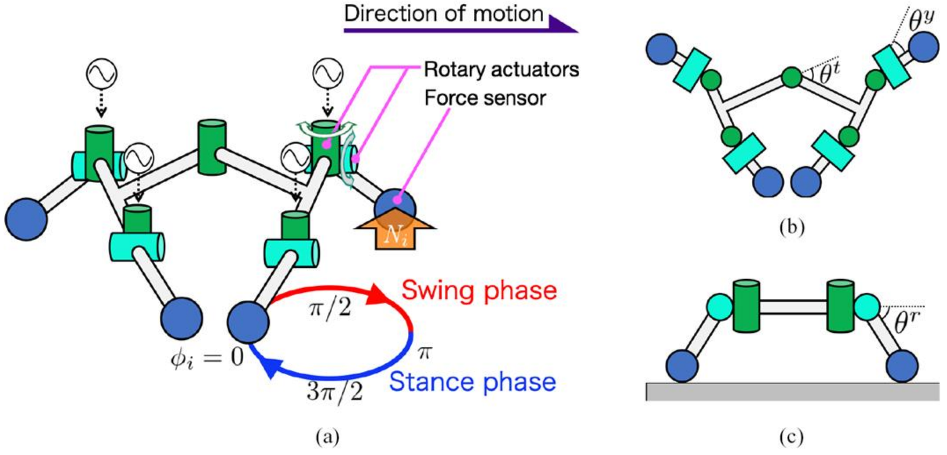
- Limb to body feedback

The foot sensors measure the ground reaction force(N1, N2, N3, N4). This information is used to adjust the trunk's torque.

Simplified system(omit the rule 4)

This model focus only on the mechanism about the body-limb corporation, the rule 4, which involves orchestrating other body parts like tail and head, is omitted.

Mechanical Structure



Actuator

Trunk: one rotary actuator

Leg segments: Two Rotary Actuators

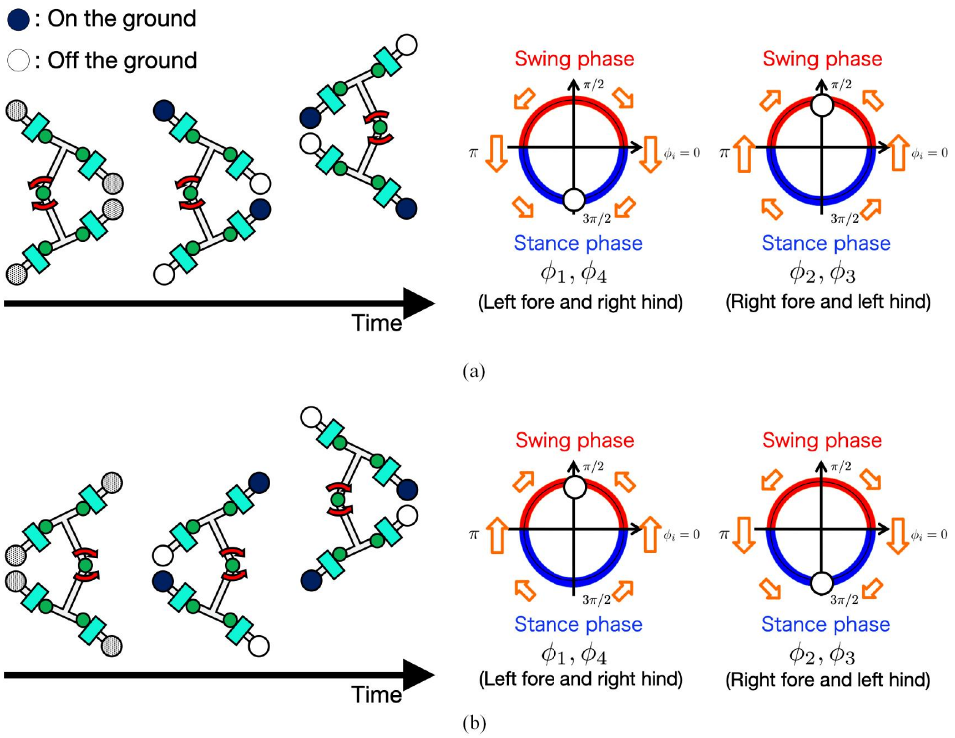
- One for yaw direction(side-to-side motion, θ_y)
- One for roll direction(up-and-down rotation, θ_r)

Sensors

Trunk: Torque sensor and angle sensor(measuring θ_t)

Leg segments: Force sensor

Control System – Leg control



Target angles of the actuators

$$\bar{\theta}_i^y = C_0^y - C_{amp}^y \cos \phi_i,$$
$$\bar{\theta}_i^r = C_0^r - C_{amp}^r \sin \phi_i,$$

$\bar{\theta}_i{}^y$, $\bar{\theta}_i{}^r$: the target angles

C_0^y, C_0^r: the neutral angles

C_{amp}^y, C_{amp}^r: the amplitude of the yaw and roll actuators

φ_i: the phase of the oscillator

Phase of the oscillator in each leg

$$\dot{\phi}_i = \begin{cases} \omega - \sigma_1 N_i \cos \phi_i - \sigma_2 \tau_a \cos \phi_i & (i = 1, 4) \\ \omega - \sigma_1 N_i \cos \phi_i + \sigma_2 \tau_a \cos \phi_i & (i = 2, 3) \end{cases}$$

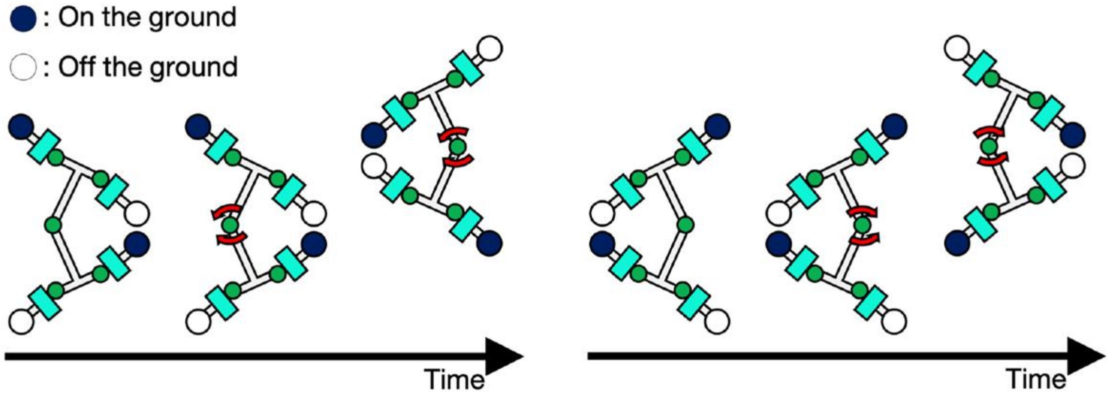
ω: the intrinsic angular velocity

σ_1: σ_2: weights of sensory feedback terms

τ_a: the torque generated at the trunk actuator

N_i: the normal force detected at tip of the foot

Control System – Body Control



(a) (b)

$$\tau = -k_p\theta^t - k_d\dot{\theta}^t + \tau_a,$$

$$\tau_a = \sigma_3 \tanh\{\rho(N_1 + N_4 - N_2 - N_3)\},$$

- K_p: spring coefficient
- K_p: damper coefficient
- τ_a: the torque at the trunk actuator
- σ_3, ρ: the weight of the sensory feedback
- N1, N2, N3, N4: forces detected by the limbs
- θ_t: trunk-joint angle

Experiments in Simulation

1. **Steady locomotion**
   - **Mean speed**
   - **Cost of Transportation**
2. **Ablation Study**
   - **w/o sensory feedback**
   - **w/o movable trunk**
   - **w/o trunk actuator**
3. **Fault tolerance**
   - **Fore-leg paralysis**
   - **Hind-leg paralysis**
4. **Effects of the bidirectional sensory feedback**
   - **Grid search on bidirectional feedback weight**

Steady locomotion

$$v_m = \frac{D}{T_2 - T_1},$$

Mean Velocity

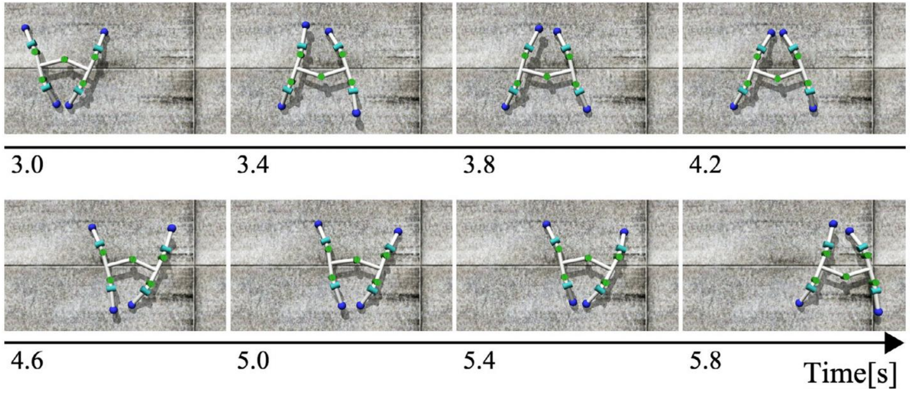
$$\mathrm{CoT} = \frac{1}{Dmg} \int_{T_1}^{T_2} P(t)dt,$$

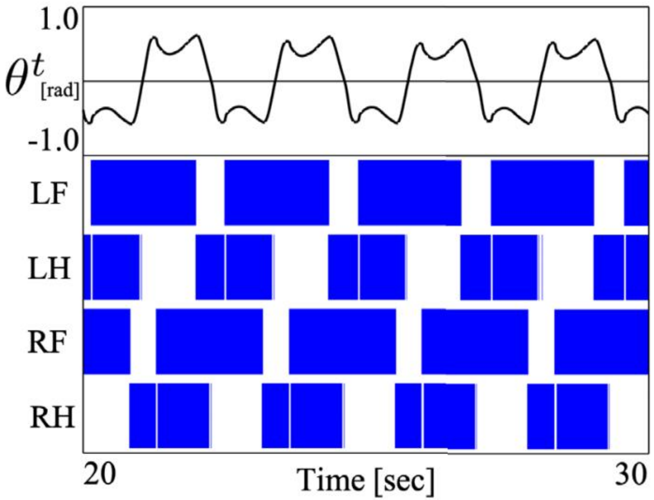
$$P(t) = \sum_k (\chi(\tau_k(t)\dot{\theta}_k(t)) + \gamma\tau_k^2(t)),$$

$$\chi(z) = \begin{cases} 0 & (z \leqslant 0), \\ z & (z > 0), \end{cases}$$

Cost of Transportation

Steady locomotion

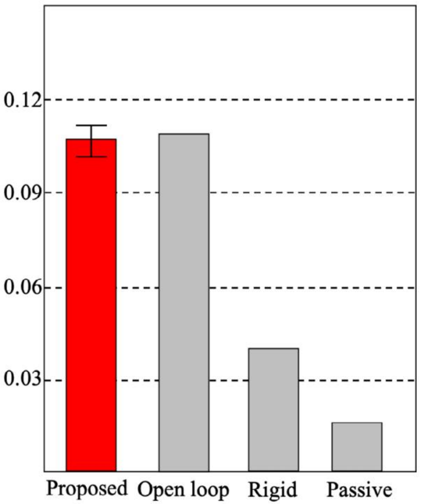




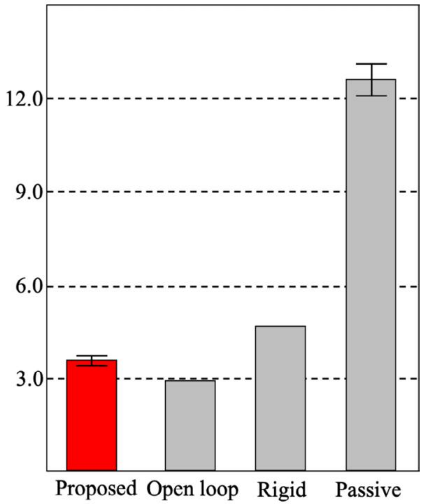
$$V_m = 0.099$$
$$CoT = 3.57$$

EPFL

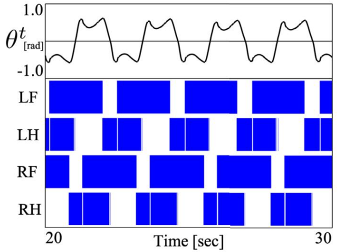
Ablation Study



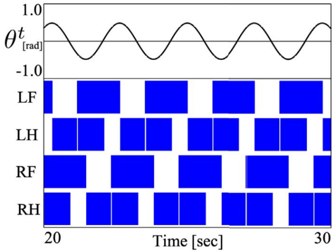
Mean Velocity



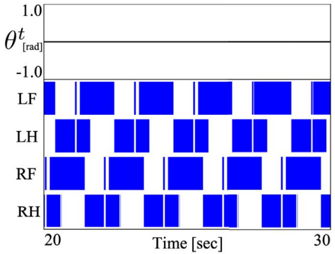
CoT



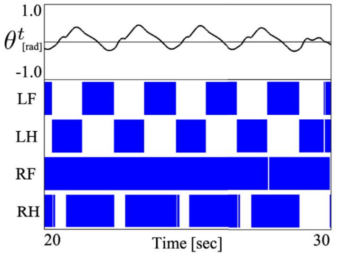
Proposed



Open Loop



Rigid Trunk



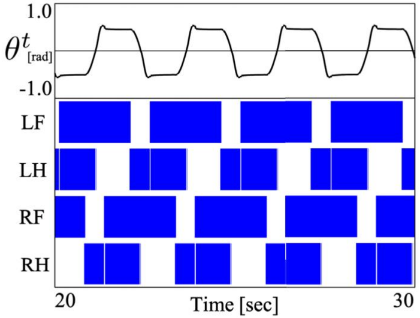
Passive Trunk

Open Loop:

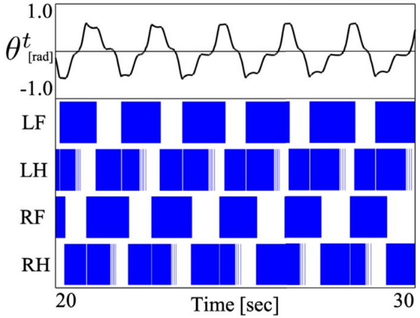
$$
\begin{aligned}
\dot{\phi}_1 &= \omega' \\
\phi_i &= \phi_1 + \psi_i \quad (i = 2\text{–}4), \\
\phi_t &= \phi_1 + \psi_t, \\
\bar{\theta}^t &= C^t_{amp} \sin \phi_t,
\end{aligned}
$$

Speaker

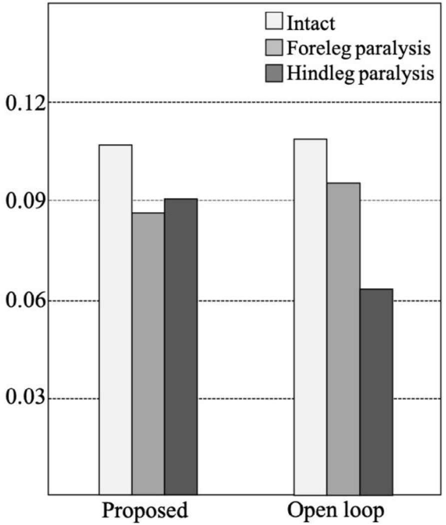
Fault Tolerance



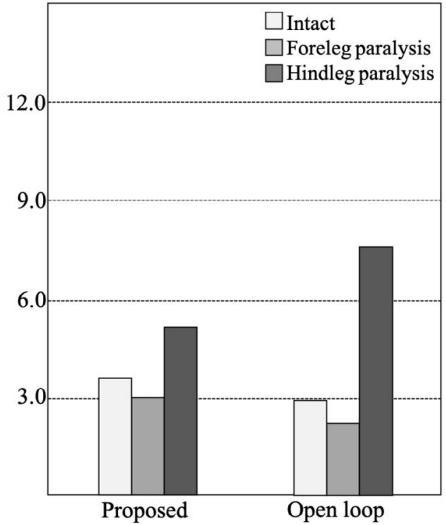
Fore-leg Paralysis



Hind-leg Paralysis



Fore-leg Paralysis

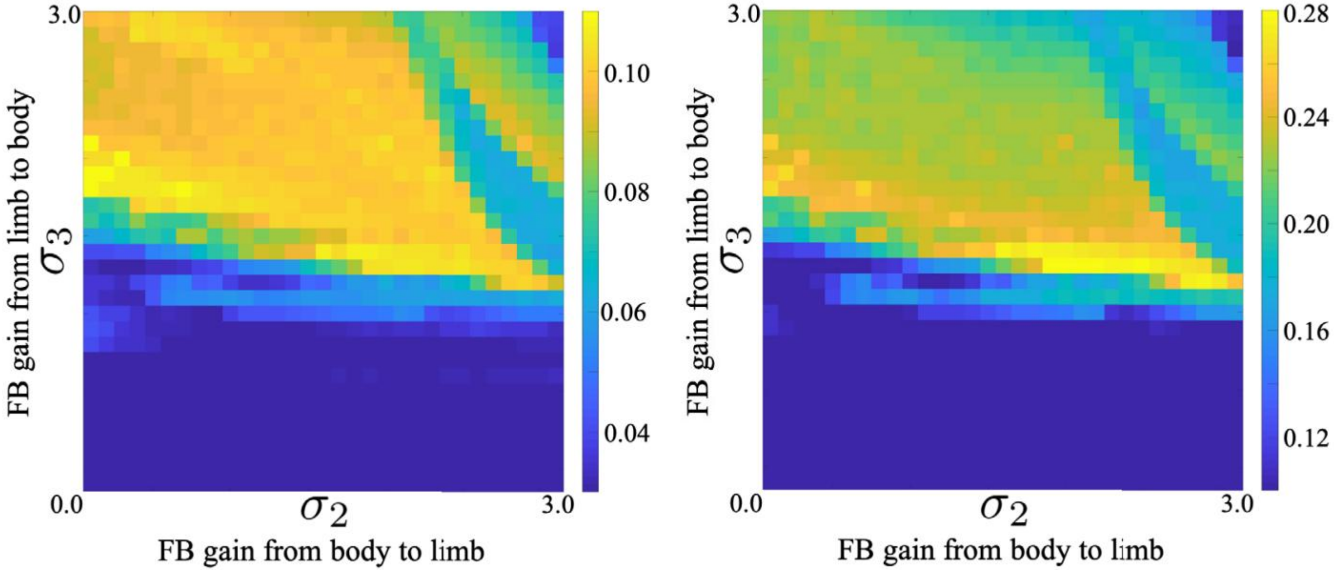


Hind-leg Paralysis

Observation:

1. Proposed method is more robust to paralysis
2. Hind-leg provides more efficient propulsions

Effects of the bidirectional sensory feedback



Velocity

1 / CoT

Observation:

1. Proposed method is NOT sensitive to parameter changes

Pros & Cons

- Pros:
- Leg failure Adaptation
- Environment Adaptation
- Relaxing parameters tuning
- Higher speed and energy efficiency
- Robust to body structure design

- Cons:
- Difficult to examine if real salamander has the same model
- Limited to straight walking
- Only 1 DoF in trunk

Article Impact

- Who’s citing this article?
- Cited 14 times [Google Scholar]
- Sprawling Quadruped Robot Driven by Decentralized Control With Cross-Coupled Sensory Feedback Between Legs and Trunk

- Influence: provide insight for paradigm of fault-tolerant legged robots

Possible Exam Questions

1. In the experiments, why the open loop outperforms the proposed method in both maximum velocity and efficiency?
ANS: The open-loop performance is optimized for a specific environment, allowing it to outperform the proposed method in that context. However, it lacks the generalization capability and adaptability required to perform effectively in diverse environments.

2. What's the meaning of function tanh() in the body control formula?
ANS: To address differences in quantitative magnitudes and ensure smoother output during spikes.

3. The authors claimed there is leg-leg sensory feedback in the model, but in the formula, there is no such a term explicitly define such a feedback. Why?
HINT: on Slides 7. The N_i (normal force) term.

Thank You!