Interlimb Coordination Mechanism Underlying High-Speed Quadrupedal Locomotion

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論文内容要約

Quadrupeds exhibit versatile gait patterns in response to locomotion speed, their morphology, and the environment. For example, dogs change their gait patterns from walking to trotting to galloping as locomotion speed increases. These gait patterns are generated by the coordination between limbs, that is, interlimb coordination. By changing interlimb coordination, quadrupeds achieve a low cost of transport over a wide range of speeds. While quadrupeds have a large diversity in their morphology, different species have similar gait patterns. These facts suggest that there is some common principle to generate flexible locomotive patterns. Understanding the underlying control mechanism of interlimb coordination is essential to establish a design principle for legged robots that can adaptively generate energy-efficient locomotive patterns.

Biological findings suggest that adaptive interlimb coordination is partially generated by decentralized control mechanisms, i.e., central pattern generators (CPG) and reflexes, i.e., sensory feedback. For instance, decerebrated cats could exhibit spontaneous gait transitions from walking to trotting to galloping as locomotion speed increased, even though the higher brain was removed. Based on these biological findings, various CPG models have been proposed. While wired CPG models design interlimb coordination using neural communication between the limbs, non-wired CPG models enable the robot to generate various gait patterns in response to morphology and locomotion speed even though there is no preprogrammed neural connection between the limbs. These results suggest that physical communication is essential for generating adaptive locomotive patterns for quadrupedal locomotion. Although the previous non-wired CPG model has

succeeded in reproducing bounding gait, in which the left and right limbs move synchronously, the galloping gait, in which the left and right limbs coordinate asymmetrically, has not been well-reproduced. Because almost all cursorial quadrupeds likely use the asymmetrical gait patterns, something is missing in understanding the essential control mechanism of interlimb coordination underlying high-speed quadrupedal locomotion.

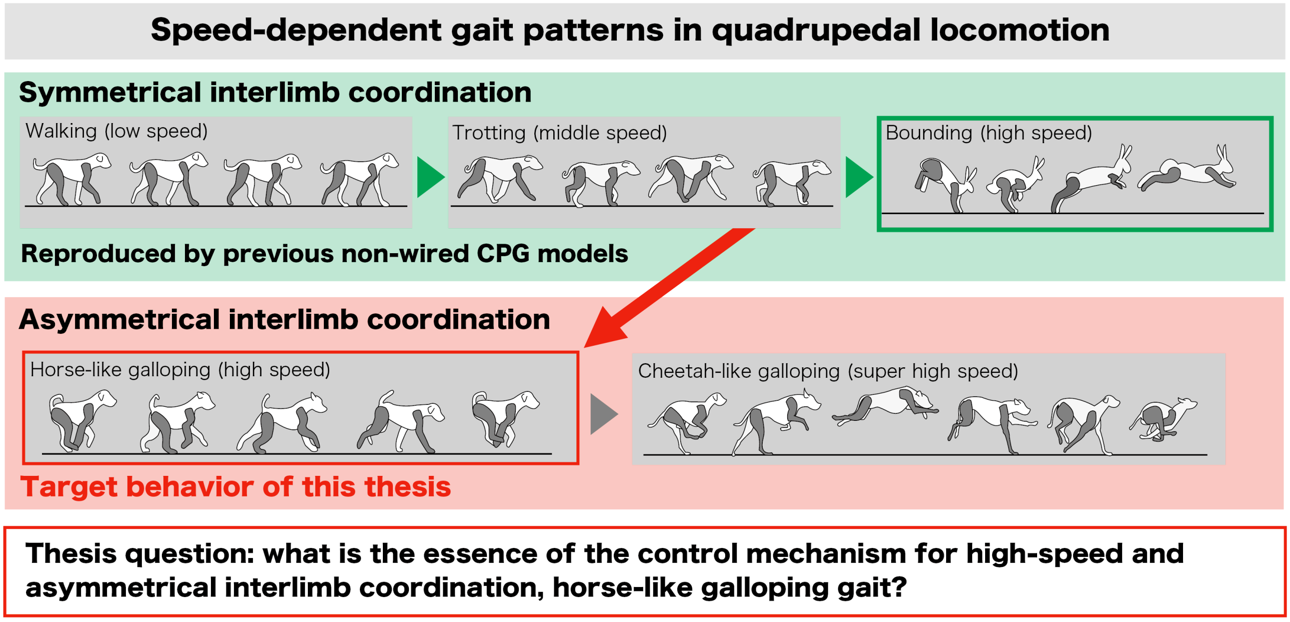

Fig. 1: Target behavior and thesis question.

To address the above issue, we reconsider the interlimb coordination mechanism (Fig. 1). In legged locomotion, limbs are required not only to support the body weight, but also to move the body forward, that is, to provide body support and propulsion. Quadrupeds are clever to utilize various gait patterns and realize simultaneously these roles over various speed ranges. In order to reproduce the high-speed gaits, not only body support roles but also propulsion roles are essential. Based on these ideas, in this thesis, we design a simple interlimb coordination mechanism from the viewpoint of "Tegotae". Tegotae is a Japanese concept describing how well a perceived reaction from the environment matches an expectation of the controller. Although a design principle for decentralized control scheme has not been established, owing to this concept, we can systematically formulate the local sensory feedback rules, which use the vertical and horizontal components of the ground reaction force (GRF) to modulate the phase of the controller (Fig. 2).

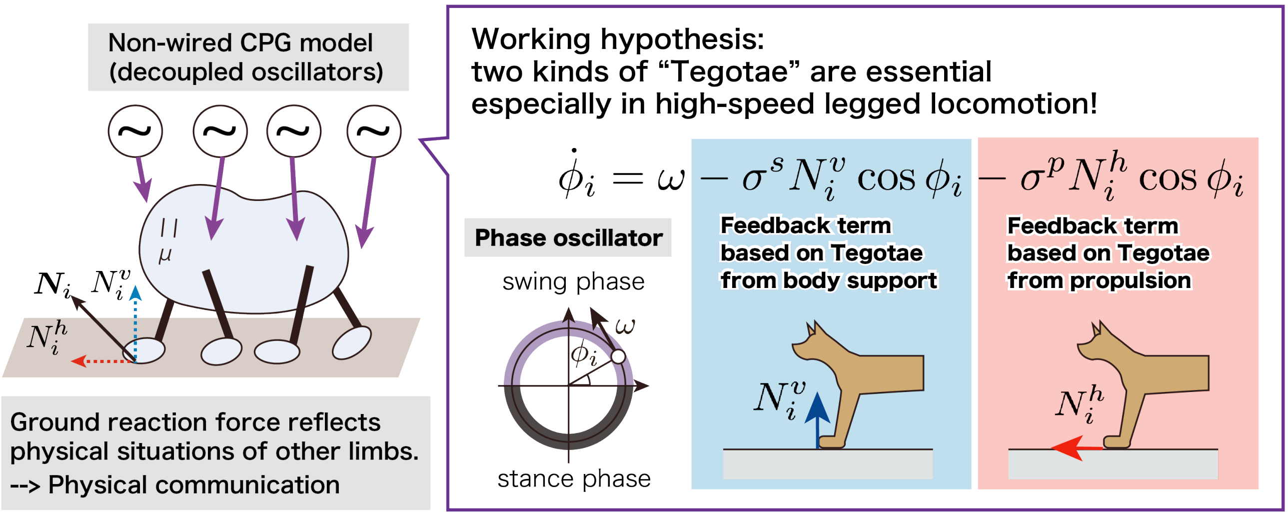

Fig. 2: Proposed interlimb coordination mechanism focusing on body support and propulsion.

In order to verify the proposed model, we conducted 2D simulation experiments and 3D hardware experiments using a developed quadruped robot (Fig. 3). The simulation results show that the robot exhibits spontaneous gait transition to galloping via the feedback based on Tegotae from both body support and propulsion while the bounding gait emerges via the feedback based on Tegotae from only body support. In hardware experiments, the robot also spontaneously exhibits galloping gait, which is faster and more energy-efficient than the emerged bounding gait. The results in 3D hardware experiments also suggest that 3D physical interaction between the limbs helps the robot to break the symmetry between the left and right limbs at lower locomotion frequency comparing to the 2D simulation environment.

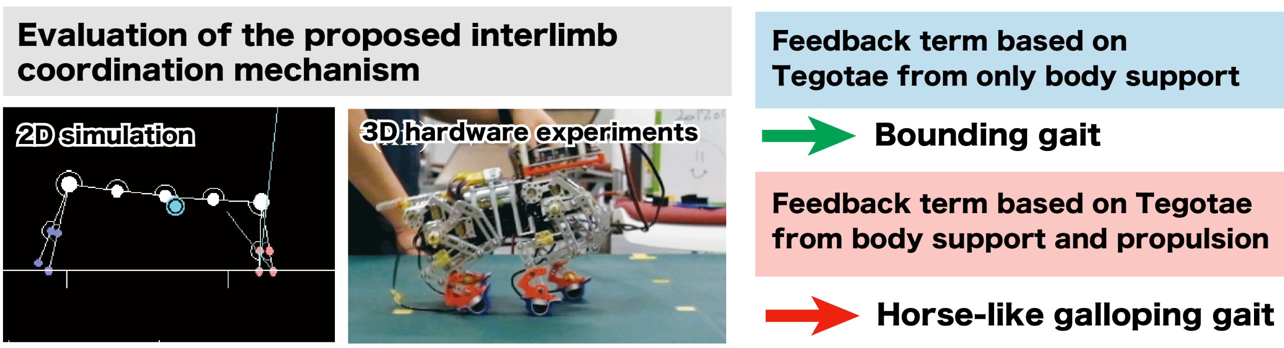

Fig. 3: Two different high-speed gaits emerge depending on the balance between feedback terms.

Results of the evaluations show that different roles between the limbs are essential for reproducing interlimb coordination during the galloping gait. The feedback from body support promotes gait transition at higher locomotion speeds, but it affects the synchronization of the left and right limbs. However, the feedback for propulsion promotes the different roles between the limbs, resulting in deviation of the horizontal component of GRF between the left and right limbs. In fact, galloping quadrupeds exhibit all of the limbs contributing to the motion of the whole body in different ways: trailing hindlimb generates more propulsive force while leading forelimb generates more braking force. The essence of the proposed model is that each limb can behave different roles (e.g., generating more propulsion or braking force) via the feedback term based on the horizontal component of GRF. The proposed model reproduces these behaviors during the galloping gait, suggesting that local sensory feedback based on the horizontal component is essential for the interlimb coordination mechanism underlying high-speed quadrupedal locomotion.