A Simple Torque Feedback-based Innate Mechanism for Intra-leg Coordination of Different Robot Morphologies

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1 Introduction

Locomotion is one of the most important functions of biological behaving systems. While humans take several months to learn to walk [1], some quadrupeds and insects can walk soon after birth [2], [3]. Despite their different morphologies, we hypothesize that there should be a general mechanism that allows animals with different morphologies to coordinate their leg joints (intra-limb coordination) for lifting and placing their legs at the right moment for locomotion. Therefore, we propose here an innate mechanism that can quickly learn to form intra-limb coordination with a proper leg trajectory for locomotion. We demonstrate that the proposed innate mechanism is generic and can be directly applied to different morphologies, such as quadruped-like, typical insect-like, and dung beetle-like leg morphologies.

2 Related Works

Typically, the kinematic or dynamic model of a legged robot can be used to plan the leg movement trajectories and form locomotion [4]. Reinforcement learning can also be applied to teach a robot to walk [5]. However, the model-based approach typically requires a robot model, whereas the reinforcement learning approach requires time to train the robot to walk. Another approach that does not require a robot model and takes less time to learn to walk, inspired by nature, utilizes a central pattern generator (CPG) with adaptive mechanisms to enable self-organized intra-limb coordination for locomotion [6]. However, most CPG-based control usually predefines the control parameters for a specific morphology. In contrast, this study introduces a simple torque feedback-based innate mechanism for self-organized intra-limb coordination that can be directly applied to different robot morphologies (Fig. 1). Here, CPG-based control is used for generating a basic rhythmic pattern with the innate mechanism employed to adapt the connection weights or gains for transmitting a CPG-based control output to the leg joints (see dashed lines in Fig. 1).

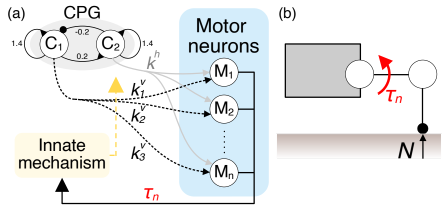

Figure 1: (a) CPG-based control with the proposed innate mechanism. (b) Free body diagram of a robot's leg. τ_n is the joint torque and N is the ground reaction force.

Table 1: Parameters of the neural control for stance phase generation.

Leg morphology	k_1^h	k_2^h	k_3^h
Typical insect-like leg	1.0	0	0
Dung beetle-like leg	0.6	-0.4	0
Quadruped-like leg	0	-1	0

3 Methods

3.1 CPG-based Control

A two-neuron recurrent network is employed as a CPG [7] (Fig. 1). It is described as follows:

$$\begin{bmatrix} o_1 \\ o_2 \end{bmatrix} \leftarrow \tanh \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \tanh \begin{bmatrix} w_{11}o_1 + w_{12}o_2 \\ w_{21}o_1 + w_{22}o_2 \end{bmatrix} \tag{1}$$

where o_1, o_2 and a_1, a_2 represent outputs and activations of the neurons C_1 and C_2 of the CPG. $\boldsymbol{w}$ represents synaptic connections of the CPG, where w_{11} and w_{22} are set to 1.4, w_{12} is -0.2, and w_{21} is 0.2. The weight setup, based on our previous study [7], results in the periodic signals of C_1 and C_2 being at a certain frequency. The signals are projected to the motor neurons of leg's joints (Fig. 1). The output of a motor neuron is given by:

$$M_n = b_n + o_1 k_n^v + o_2 k_n^h \tag{2}$$

where b_n represents the bias value of joint n. The horizontal and vertical gains for horizontal and vertical leg movements of joint n are k_n^h and k_n^v, respectively. k_n^h of each joint for stance phase control in this study is set, as shown in Table 1, while the vertical gain k_n^v is learned through our innate mechanism (described below). This allows us to first investigate the vertical movement of the leg as a fundamental component of the stepping motion in locomotion.

3.2 Torque Feedback-based Innate Mechanism

Typically, legs are required to support the body while walking on the ground (Fig. 1). Each leg receives a ground reaction force that is distributed to each joint. So, each joint needs to provide torque in one direction to counter the ground reaction force. Therefore, the opposite direction could imply that the leg moves away from the ground. Thus, we utilize the joint's torque sensing information to learn the vertical gain for intra-limb (leg joint) coordination of the leg lifting pattern (Fig. 1). The innate mechanism to learn the vertical gain k_n^v is described as:

$$k_n^v = \frac{\tau_n}{\sum_{n=1}^{N} \tau_n}, \tag{3}$$

where τ_n represents the torque feedback of joint n. N is the total number of leg joints. The amplitude of the vertical gain k_n^v of a joint n is determined by the contribution of each joint to support the body weight (Eq. (3)), where the sign of the gain indicates the direction of the torque at the joint resulting from the ground reaction force.

4 Results

The innate mechanism was tested with three different leg morphologies including typical insect-like, dung beetle-like, and quadruped-like leg morphologies (Fig. 2(a)). The horizontal leg movements (stance phase, (Fig. 2(b)) were predefined through the given horizontal gain (k_n^h, see Table 1). The self-organized vertical leg movements (swing phase) realized by adapting the vertical gain k_n^v are shown in Fig. 2(c). Due to the setup and our innate mechanism, as soon as we placed the leg with a fixed posture on the ground, k_n^v of each joint was quickly adapted (learned) within one step (approximately 16 ms of simulation time, see Fig. 3). The learned gain values of each leg show different signs (positive and negative) and magnitudes (Fig. 3), leading to different lifting patterns for different leg morphologies (Fig. 2(c)). The intra-limb coordination for vertical and horizontal movements results in a full stepping pattern, capable of moving forward (Fig. 2(d)). Even though the mechanism enables the leg to lift in the air at the right moment, the leg trajectory is still not perfectly aligned vertically, especially for the quadruped-like leg. Therefore, the innate mechanism should be further optimized for each leg morphology to generate a more precise vertical lifting pattern.

5 Conclusion

This study proposes a simple torque feedback-based innate mechanism that learns the intra-leg coordination for the lifting pattern (moving the leg toward and away from the ground) of various leg morphologies. The mechanism can be applied to typical insect-like, dung beetle-like, and quadruped-like leg morphologies. The learned vertical gains can be used directly with given horizontal gains to create a full stepping cycle (or complete foot trajectory). In the future, the horizontal gain (k_n^h) for horizontal movement will

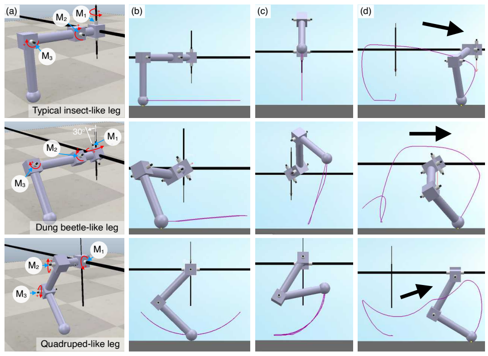

Figure 2: The leg trajectories generated by the CPG-based neural control with the innate mechanism (a) Leg morphologies. (b) Given horizontal movement of each leg. (c) Learned vertical movement of each leg. (d) A self-organized stepping trajectory of each leg. The robot simulator CoppeliaSim and physics engine Newton were used to simulate the robot environment. A supplementary video of this experiment can be viewed at www.manoonpong.com/AMAM2023/Innate/Video.mp4.

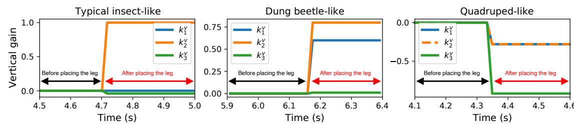

Figure 3: Vertical gain values of different leg morphologies. k_n^v was initially set to zero.

also be learned to fully achieve self-organized intra-limb coordination. Self-organized inter-limb coordination [6] will be also applied to fully obtain fast self-organized locomotion like walking animals.

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