Gait Transition and Adaptation Using the Spinal Cat Model

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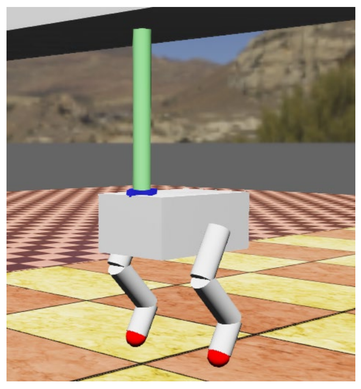


1. Introduction

Animals can adapt to various environments – but How?

- The adaptive motion of animals emerges through the interaction among the central neural system (CNS), the body, and environment. The detailed mechanisms, however, are largely unknown.
- Neural networks in **the spinal cord** (with **sensory feedback** but without higher CNS influences) **can generate a specific and detailed locomotor pattern**[Forssberg 1980].
- We are interested in **how the spinal cord utilizes the natural dynamics of the body**. Therefore, we focus on the locomotion experiments with a spinal cat*.

(*Cat with part of the spinal cord separated at the thoracic or cervical vertebrae and disconnected from the higher CNS.)

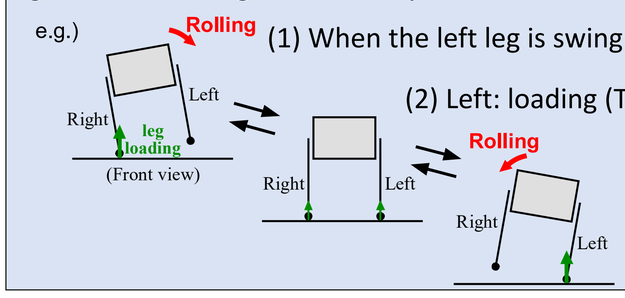
Objective

To understand the mechanisms in the emergence of adaptive motion at the level of sensorimotor functions by constructive approach.

2. Rhythm & Gait Generation Mechanism

Rhythm & gait are determined by time of touch-down (TD) and lift-off (LO)

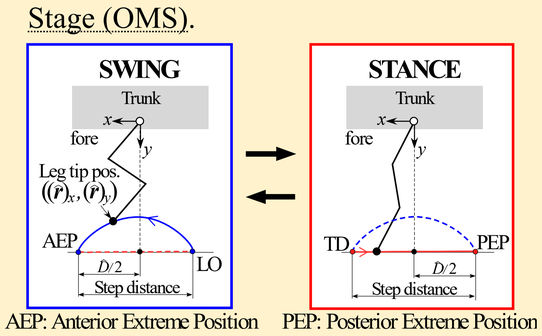
- It was shown in decerebrate cats that **hip flexion**[Pearson 2005] contributes to timing of TD, and both **hip extension**[Grillner 1978] & **leg unloading**[Pearson 1980] contribute to timing of LO.
- By using leg loading as the leg phase transition conditions, we can construct a rhythm generator utilizing the natural dynamics of the body.



3. Leg Controller (LC) as the Spinal Cat Model

LC is designed referred to the limb controller[Orlovsky 1999] at the spinal cord

LC consists of CPG (Rhythm Generator (RG) + Pattern Formation (PF)) and Output Motor Stage (OMS).



AEP: Anterior Extreme Position PEP: Posterior Extreme Position

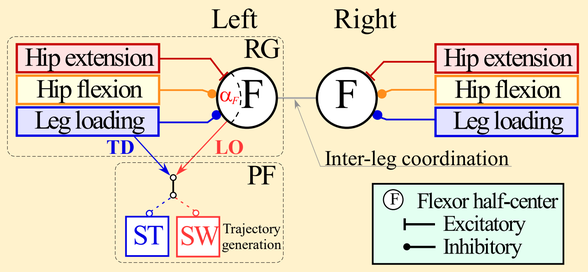
In the PF of the LC, nominal leg trajectories are given in the swing and stance phases, respectively.

- RG: Original RG (**RG***) for the transition between the swing and stance phases referring to [Ekeberg 2005, Maufroy 2010].
- PF: Trajectory generation of the leg tip position & the inverse kinematics to calculate the reference angle of joints.
- OMS: PD-controller at the joints.

⇨ **Each leg steps in the pitch plane.**

4. Leg Phase Transition

Timing of TD and LO are determined by sensory feedback



α_F: Flexor activity

Original:
$$\alpha_F = \frac{(\bar{\boldsymbol{r}})_x}{\hat{D}/2} - C_{frc} \cdot \frac{\bar{f}_n - \hat{\chi}_{LO}}{\hat{\chi}_{TD}}$$

Used in the simulation:
$$\alpha_F = \frac{\max(\bar{r}_{ext},0) - \max(\bar{r}_{flx},0)}{\hat{D}/2} + C_{frc} \cdot \frac{\hat{\chi}_{LO} - \min(\bar{f}_n, \mu\hat{\chi}_{LO})}{\hat{\chi}_{TD}}$$

$\bar{\boldsymbol{r}}$: Measured leg tip position $\bar{f}_n$: Measured leg loading
$\bar{r}_{flx}$: Measured hip flexion $(= (\bar{\boldsymbol{r}})_x)$ $\bar{r}_{ext}$: Measured hip extension $(= -\bar{r}_{flx})$
$\hat{\chi}_{LO}, \hat{\chi}_{TD}$: Leg loading thresholds $\hat{D}, C_{frc}, \mu$: Constant parameters

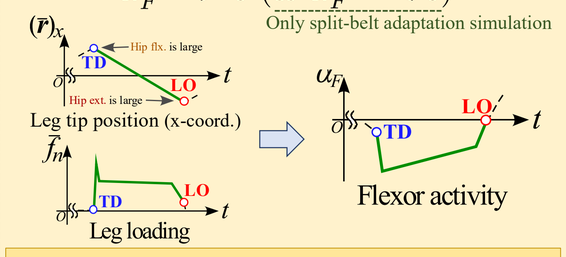
TD (swing-to-stance) condition

Leg loading is large and the leg is in the late swing phase

LO (stance-to-swing) condition

$$\alpha_F^{self} > 0 \ (\& \ \alpha_F^{cntr} < 0)$$

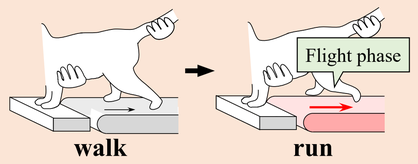
Only split-belt adaptation simulation



Hip extension is large and/or **leg loading is small** (and the contralateral leg is not in the early swing phase)

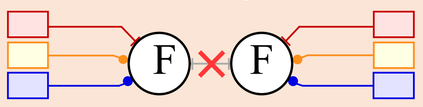
5. Walk-to-Run [Forssberg 1980]

To evaluate RG*, we simulated the walk-to-run transition



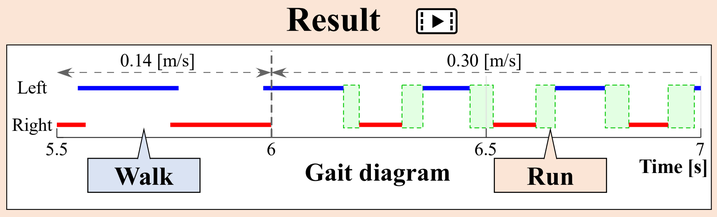
Spinal cats showed the **walk-to-run gait transition** according to the **increase of the belt speed**.

Without the inter-leg coordination

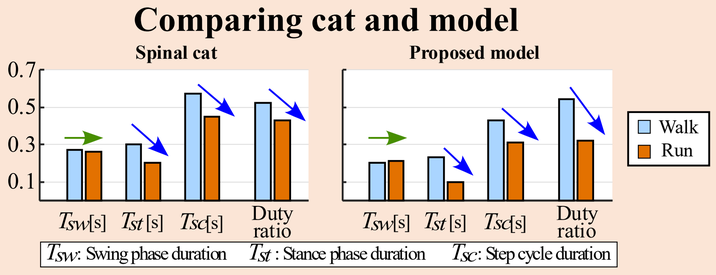


Fixtures: -PD control for front/back and vertical directions
-Firmly fixed around yaw axis

Result



Comparing cat and model

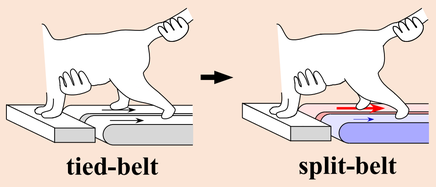


⇨ **By sensorimotor functions, RG* autonomously varied the rhythm similar to that of spinal cats.**

6. Split-belt Adaptation [Frigon 2017]

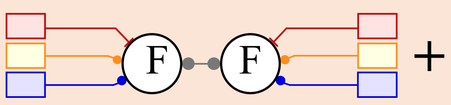
To investigate the inter-leg coordination, we simulated the split-belt adaptation

Spinal cats could show a symmetrical gait while **keeping the TD phase difference be almost 0.5** in tied-belt locomotion and even in **normal split-belt locomotion**.



However, in **slower split-belt locomotion**, spinal cats could not show a symmetrical gait. They often showed the gait switch **from the single-step to the double-steps** of the fast-leg.

With the inter-leg inhibition coordination



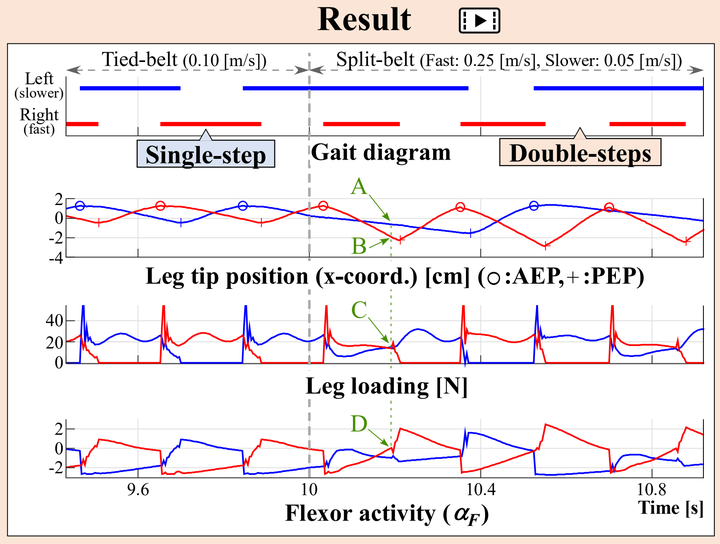
Fixtures: -PD control for front/back directions and around roll axis
- Firmly fixed around pitch & yaw axis

Proposed Responses

When the hip extension of the fast-leg is quite large, responses are triggered.

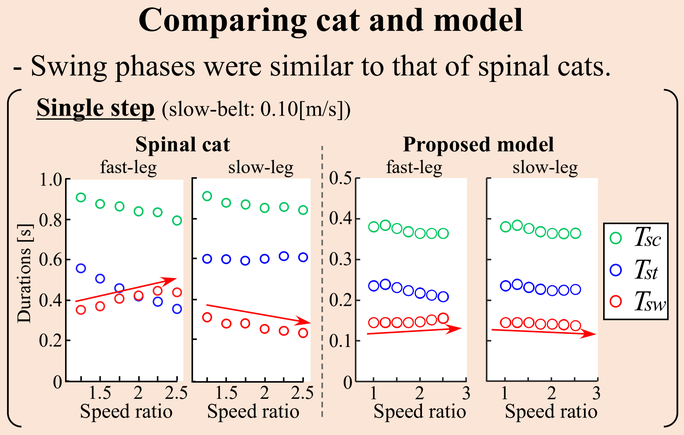
e.g.)
TD of the slow(er)-leg is quickened as inter-leg coordination.
(Contralateral Adjustment of the Swing phase duration, **CAS**)

Result



Hip extension of the slower-leg was small (A), but that of the fast-leg was large (B), while leg loadings were almost the same (C). Therefore, LO condition for the fast-leg was satisfied before the slower-leg (D), and the gait switched to double-steps.

Comparing cat and model

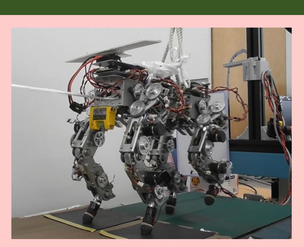


- Swing phases were similar to that of spinal cats.
- TD phase difference kept 0.49 ± 0.02 in single-step regardless of speed ratios (fast-belt/slow-belt).
- The gait autonomously switched to double-steps in slower split-belt locomotion.

⇨ **Proposed spinal cat model has validity.**

7. Conclusion & Future Challenge

- **The design concept of RG* works well, and the proposed spinal cat model has validity.**
- **Simulations show that hip extension/flexion and leg loading are important in generating some adaptive motions.**
- **These results might indicate a possibility that the basic locomotion pattern of a cat is emergently generated in the spinal cord primarily by sensory feedback.**
- **Robot experiments are future challenges.**



Quadrupedal robot "Kotetsu"