Asynchronous Bilateral Body Bending Enables Fast Cheetah-like Rotary Galloping

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1 Introduction

Galloping, as the fastest gait of quadruped animals, is divided into two types based on the footfall pattern, i.e., rotary gallop and transverse gallop [1]. In rotary gallop, the feet touch the ground in the order of left hind, right hind, right fore, left fore, while in transverse gallop, the sequence is left hind, right hind, left fore, right fore. Despite rotary gallop being faster than transverse gallop, the relationship between footfall pattern and running speed is not fully understood.

This study aimed to examine the contribution of footfall pattern to locomotion speed and proposed a working hypothesis that rotary gallop facilitates the effective utilization of body trunk flexion and extension. To validate this hypothesis, we present a simple quadruped robot model and the simulation. These results suggest that flexible body trunk motion effectively extends stride length in the rotary gallop.

2 Working Hypothesis

We first considered an advantage of rotary gallop in using body bending. The body bending during the rotary gallop contributes to the extension of stride length [2]. Therefore, we hypothesized efficient coordination between the body and leg movements would result in an extended stride length, as shown in Fig. 1. When the hind leg is on the ground, the ipsilateral side of the body trunk extends, while when the fore leg is on the ground, the ipsilateral side of the body trunk flexes. Here, we focused on the discrepancy in the bending timing of the left and right sides, i.e., asynchronous bilateral body bending. This discrepancy arises from the differences in footfall timing between the left and right legs, and leads to an extended stride length.

3 Model

We present a simple quadruped model to investigate the contribution of the asynchronous bilateral body bending to the locomotion speed. To simplify the model and focus on the coordination of footfall pattern and body flexion, we employed a two-dimensional model in the horizontal plane. The control algorithm is a simple feedforward control to imitate a cheetah-like rotary gallop.

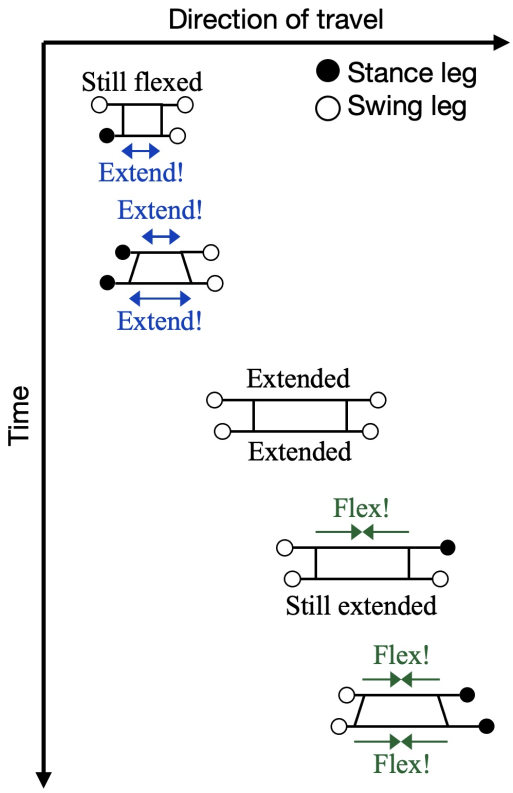

Figure 1: Asynchronous bilateral body bending extends stride length in a rotary gallop.

Figure 2 shows the overview of the quadruped robot body. The body dynamics is described as a mass-spring-damper system, where point masses are located at both sides of the shoulder, hip, forefeet, and hindfeet.

The resistive force between each mass point at the feet and the ground is described as viscous friction, and the coefficient of the leg is given by

$$\mu_{ij} = \begin{cases} 0 & (0 < \phi_i \leq \pi) \\ C_m & (\pi < \phi_i \leq 2\pi), \end{cases} \tag{1}$$

where μ_{ij} denotes the friction coefficient of the ith leg (fore:1, hind:2) of j side (left:1, right:2). The variable ϕ_{ij} represents the phase of the oscillator implemented in each

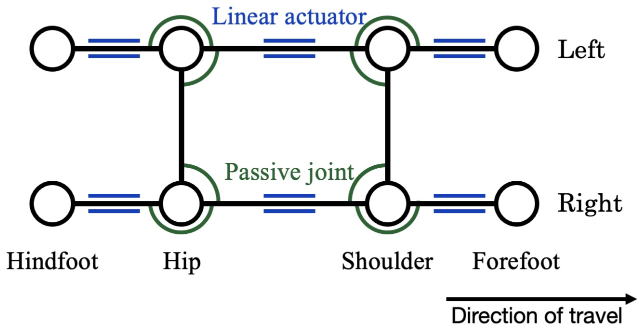

Figure 2: Quadruped robot model in the horizontal plane.

leg. When $0 < \phi_{ij} \le \pi$, the leg is in the swing phase and experiences no resistive force from the ground ($\mu_{ij} = 0$), while when $\pi < \phi_{ij} \le 2\pi$ is in the stance phase and obtains a resistive force ($\mu_{ij} = C_m$). The variable C_m denotes a positive constant.

The time evolution of the oscillator phase is described as follows:

$$\dot{\phi}_i = \begin{cases} \dfrac{\pi}{(1-d)T} & (0 < \phi_i \le \pi) \\ \dfrac{\pi}{dT} & (\pi < \phi_i \le 2\pi), \end{cases} \tag{2}$$

$$\phi_{\text{initial},ij} = \psi_{ij}, \tag{3}$$

where the angular frequency of the oscillator is derived by the gait cycle T, which refers to the time elapsed between two consecutive steps, and duty factor d, which represents the proportion of time spent in the stance phase by one foot during a gait cycle. The initial oscillator phase is represented by $\phi_{\text{initial},ij}$, and the phase difference between the oscillator ϕ_{ij} and the left fore leg's ϕ_{11} is represented by ψ_{ij}.

The leg and body linear actuators are position-controlled by the phase of the oscillator implemented in each leg,

$$\bar{l}^L_{ij} = \begin{cases} l^L_{\text{offset}} - l^L_{\text{amp}} \cos\phi_{ij}, & (i = 1) \\ l^L_{\text{offset}} + l^L_{\text{amp}} \cos\phi_{ij}, & (i = 2), \end{cases} \tag{4}$$

$$\bar{l}^B_j = l^B_{\text{offset}} + f(\phi_{1j}, \phi_{2j}), \tag{5}$$

$$f(\phi_{1j}, \phi_{2j}) = \begin{cases} -l^B_{\text{amp}} & (0 < \phi_{1j} < \phi_{2j} \le \pi) \\ l^B_{\text{amp}} & (0 < \phi_{2j} < \phi_{1j} \le \pi) \\ -l^B_{\text{amp}} \cos\phi_{1j} & (\pi < \phi_{1j} \le 2\pi) \\ l^B_{\text{amp}} \cos\phi_{2j} & (\pi < \phi_{2j} \le 2\pi), \end{cases} \tag{6}$$

where $\bar{l}^L_{ij}$ and $\bar{l}^B_j$ represent the target length of the leg and body actuators, respectively. The variables l^L_{offset}, l^L_{amp}, l^B_{offset} and l^B_{amp} denote positive constants. Each leg actuator works to move the foot forward in the swing phase and backward in the stance phase. The body trunk extends when the ipsilateral hind leg is in the stance phase ($\pi < \phi_{1j} \le 2\pi$), and retracts when the ipsilateral fore leg is in the stance phase ($\pi < \phi_{2j} \le 2\pi$). When both ipsilateral legs are in the swing phase, the body trunk remains extended ($0 < \phi_{1j} < \phi_{2j} \le \pi$) or retracted ($0 < \phi_{1j} < \phi_{2j} \le \pi$).

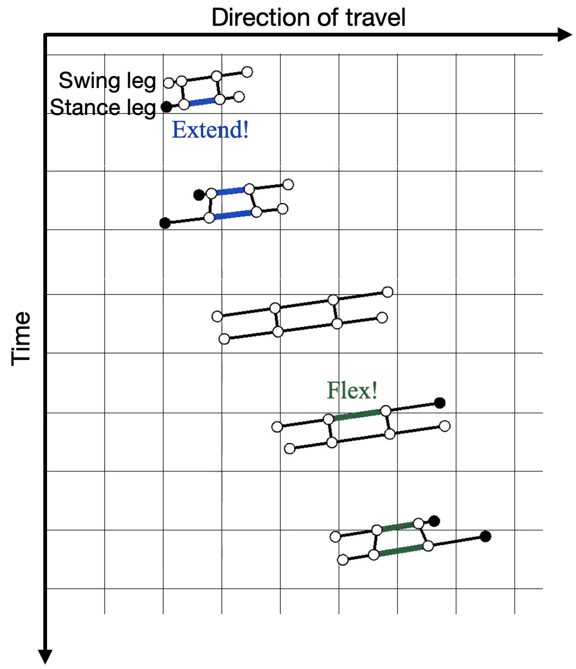

Figure 3: Snapshots of the simulated model that exhibits asynchronous bilateral body bending.

4 Simulations and Results

We conducted simulations and compared the locomotion speed with and without asynchronous bilateral body bending. The experiment was conducted by adjusting the torsional spring coefficient F of the passive joints connecting the trunk and girdle. The flexible body with low F is allowed for asynchronous bilateral body bending, while the stiff body with high F leads to synchronous bilateral body bending. The other parameters were determined by referring to the cheetah's rotary galloping [3]. The results showed the mean speed of the flexible body model ($F = 1000$) was 18.33 m/s, while the speed of the stiff body model ($F = 100000$) was 17.85 m/s. Figure 3 provides snapshots of the flexible body model during locomotion, demonstrating a rotary gallop with asynchronous bilateral body bending, similar to that as shown in Fig. 1. The results suggest that asynchronous bilateral body bending can improve the speed of the rotary gallop.

Acknowledgements

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