P26

# Gait Transition to Gallop via an Interlimb Coordination Mechanism Based on Tegotae from Body Support and Propulsion

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## 1 Introduction

Quadrupeds change the coordination patterns between thier limbs (gait) in response to locomotion speed [1]. For example, when dogs walk at low speed, their feet move in the following order: left fore (LF), right hind (RH), right fore (RF), and left hind (LH). When dogs trot at a middle speed range, their diagonal pairs of legs move synchronously. Finally, when dogs gallop at high speed, their left and right limbs move asymmetrically. By changing their gait, quadrupeds achieve low-cost of transport over a wide locomotion speed range [2].

In order to understand the mechanism of gait transition in response to locomotion speed, we focused on the important facts obtained from the neurophysiological experiments conducted on decerebrate cats [3]. These cats could change their gait pattern from walk to trot to gallop while on a treadmill with accelerating, even though communications with the higher brain have been removed. These results suggest that limb coordination is controlled partially by the spinal neural network, i.e., central pattern generator (CPG). Although many researchers have proposed various structures of CPG models [4–8], the mechanism for interlimb coordination remains unclear so far.

While many researchers focused on the neural connection between limbs, Owaki et al. proposed a CPG model focusing on physical communication between limbs [9]. In this CPG model, interlimb coordination is self-organized via a simple local sensory feedback rule: if a limb feels a ground reaction force (GRF), the limb tends to keep supporting the body. This simple rule reproduced various gait patterns in response to morphology and the locomotion speed of the robots [9, 10]. However, the phase relationships between the left and right limbs of the robot were almost in-phase at high speed gait, while quadrupeds exhibit distinct differences between the left and right limbs [11]. From these results, we expect that more reasonable feedback rules can accurately reproduce high-speed gait.

In order to design local sensory feedback rules more suitable for quadruped locomotion, we focused on *Tegotae* from both body support and propulsion. Tegotae is a Japanese concept describing how well the received reaction matches an expectation. More specifically, we defined a Tegotae function that quantifies Tegotae, and designed local sensory feedback rules in which Tegotae is increased in each limb. In a two-dimensional simulations, we reproduced gait transition from walk to trot to gallop via the proposed model.

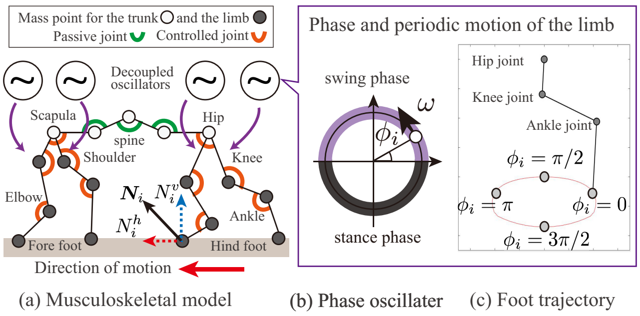


**Figure 1:** Musculoskeletal model and basic leg control.

## 2 Tegotae-based interlimb coordination rule

We constructed a two-dimensional model of the whole body of a robot using a spring, mass, and damper (Fig.1 (a)). The robot consists of a passive bendable trunk segment and four limb segments. For leg control, we employed a phase oscillator to represent the periodic motions of the limb (Fig.1(b)). $\phi_i$ is the phase of the oscillator implemented in each limb. The basic period of motion is controlled by $\omega$, the intrinsic angular velocity. When $0 < \phi_i < \pi$, the limb is in a swing phase. When $\pi < \phi_i < 2\pi$, the limb is in a stance phase. The foot follows a specified target trajectory according to $\phi_i$ (Fig.1(c)). If $\phi_i$ is controlled by only $\omega$, the phase differences between limbs will never change from their initial condition.

In this study, interlimb coordination is self-organized by only local sensory feedback. We designed the feedback terms from the viewpoint of Tegotae as follow:

$$\dot{\phi}_i = \omega + \frac{\partial T_i(\phi_i, \boldsymbol{N}_i)}{\partial \phi_i}, \qquad (1)$$

where function $T_i$ denotes the Tegotae, $\boldsymbol{N}_i$ is the GRF vector obtained from $i^{\text{th}}$ limb. The function $T_i$ is generally described in the form of the product of the intention of controller and the reaction from the environment, and it is defined such that $T_i$ attains higher values when the controller receives good reaction. In the Tegotae-based control scheme, the controlled parameter $\phi_i$ is modulated in order to increase Tegotae in each limb [12].

In this study, we hypothesized that Tegotae from both body support and propulsion is essential for gait transition to gallop. We defined $T_i$ as follows:

**Table 1:** Parameters in simulation

| parameter | value [unit] |
|---|---|
| body length | 1.1 [m] |
| body height | 0.6 [m] |
| total Mass | 33.5[kg] |
| $\sigma^s$ | 1.3e-2[rad/Ns] |
| $\sigma^p$ | 2.0e-2[rad/Ns] |
| initial $\phi_0$ (LF) | $-\pi/10$[rad] |
| initial $\phi_1$ (LH) | $\pi/10$[rad] |
| initial $\phi_2$ (RF) | $\pi/10$[rad] |
| initial $\phi_3$ (RH) | $-\pi/10$[rad] |

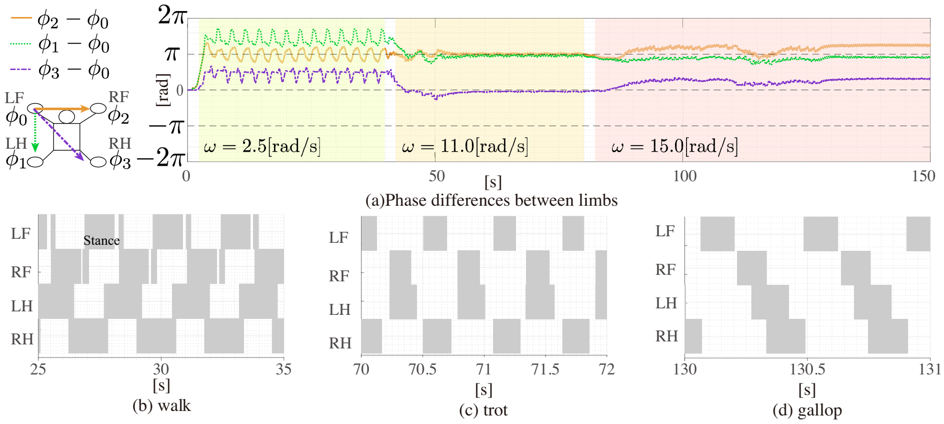


**Figure 2:** Gait transition from walk to trot to gallop

$$T_i = \sigma^s T_i^s(\phi_i, \boldsymbol{N}_i) + \sigma^p T_i^p(\phi_i, \boldsymbol{N}_i), \quad (2)$$
$$T_i^s = (-\sin\phi_i)N_i^v, \quad (3)$$
$$T_i^p = (-\sin\phi_i)N_i^h, \quad (4)$$

where $T_i^s$ denotes Tegotae from body support, $T_i^p$ denotes Tegotae from propulsion; $\sigma^s$ and $\sigma^p$ are positive weighting values for body support and propulsion, respectively; $N_i^v$ is the vertical component of GRF, and $N_i^h$ is the horizontal component of GRF, respectively. We simplified the intention of body support and propulsion as $(-\sin\phi_i)$ so that the intention part reaches maximum in the middle of the stance phase. The meanings of $T_i^s$ and $T_i^p$ are explained as follows. In the middle of stance phase, the posture of the limb becomes suitable for body support. In addition, the limbs need to make propulsive force during stance phase. For these reasons, the intention of both body support and propulsion are modeled as $(-\sin\phi_i)$. When $N_i^v$ is positive, it is desirable for the limb to support the body. When $N_i^h$ is positive, it is desirable for the limb to move the body forward. According to Equations (1) – (4), the Tegotae-based interlimb coordination rule can be formulated as follows:

$$\dot{\phi}_i = \omega - \sigma^s N_i^v \cos\phi_i - \sigma^p N_i^h \cos\phi_i. \quad (5)$$

## 3 Simulation

In order to verify the proposed interlimb coordination rule, we changed only $\omega$ from 2.5 to 11.0 to 15.0 [rad/s], and checked the phase difference between the limbs. We set the body parameters of the robot to be like those of large dog breeds [11] and control parameters as shown in Table 1.

According to the results (Fig. 2), the phase differences of limbs between left and right limbs changed from anti-phase to asymmetric in response to $\omega$ input. In addition, the robot exhibited a walk, trot, and gallop gait at low, middle, and high $\omega$, respectively. The average locomotion speed changed from 0.33 to 2.37 to 3.66 [m/s], and the locomotion period changed from 2.51 to 0.57 to 0.41 [s]. While gait transitions did not converge spontaneously, the speed and the period at each gait were similar to the locomotion of dog at the same scale [11]. While other studies have assumed the neural coupling between the limbs so far, we successfully reproduced gait transition to gallop via only the simple local sensory feedback rules.

## 4 Conclusion

In order to understand the essence of the underlying mechanism of adaptive gait transition in quadrupeds, we focused on the two limbs roles: body support and propulsion. Furthermore, we introduced a concept, Tegotae, for systematical design of the local sensory feedback rules. In the two-dimensional simulation, the robot reproduced the gait transition from walk to trot to gallop. These results suggest that feedback from both $N_i^v$ and $N_i^h$ are essential for gait transition to gallop.

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