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Phase dynamics on the modified oscillators in Bipedal locomotion

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(joint work with Shin-Ichiro Ei and Kunishige Ohgane)

1. INTRODUCTION

Based on neurophysiological evidence, the theoretical studies by Taga et al. [1] has demonstrated that bipedal walking can be generated by mutual entrainment between of oscillations of a central pattern generator (CPG) [2] and a musculoskeletal system (Body).

For motor control, time delay of signal transmission in sensorimotor loop cause serious problem in general. It is well known that the loop time delay of human locomotion system is very long [3]. How human overcomes the loop time delay becomes a large problem.

Taga [3] has also reported that even a short time delay in a sensorimotor loop between CPG and Body causes the system walking to fall. On the other hand, Ohgane et al. [4] have found that the walking model can be overcome loop time delays by an emergent adaptive phenomenon. They called it “flexible phase locking”, in which the phase of CPG activities forward shifts according to an interval of loop time delay. Flexible phase locking has been induced by modification of the walking model. The main point of the modification was replacement of neuron model for composing CPG. In Ohgane et al. [4], harmonic oscillators [1] have been replaced by BVP neuron model which is known as physiologically faithful neuron model.

The mechanisms for causing flexible phase locking are interesting for motor control or neuroscience. Simplify the waking models and analyze the simplified walking model, theoretical studies [5] have argued that one of the mechanisms for causing flexible phase locking is limit cycle of CPG activity. However, the simplification has been based on only a few characteristics of the walking model and conveniences for analysis. That is, the simplified model has been not described by reduction of the walking model. Whether the mechanisms gained by the simplified model have an universality in human locomotion phenomena or not becomes an open question. That is, whether the mechanisms induce flexible phase locking in human locomotion model or not is an important problem.

This study direct toward its confirmation. In this study, we investigate validity of limit cycle as a mechanism of flexible phase locking in human walking model. Replacing description of the CPG with it of other limit cycle oscillator, we observe phase shift behaviors.

2. THE WALKING MODEL WITH BVP OSCILLATORS

In this section, we introduce a walking model in which flexible phase locking can occur [5]. The model is *the delay direct coupled CPG and Body* (FIG.1).

The time delays through the sensorimotor loop are assumed to be represented as follows: The total time delay Δ_t through the loop consists of two equivalent amounts of time delay $\Delta_t = \Delta_a + \Delta_e$, i.e., an afferent delay Δ_a and an efferent delay Δ_e [3] (FIG.1).

First, we assume $\Delta_a = \Delta_e (=:\Delta)$.

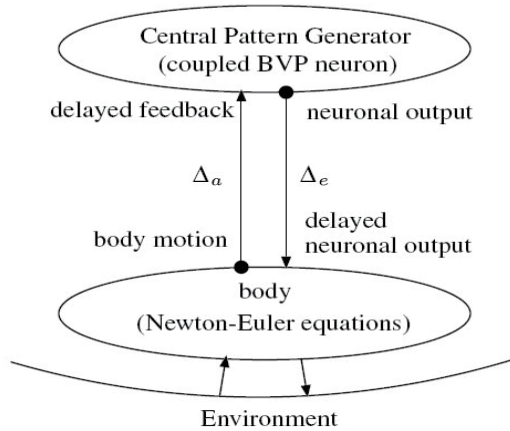


FIG 1. Outline of the walking model (a delayed synaptically coupling of CPG and Body). Δ_a is the afferent time delay and Δ_e is the efferent time delay.

The Body consists of an interconnected chain of 5 rigid links in the sagittal plane as shown in FIG.2. The motion of the Body can be represented by differential equations of a (6×1) vector of mass point positions of 1 link and inertial angles of 4 links. The equations are derived by means of the Newton-Euler method [1, 3]. The value of variables and parameters used in the equations is presented in [4].

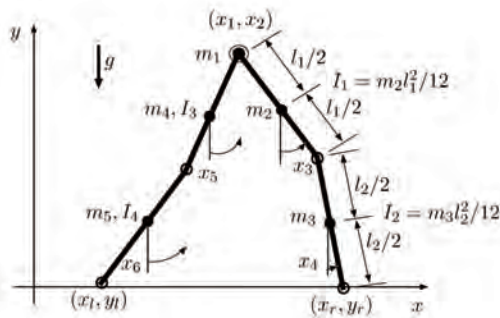


FIG 2. Model of bipedal Body as an interconnected chain of 5 rigid links (a point mass m_1 on the hip and four rigid bodies $I_i (i = 1, 4)$)

The CPG composed of 12 neurons (FIG.3) is represented by the following coupled BVP (Bonhöffer van del Pol) differential equations:

$$(1) \quad \begin{cases} \tau_i \dot{u}_i(t) = u_i(t) - v_i(t) - u_i(t)^3/3 + \sum_{ij=1}^{12} (w_{ij} y_i) + \alpha_w F_i(\mathbf{X}(t - \Delta)), \\ \tau'_i \dot{v}_i(t) = u_i(t) + a - b v_i(t), \end{cases}$$

where u_i is the potential of the i th neuron; v_i is responsible for the accommodation and refractoriness of the i th neuron; w_{ij} is the connecting weight from the i th neuron to the j th neuron; τ_i and τ'_i are the time constants of the potential and the accommodation and refractory effects, respectively; y_i is the output of the i th neuron; u_0 is the constant parameter. Δ is the time delay. α_w is a positive coefficient of afferent connections from the Body to the CPG; F_i is a sensory feedback, and $\mathbf{X} = (x_1, \dots, x_6) \in R^2$ is a vector of the mass point positions of 1 link and the inertial angles of 4 links; t is the time; a and b are positive constants; the natural frequency of each joint neuron (τ_i, τ'_i) is a set of values similar to the natural frequency of each joint [1].

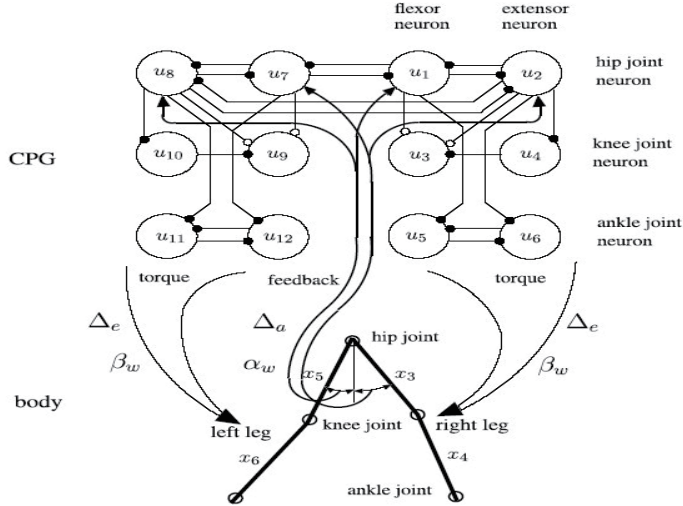


FIG 3. Central pattern generator (CPG) and feedback pathway. u_i is the potential of the i th neuron in the CPG. \circ and \bullet denote an excitatory connection and an inhibitory connection, respectively. x_3, x_4, x_5 , and x_6 are the angles of Body segments. The motion of the hip, the knee joint and the ankle joint in the right leg are governed by neurons 1-2, 3-4, and 5-6, respectively. Similarly, the motion of the joints in the left leg is governed by neurons 7-12. Odd-numbered neurons control flexion of the joint, while even-numbered neurons control its extension. The hip joint angles of both legs are used as feedback to the hip joint neurons. The afferent delay Δ_a and the efferent delay Δ_e take place in the transmission of the neuronal output and of the feedback, respectively. α_w and β_w are the afferent coupling strength and the efferent coupling strength. It is confirmed by computer simulation that the CPG itself has an asymptotically stable limit cycle.

It is well known that a BVP potential has an asymptotically stable limit cycle attractor with appropriate parameters [6]. The value of parameters used here is presented in Ohgane [5]. We confirmed by computer simulation that the CPG itself has an asymptotically stable limit cycle.

In the simulations, the loop time delay Δ_t was the only selected simulation parameter in our consideration. The other parameters were fixed to certain values.

For $\Delta_t = 0$ ms, the model resulted in a stable walking pattern. Our result also shows that the Body oscillation can be characterized by a stable limit cycle.

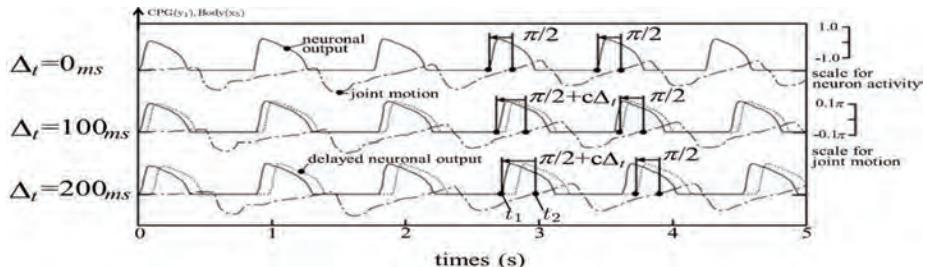


FIG 4. Flexible-phase locking of neuron activity in the walking model. The graph shows the activities of flexor neuron (y_1) and angle motion (x_5) in the left leg. Solid line, dotted line, and dot-dashed line denote the neuronal output, the delayed neuronal output, and the joint angle motion, respectively. Arrows indicate the phase difference between neuronal output and joint angle motion, and between delayed neuronal output and joint angle motion, taking as reference the time when the joint angle becomes larger than 0. The phase of neuronal output is shifted forward according to Δ_t ; t_1, t_2 are the times respresented in this figure, c represents a constant value. Therefore, the phase relationship between delayed neuronal output and joint angle motion is maintained constant.

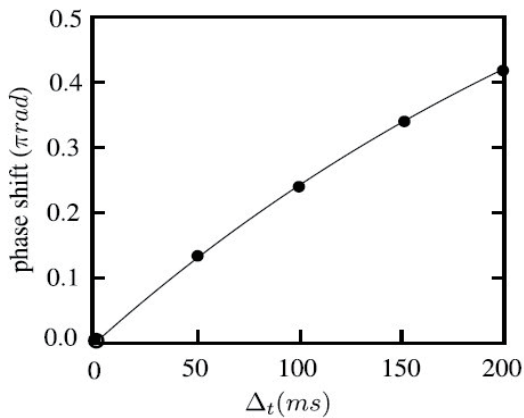


FIG 5. The graph shows the forward phase shift of neuronal output as a function of the total time delay Δ_t . The vertical axis denotes $\frac{t_2 - t_1}{T} - \frac{\pi}{2}$. T is a period of walking cycle. t_1, t_2 are the times represented in . The phase of neuronal output is shifted forward according to Δ_t .

For a loop delay $\Delta_t > 0$, our model clearly showed an ability to generate a stable walking pattern similar to that in the case of no delay $\Delta_t = 0$. FIG.4 shows the hip neuronal output y_1 , the delayed neuronal output, and the hip joint angle x_5 simulated under three conditions of Δ_t ; $\Delta_t = 0, 100$, and 200 ms.

As showed in FIG.4, the phase of the neuronal output could shift forward on that of the joint motion according to Δ_t ; When $\Delta_t=0$, the phase shift of neuronal output shifted $\pi/2$ ahead of the joint motion; besides, this phase shift increases in proportion to the increase of Δ_t (see FIG.5). Therefore, the phase relationship between the delayed neuronal output and the joint angle is constantly maintained in spite of changes of Δ_t .

3. MODIFIED MODELS

As shown above, theoretical studies [5] have argued that one of the mechanisms for causing flexible phase locking is limit cycle of CPG activity by analyzing a simplified model. In this study, we investigate validity of limit cycle as a mechanism of flexible phase locking in human walking model. Replacing description of the CPG with it of other limit cycle oscillator, we observe phase shift behaviors.

In this section, we introduce two limit cycle oscillators described by a $\lambda - \mu$ system [7] and a Van der Pol oscillator [8] to replace the BVP parts in Ohgane model (1).

The $\lambda - \mu$ system is

$$(2) \quad \begin{cases} \dot{u} = (\lambda - u^2 - v^2)u - \mu v, \\ \dot{v} = (\lambda - u^2 - v^2)v + \mu u, \end{cases}$$

for positive constants $\lambda > 0$ and $\mu > 0$. It is easy to see that (2) has a stable periodic solution $S(t) = \sqrt{\lambda}(\cos \mu t, \sin \mu t)$ with the period $p := 2\pi/\mu$ and amplitude $\sqrt{\lambda}$.

The revised CPG equation is represented by the following differential equations just replaced the BVP parts in (1) by (2):

$$(3) \quad \begin{cases} \dot{u}_i(t) = (\lambda_i - u_i^2(t) - v_i^2(t))u_i(t) - \mu_i v_i(t) + u_0 + \alpha_w F_i(\mathbf{x}(t - \Delta)), \\ \dot{v}_i(t) = (\lambda_i - u_i^2(t) - v_i^2(t))v_i(t) + \mu_i u_i(t). \end{cases}$$

The Van der Pol oscillator is

$$(4) \quad \begin{cases} \dot{u} = v, \\ \dot{v} = \varepsilon(1 - u^2)v - u, \end{cases}$$

for a parameter $\varepsilon > 0$. It was used to prove that the system has a stable limit cycle.

The revised CPG equation is represented by the following differential equations just replaced the BVP parts in (1) by (4):

$$(5) \quad \begin{cases} \dot{u}_i(t) = v_i(t) + \sum_{ij=1}^{12} (w_{ij} y_{ij}) + u_0 + \alpha_w F_i(\mathbf{x}(t - \Delta)), \\ \dot{v}_i(t) = \varepsilon_i(1 - u_i^2(t))v_i(t) - u_i(t). \end{cases}$$

In this study, We give a confirmation of the mechanism in the human locomotion by simulations of the two revised models (3) and (5).

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