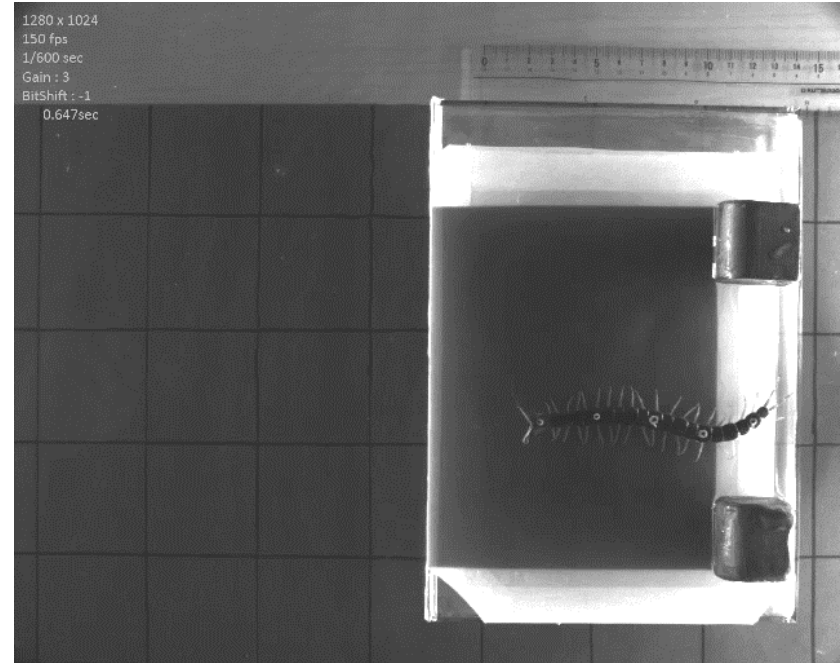


# Decoding the essential interplay between central and peripheral control in adaptive locomotion of amphibious centipedes

Paper by Kotaro Yasui,  
Takeshi Kano, Emily M.  
Standen, Hitoshi  
Aonuma, Auke J.  
Ijspeert and Akio  
Ishiguro

# Introduction

- Study on multi-segmented amphibious locomotion
- Combines biological experiments + mathematical modelling
- Why centipede?
  - homogeneous, long, segmented,
  - clear visibility of gait transitions,
  - capable of walking and swimming
- Locomotion results from balance between central and local control



=> Enhance the adaptability of robotic locomotion to environmental changes and to investigate the effect of descending control from the brain : transected the connectives of the ventral nerve cord between the ganglia in the 12th and the 13th body segments

# Executive summary of key aspects

Type of robot: Homogeneous, repeated body segment ideal to study local sensory feedback

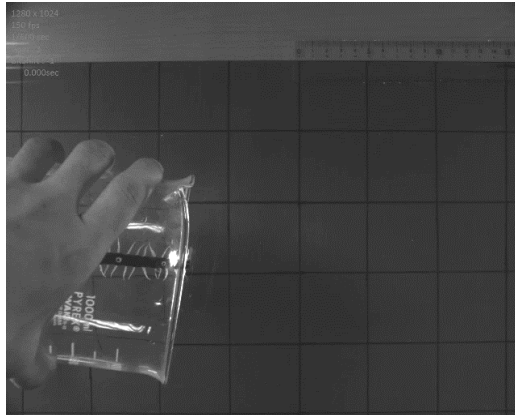
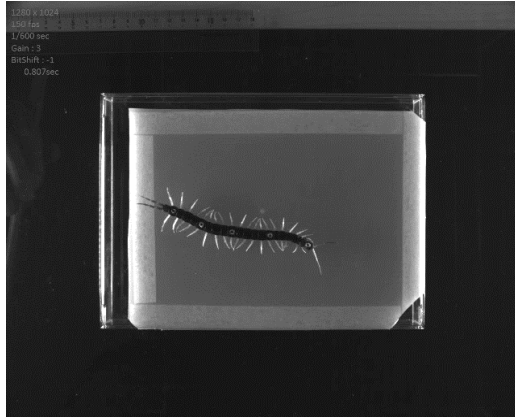
Control: 1) Descending commands (brain) -> trigger swimming  
2) Local CPGs -> rhythmic leg & body motion  
3) Sensory feedback -> enforce walking

Design method: Phenomenological mathematical model based on observations, nerve-cord transection experiment

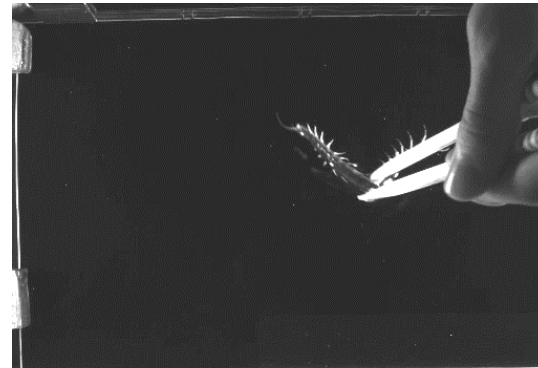
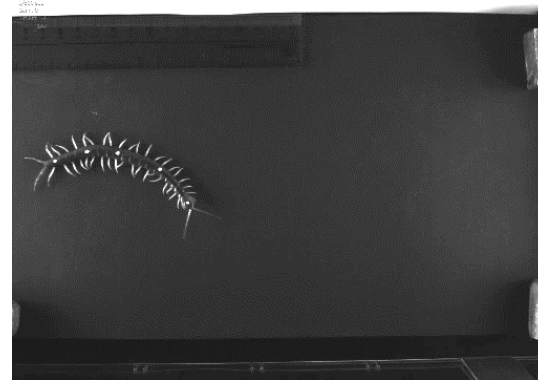
Sensor: mechanosensory feedback (ground reaction forces + environmental substrate changes)

# Amphibious locomotion

## Intact animals



## Nerve corde transected animals



# Amphibious locomotion

## Intact animals

Environment	Legs motion	Body motion
Land	Propagation of a wave of legs movement posteriorly	No body undulation during straight walking
Water	Folded along the body Few anterior legs remain unfolded	Posteriorly travelling wave of body undulation

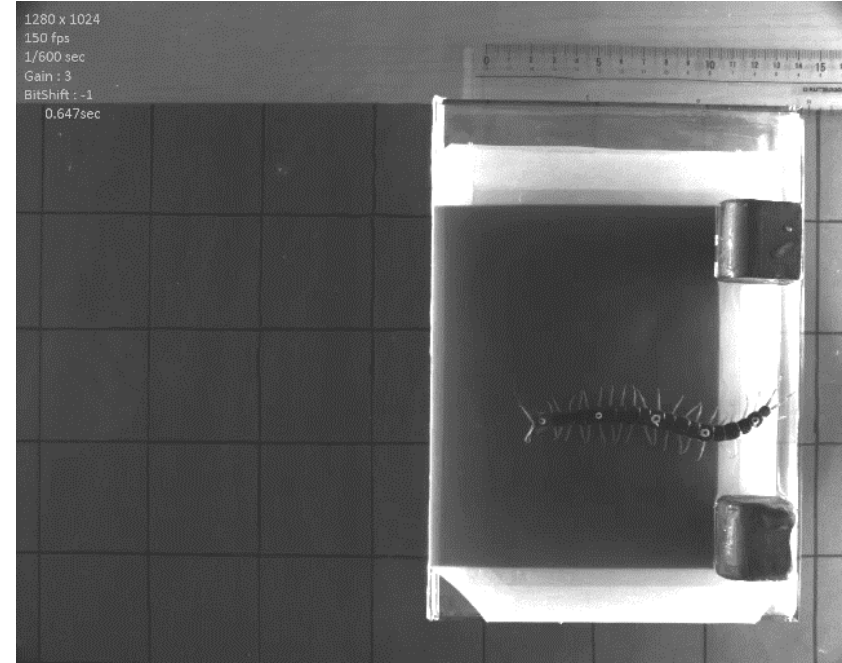
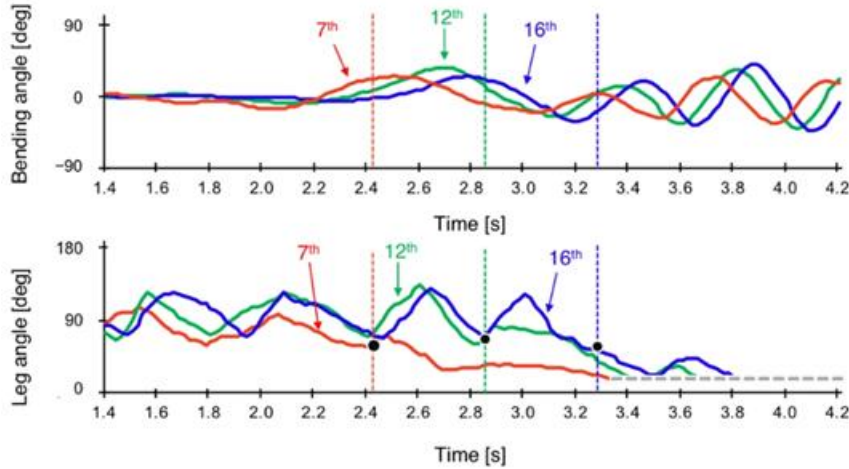
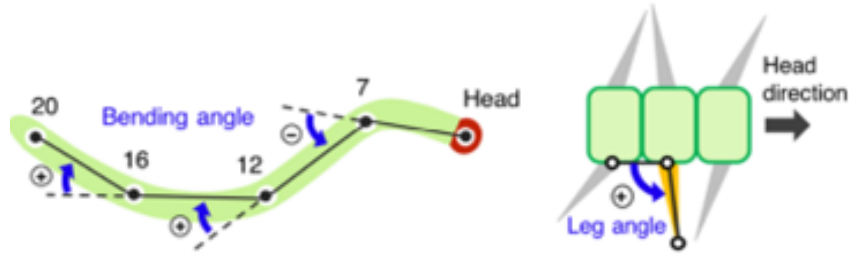
# Amphibious locomotion

## Nerve corde transected animals

Environments	Legs motion	Body motion
Land	Similar to intact animals	Similar to intact animals
Water	Leg folded in the anterior section Legs on the posterior section being paused in the unfolded positions	Body undulation in the anterior section No movements in the posterior section

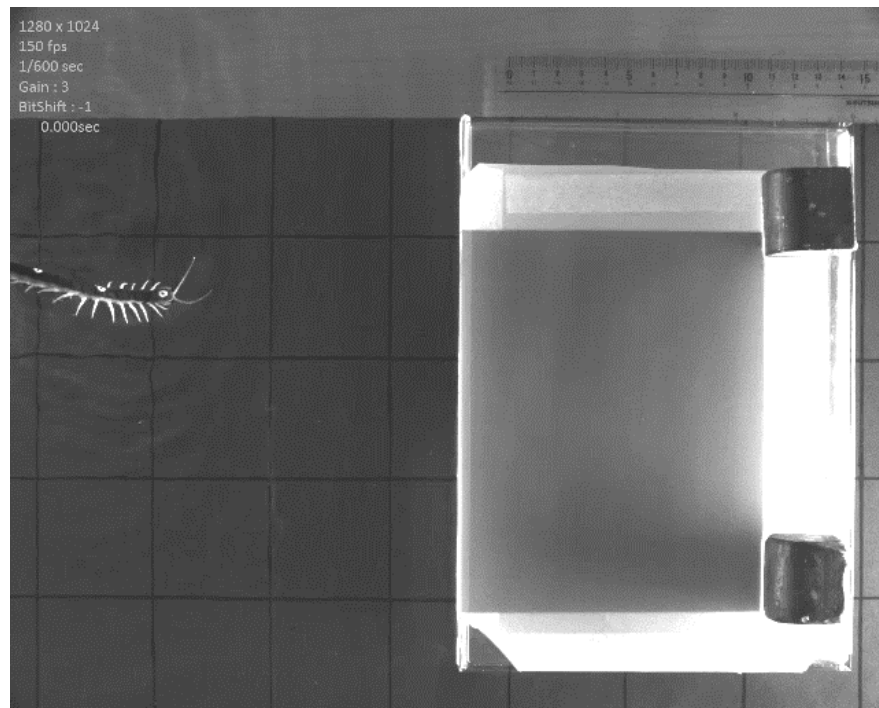
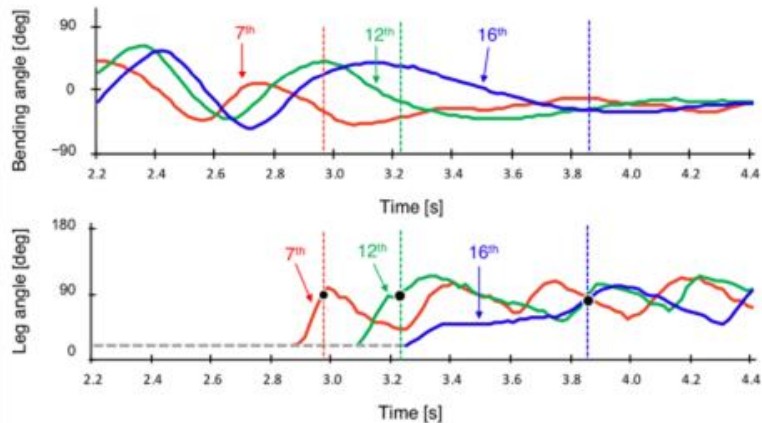
# Amphibious locomotion : Land $\rightarrow$ Water

## Intact animals



# Amphibious locomotion : Water $\rightarrow$ Land

## Intact animals



# Amphibious locomotion

## Intact animals

Transition		Legs motion	Body motion
Land → Water	Before the leg being submerged in water	Continue periodic walking motion	Little body bending
	After the leg being submerged in water	Begins to fold along the body	Body bending motion increases
Water → Land	Before reaching the ground	Start to unfold Delay in the start of leg oscillation for the posterior legs	Body bending
	After reaching the ground	Walking motion	Diminution of the body bending motion

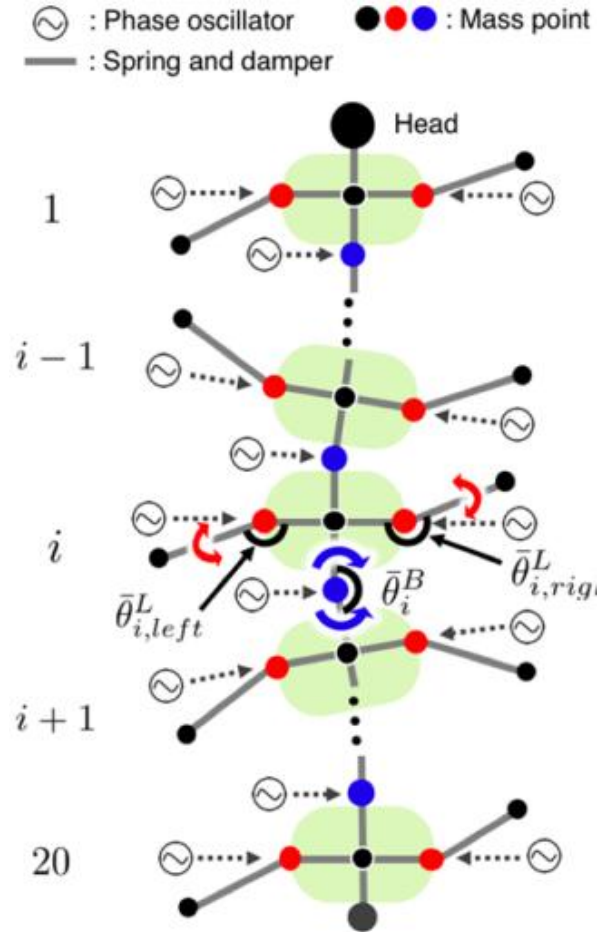
In response to the environmental changes, the legs and the body motions change at the local segment level

# Mathematical model

2D physical model of the centipede body :  
mass-spring-damper system

Each leg and body trunk :

1 rotational DoF for leg swinging and  
body bending



# Mathematical model - Hypotheses

1. Each body segment has two locomotor modes:

<b>Walking</b>	<b>Swimming</b>
Legs are unfolded, away from the body and move periodically if they detect ground contact	Legs are folded along the body side
Little body bending	Periodic bending motion of body trunk

# Mathematical model - Hypotheses

2. Brain can switch between walking and swimming by transmitting the decision command to the first body segment
3. Each body segment follows the locomotor mode of its anterior segment
4. Mechano-sensory feedback based on ground contact can inhibit swimming mode and induce walking mode

$M_i$  = locomotor mode of the  $i^{th}$  body segment

Walking:  $M_i = 0$

Swimming:  $M_i = 1$

Transient state between walking and swimming mode:  $M_i \in [0,1]$

$M_0$  = descending command from the brain

Time evolution of  $M_i$ :

$$\tau_M \dot{M}_i = -M_i + \max \left[ 0, M_{i-1} - \sum_{j \in \{left, right\}} S_{i,j} \right], i \in \mathbb{N}$$

$\tau_M$  = time constant

$S_{i,j}$  = activity level of the mechano-sensory neurons that burst when the  $i^{th}$  leg in the  $j$  side detects a force larger than the threshold.

Inside water:  $S_{i,j} = 0$

Receiving a reaction force from the ground:  $1 \geq S_{i,j} > 0$

# Quotations in other articles

- Cited by 21 articles
- An article about frictional swimming in multi legged locomotors [1]
- An article about a general locomotion control framework for multi-legged locomotors [2]

# Pros of the model

- Well model the segment-by-segment transition and the nerve cord transection of the real centipede
- Shows the interplay between descending control, CPGs, and sensory feedback
- Simple enough to wonder about other species
- 2 different locomotion to achieve effective propulsion depending on the environment
- Provide a fault tolerant robot to physical damage
- Pave the way for highly adaptive and resilient amphibious robots

Contributions to biology

Contributions to robotics

# Cons of the model

- Could not generate walking motion on an extremely slippery surface, unlike real centipedes
- Could not reproduce the adaptive locomotion in response of varying locomotion speed

Videos : <https://www.nature.com/articles/s41598-019-53258-3#Sec12>

Articles:

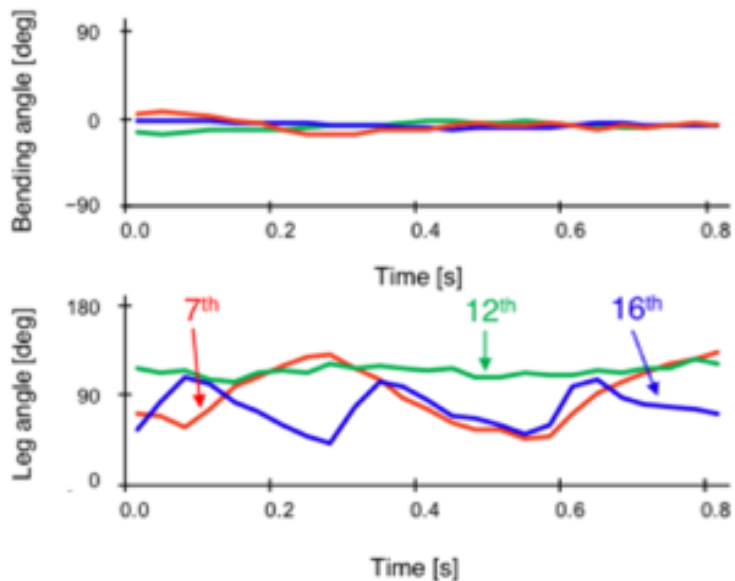
[1] Chong, B., He, J., Li, S., Erickson, E., Diaz, K., Wang, T., Soto, D., & Goldman, D. I. (2023). *Self-propulsion via slipping: Frictional swimming in multilegged locomotors*. **Proceedings of the National Academy of Sciences**, 120(11), e2213698120.

[2] Chong, B., Aydin, Y. O., Rieser, J. M., Sartoretti, G., Wang, T., Whitman, J., Kaba, A., Aydin, E., McFarland, C., Diaz Cruz, K., Rankin, J. W., Michel, K. B., Nieceza, A., Hutchinson, J. R., Choset, H., & Goldman, D. I. (2022). *A general locomotion control framework for multi-legged locomotors*. **Bioinspiration & Biomimetics**, 17, 046015.

# Appendix

## Nerve corde transected centipedes locomotion plots

### Walking



### Swimming

