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Generation of adaptive splitbelt treadmill walking of a biped robot using learning of intralimb and interlimb coordinations

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***Abstract*— In this paper, we proposed a control system with learning to investigate neuromechanical functions for generating adaptive bipedal locomotion on a splitbelt treadmill. Humans show two types of adaptations, called early adaptation and late adaptation, in splitbelt treadmill walking. In our previous work, we investigated the locomotor behavior of a biped robot driven by nonlinear oscillators with phase resetting and showed that it produced the early adaptation like humans. However, because the locomotion control system did not contain any learning mechanism, it did not show the late adaptation. In this paper, we newly develop learning systems, which modulate the interlimb and intralimb coordination patterns, and incorporate them to our locomotion control system. We investigated the locomotor behavior of a biped robot using computer simulations and robot experiments. The results showed the early and late adaptations during the splitbelt treadmill walking and the time evolution of locomotion parameters was similar to that of humans, which might contribute to understanding of adaptive mechanism in humans and to guiding principle for designing a control system of biped robots.**

I. Introduction

Humans and animals are capable of adaptive locomotor behavior to various environments by controlling their legs skillfully. Adaptive modulations in the movement of each leg (intralimb coordination) and the relationship of the movements between the left and right legs (interlimb coordination) are crucial. To investigate the adaptation mechanism in the intralimb and interlimb coordinations in locomotion, a splitbelt treadmill has been often used [4], [15], [18]. It has two parallel belts and their speeds are controlled independently, which artificially produces an asymmetric environment.

In human splitbelt treadmill walking, two types (different time scales) of adaptations are observed (Fig. 1) [15]. One is observed when the configuration of the treadmill switches from the tied configuration (TC: same speed between the belts) to the splitblelt configuration (SC: different speeds between the belts). At that time, locomotion parameters related to the intralimb coordination, such as duty factors, and locomotion parameters related to the interlimb coordination, such as double support duration and relative phase between the leg motions, suddenly change. It is called early adaptation (red arrow in Fig. 1). The other shows gradual changes in locomotion parameters, such as double support duration and relative phase between the leg motions, after the early adaptation and is called late adaptation (green arrow in Fig. 1). In addition, the late adaptation produces aftereffect after the treadmill configuration returns to the TC (blue arrow in Fig. 1). From these results, the late adaptation seems related to motion memory and learning. Although the late adaptation clearly emerged through functions of the nervous system, the underlying mechanism remains unclear.

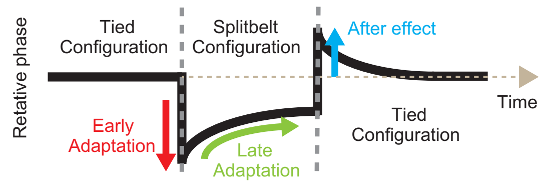

Fig. 1. Adaptation in the relative phase between the leg motions during human splitbelt treadmill walking (modified from [15])

Locomotion is generated through dynamic interactions between the nervous system, the body mechanical system, and the environment. To elucidate the adaptation mechanisms in locomotion, neuromechanical models have been developed. Physiological studies have suggested that central pattern generator (CPG) in the spinal cord strongly contributes to rhythmic movement, such as locomotion [13]. Many researches have developed CPG-based nervous system models [8], [10], [17]. As a modulation mechanism for the rhythm of the CPG, physical modeling of phase resetting based on physiological evidence [5], [6], [16] contributed to generating robust walking against force perturbations and environmental variations [1], [3], [11], [12]. In our previous work [7], we developed a biped robot and a locomotion control system based on the CPG with phase resetting to investigate the neuromachanical functions during a splitbelt treadmill walking. Although the robot without phase resetting easily fell down, the robot with phase resetting produced straight walking during the SC. Instead, the relative phase between the leg motions and duty factors changed autonomously. These changes emerged through dynamic interactions between the locomotion control system, the robot mechanical system, and the splitbelt treadmill. These changes had similar trend to the early adaptation during human splitbelt treadmill walking. However, because the control system did not contain any learning mechanism, our robot did not show the late adaptation.

To explain the adaption mechanism including the late adaptation, some models have been proposed. Otoda *et al.* [14] used a biped robot in the sagittal plane and produced adaptive locomotor behavior by modulating the feedback gains of hip joints. In their system, they used the information of one leg's state only to modulate the gain of the leg and did not use the information of the interlimb coordination. Ito *et al.* [9] modeled adaptive locomotion of cats by using four

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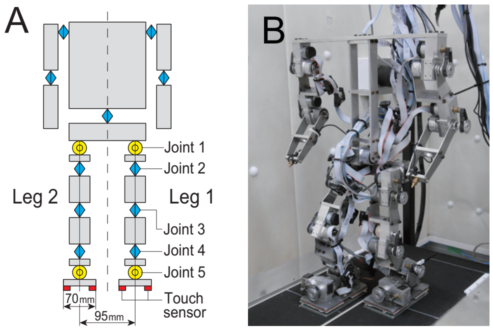

Fig. 2. Biped robot (**A**: Schematic mode, **B**: Robot)

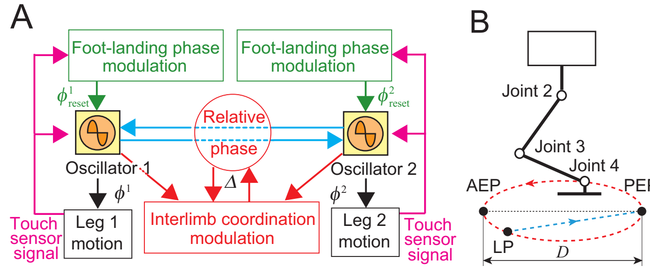

Fig. 3. Locomotion control system. (A) Each oscillator generates the leg motion. The relative phase between the oscillators ($\phi^1 - \phi^2$) approaches into Δ, which is modulated by the interlimb coordination modulation. Based on the touch sensor signal the phase of oscillator i is reset to the reference value ϕ^i_{reset}, which is also modulated by the foot-landing phase modulation. B : Leg motion

oscillators corresponding to the leg motions and a potential function about the relative phases of the oscillators. They modulated the relative phases based on the potential function and showed the late adaptation in their model. However, their model did not involve the body dynamics.

In this study, to overcome the limitation of our previous model to investigate neuromechanical functions related to the late adaptation, we newly introduce two types of learning systems to our control system. One is to control the interlimb coordination pattern directly using the relative phase between the leg motions. The other is to control the foot-landing phase of each leg depending on changes of the timing of foot landing, which corresponds to modulation of the intralimb coordination. We first conduct computer simulations using a robot model and then perform robot experiments to verify the validity of simulation results in the real world. We show that our robot shows early and late adaptations in the splitbelt treadmill walking and the time evolution of locomotion parameters is similar to that of humans.

II. Experimental Setup

A. Biped robot

Figure 2 shows the biped robot used in this study. It was developed in our previous work [7]. For the computer simulation, we derived the equation of motion of the robot model using Lagrangian equations as in [2] and solved the equation using the fourth order Runge-Kutta method with a step size of 0.1 ms. For the robot experiment, the robot gains electric power supply externally. An external host computer (Intel Pentium 4 2.8 GHz, RT-Linux) controls the robot and sends the command signals at intervals of 1 ms.

B. Splitbelt treadmill

We used a splitbelt treadmill developed in our previous work [7]. The width of each belt is 15 cm and the length between the rotation axes is 64 cm. To simulate the walking of the robot model on a splitbelt treadmill, we prepared two floors for the left and right legs to contact and moved the floors independently. We used a linear spring and damper system for modeling the foot contact with the floor and reaction forces.

By following [4], [15], we used two types of speed conditions for the splitbelt treadmill: 1. TC with $v_1 = v_2 =$ 6.9 cm/s and 2. SC with v_1 = 8.5, and v_2 = 5.4 cm/s, where v_1 is left belt speed and v_2 is right belt speed. Because the robot mechanical system has bilateral symmetry, we examined only the configuration ($v_1 \geq v_2$). To clearly see the difference of the locomotor behavior between these speed conditions as in [7], firstly the robot walked on the TC. After the robot established steady walking, we suddenly changed the speed condition from TC to SC and the robot walked on the SC.

III. Basic Locomotion Control System

Before explaining the learning system proposed in this study, we briefly introduce the locomotion control system used in our previous study (see [7] for the details). The locomotion control system was constructed using nonlinear oscillators based on the CPG and phase resetting, which consists of trajectory generator (Section III-A) and rhythm generator (Section III-B) (Fig. 3**A**).

A. Trajectory generator

For the locomotion system, we used two simple phase oscillators (oscillators 1 and 2) and define ϕ^i ($i = 1, 2$) as the phase of the oscillator i. The desired joint movements are determined by these oscillator phases.

The desired leg motion consists of the swing and stance phases (Fig. 3**B**). The swing phase draws a simple closed curve (red line) that contains an anterior extreme position (AEP) and a posterior extreme position (PEP). It starts from the PEP and continues until the foot contacts the floor. The stance phase draws straight line from the landing position (LP) to the PEP (blue line). We used $\phi^i = 0$ at the PEP and $\phi^i = \phi^i_{\text{reset}}$ at the AEP (the value of ϕ^i_{reset} is determined in Section IV-B). Distance between the AEP and PEP is given by D. We defined the gait cycle and duty factor as T and β, respectively. The stride length S and locomotion speed v during overground locomotion are respectively given by $S = D/\beta$ and $v = D/\beta T$. We used D = 2.5 cm, T = 0.70 s, and β = 0.50, which results in S = 5.0 cm and v = 7.1 cm/s.

B. Rhythm generator

The rhythm generator produces the basic locomotion rhythm using the oscillator phases. We used the following phase dynamics:

$$\dot{\phi}^i = \omega + g_1^i + g_2^i \quad i = 1, 2 \tag{1}$$

where ω $(= 2\pi/T)$ is the basic oscillator frequency that uses the same value among the oscillators; g_1^i and g_2^i are functions related to the interlimb coordination pattern and phase resetting, respectively, given below.

1) Phase modulation based on interlimb coordination pattern: The relative phase between the oscillators represents the interlimb coordination pattern because each oscillator phase governs the corresponding leg motion. To control the interlimb coordination pattern, the function g_1^i acts as the interaction between the oscillators. We define the desired relative phase between the oscillators by Δ. The function g_1^i is given by

$$g_1^i = (-1)^i K \sin(\phi^1 - \phi^2 - \Delta) \quad i = 1, 2 \tag{2}$$

where K is a gain constant and we used K = 1.0. The relative phase approaches into the desired state by this function. Because the adaptation of the interlimb coordination is crucial for splitbelt treadmill walking, we modulated the parameter Δ through learning (see Section IV-A).

2) Phase modulation based on phase resetting: To gain robust walking, we used the phase resetting mechanism. When the foot of Leg i lands on the floor, phase ϕ^i is reset to ϕ^i_{reset}. Therefore, the function g_2^i is written by

$$g_2^i = (\phi^i_{\text{reset}} - \phi^i)\delta(t - t^i_{\text{land}}) \quad i = 1, 2 \tag{3}$$

where t^i_{land} is the time when the foot of Leg i lands on the floor and $\delta(\cdot)$ denotes Dirac's delta function. Because the modulation of the oscillator phase by the phase resetting is also crucial, we modulated the parameter ϕ^i_{reset} through learning (see Section IV-B).

IV. Modulation of control parameters through learning

Our robot produced stable, straight walking on the splitbelt treadmill using the locomotion control system explained in the previous section and its behavior showed similar trend to the early adaptation of humans [7]. However, the control system did not incorporate any learning mechanism so that the robot did not show gradual modulation unlike the late adaptation in humans. Therefore, in this paper we developed new learning systems using two control parameters and incorporated them into our control system.

A. Modulation of interlimb coordination pattern through learning

The desired interlimb coordination pattern is represented by Δ in (2) and the relative phase $(\phi^1 - \phi^2)$ is basically designed to converge to the desired state in the oscillator dynamics, which is because humans and animals have inherent or empirical interlimb coordination pattern. Yanagihara *et al.* [18] showed that cats walking on a splitbelt treadmill obtained a new interlimb coordination pattern to adapt to the splitbelt environment and kept the pattern even after the experiment. The results suggest that the cats have desired interlimb coordination pattern and modulate it through learning in perturbed environment. The function g_1^i is consistent with these findings and we modulated the interlimb coordination pattern through learning below.

For the desired relative phase between the oscillators, we define a potential function V_n at nth step inspired by the idea of Ito *et al.* [9] by

$$V_n = \frac{1}{2}\Big[\int_{t^{n-1}_{\text{land}}}^{t^n_{\text{land}}} \sin(\phi^1 - \phi^2 - \Delta_n)dt\Big]^2 \tag{4}$$

where t^n_{land} is the time when a foot lands on the ground at nth step and Δ_n indicates the value of Δ at nth step. The potential function evaluates the averaged difference between the actual and desired relative phases in one gait cycle. It is used to find a suitable interlimb coordination pattern through learning by minimizing the value of the potential function. To reduce the potential function along its gradient direction, the desired relative phase Δ_n is modulated by

$$\Delta_{n+1} = \Delta_n - \tau_\Delta \frac{\partial V_n}{\partial \Delta_n} \tag{5}$$

where τ_Δ is the learning rate. The value of the parameter Δ is modulated by (5) at each foot contact. We used τ_Δ = 0.35 and set Δ = π as the initial value.

B. Modulation of foot-landing phase through learning

As another way to produce adaptive interlimb coordination pattern, we modulated the parameters related to the intralimb coordination. That is, we regulate the individual leg motion to induce the change in the interlimb coordination.

In our previous work [7], we used $\phi^i_{\text{reset}} = 2\pi(1-\beta)$. This is because the nominal foot-landing position is set at the AEP. However, the foot-landing phases depend on the locomotion dynamics and the feet do not always land on the floor at the AEP. Therefore, we define a potential function U^i_n at nth step based on the difference between actual landing phase ϕ^i_{land} and designed landing phase ϕ^i_{reset} by

$$U^i_n = \frac{1}{2}(\phi^i_{\text{reset},n} - \phi^i_{\text{land},n})^2 \qquad i = 1, 2 \tag{6}$$

where $\phi^i_{\text{reset},n}$ and $\phi^i_{\text{land},n}$ are the values of ϕ^i_{reset} and ϕ^i_{land} at nth step, respectively. Based on the gradient direction of the potential function U^i_n, we regulate ϕ^i_{reset} as follows;

$$\phi^i_{\text{reset},n+1} = \phi^i_{\text{reset},n} - \tau_\gamma \frac{\partial U^i_n}{\partial \phi^i_{\text{reset},n}} \quad i = 1, 2 \tag{7}$$

where τ_γ is a learning rate. We used τ_γ = 0.25 and set $\phi^i_{\text{reset},0} = 2\pi(1-\beta)$ as the initial value. This modulation changes the swing phase duration because the increase of ϕ^i_{reset} lengthens the duration to move the foot from the PEP to AEP. By changing the swing phase duration, it modulates the foot-landing phase.

V. Results

A. Simulation and experimental results without learning

First, we investigated the performance of our control system without learning by computer simulations. Figures 4**A** and **C** show the relative phase between the legs using the average value for one gait cycle obtained by $\frac{1}{T}\int_0^T(\phi^1 - \phi^2)dt$

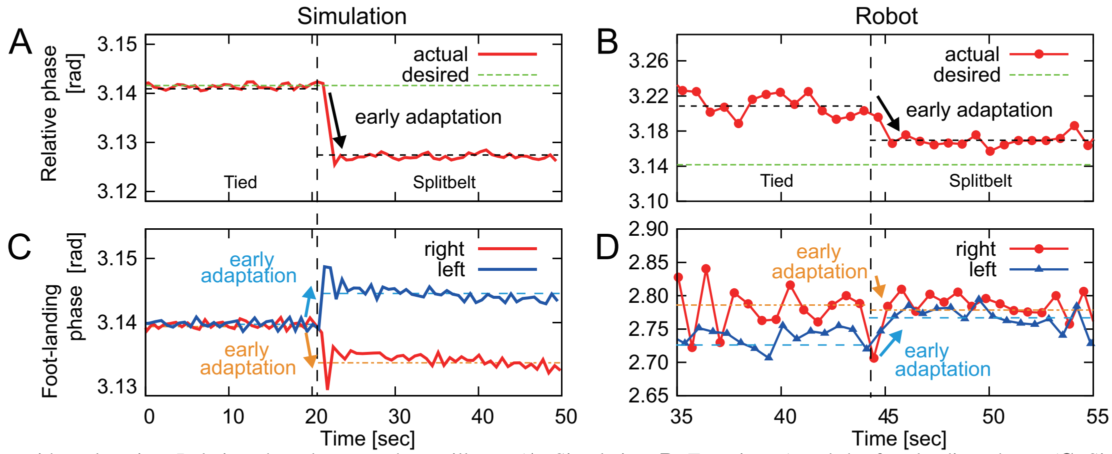

Fig. 4. Results without learning. Relative phase between the oscillators (**A**: Simulation, **B**: Experiment) and the foot-landing phases (**C**: Simulation, **D**: Experiment).

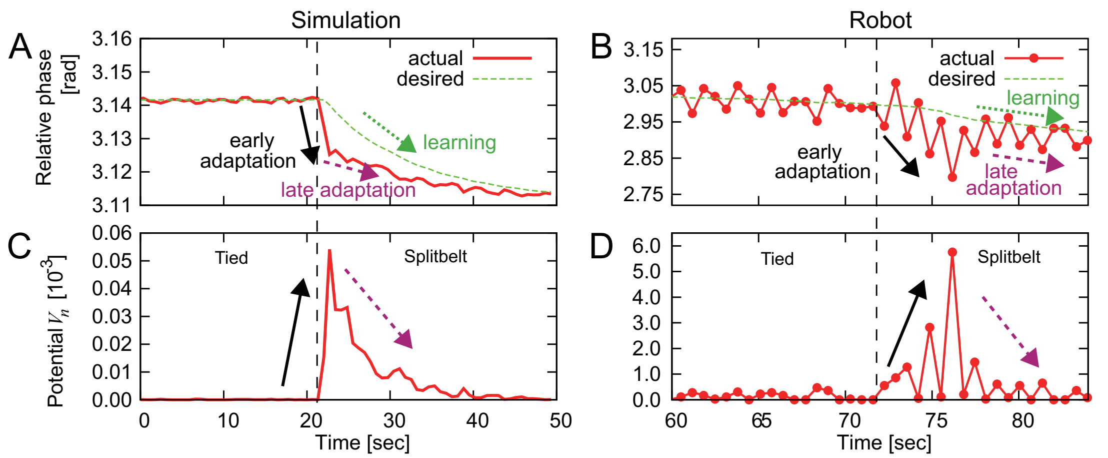

Fig. 5. Results with modulation of the interlimb coordination. Relative phase between the oscillators (**A**: Simulation, **B**: Experiment) and the potential function V_n (**C**: Simulation, **D**: Experiment).

and the phase at foot landing ϕ^i_{land}, respectively. While the relative phase remained almost antiphase in the TC, it suddenly shifted from antiphase when the configuration of the treadmill was changed. Although the phases at foot landing ϕ^1_{land} and ϕ^2_{land} have the same value during the TC, they also shifted suddenly when the treadmill configuration switched to the SC. At the change of the treadmill configuration, ϕ^1_{land} increased while ϕ^2_{land} decreased. It means that the timing of the foot landing of Leg 1 was delayed while the timing of the foot landing of Leg 2 became earlier. In this case, the early adaptation occurred but the late adaptation did not.

To verify the simulation results in the real world, we conducted robot experiments. Figures 4**B** and **D** show the relative phase and foot-landing phases. During the TC, the relative phase converged to almost 3.2 rad, which was slightly different from π, and phases at foot landing are different from each other. This might be caused by the asymmetry in the robot. When the configuration of the treadmill switched into the SC, the relative phase shifted downward from the value at the TC and ϕ^1_{land} increased while ϕ^2_{land} decreased almost simultaneously. Both simulation and experiment results have qualitatively similar trends and are almost the same as in our previous work [7].

B. Simulation and experimental results with learning

Next, we investigated functional roles of the learning systems (5) and (7). We used the same value for the control parameters and the same condition for the splitbelt treadmill, as in the previous section. In robot experiments, we started to record the data after the relative phase and modulation parameters (Δ, ϕ^i_{reset}) become the steady state during the TC.

1) Modulation of interlimb coordination: We used only the modulation (5). Figures 5**A** and **C** show the relative phase and the potential function V_n, respectively, in the computer simulation. During the TC, the relative phase is antiphase and the potential function remains almost zero. At the early stage of the SC, the relative phase shifted from antiphase. Although there is a difference between the actual and desired relative phases at this stage, the desired relative phase was modulated gradually through learning. After sufficient steps, the difference between them decreased and they converged to the same value while reducing the value of the potential function but getting away from π (antiphase). The experimental results of the relative phase and the value of potential function are shown in Figs. 5**B** and **D**, which show similar trends to the simulation results. In this case, the early and late adaptations are generated but the

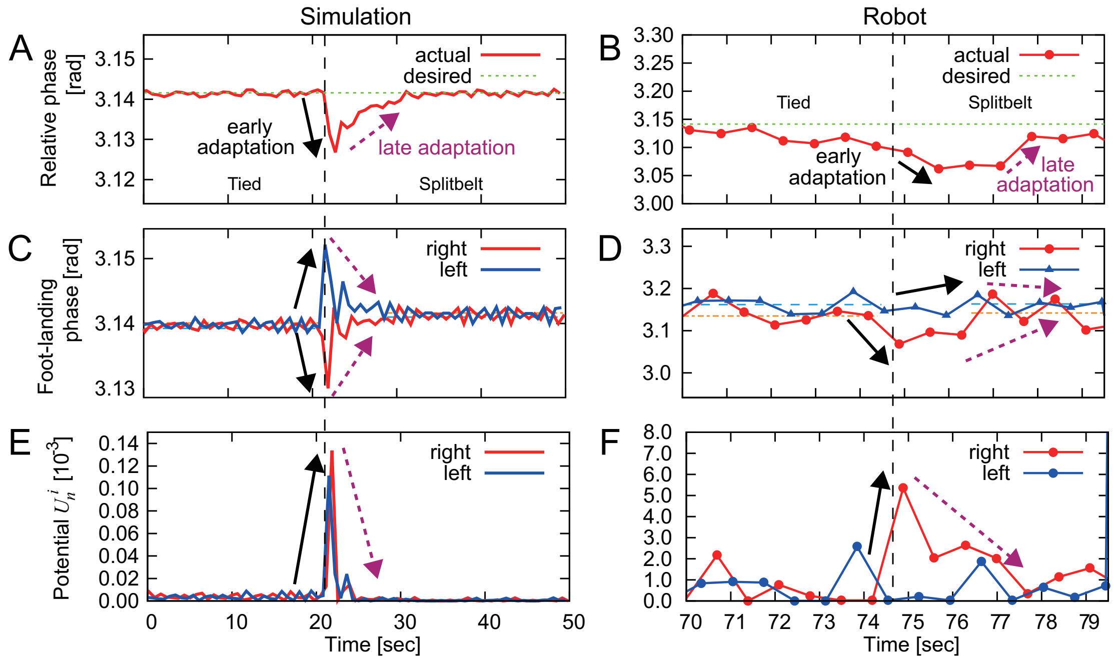

Fig. 6. Result with modulation of the foot-landing phase; Relative phase between the oscillators (**A**: Simulation, **B**: Experiment), the foot-landing phases (**C**: Simulation, **D**: Experiment), the potential function U_n^i (**E**: Simulation, **F**: Experiment).

direction of the change of the interlimb coordination pattern during the late adaptation is different from that of humans.

2) Modulation of foot-landing phase: We used only the modulation (7). Figures 6**A**, **C**, and **E** show the relative phase, the landing phase, and the potential functions U_n^i, respectively, in the computer simulation. During the TC, the relative phase shows almost the same result as above and the values of the potential functions are almost zero. At the early stage of the SC, the relative phase also shifted from antiphase and foot-landing phase of Leg 1 increased while foot-landing phase of Leg 2 decreased. However, after sufficient steps, the relative phase returned to antiphase and foot-landing phases returned to π while reducing the values of the potential functions. The experimental results of the relative phase, the foot-landing phases, and the potential function U_n^i are shown in Figs. 6**B**, **D**, and **F**. These show similar trends to the simulation results. In this case, the early and late adaptations are also generated but the interlimb coordination pattern entirely returned to antiphase after the late adaptation. This trend is slightly different from that of humans.

3) Modulation of interlimb coordination and foot-landing phase: We used the modulations of both the interlimb coordination and foot-landing phase. Figures 7**A**, **C**, **E**, and **G** show the relative phase, the potential function V_n, the foot-landing phases, and the potential functions U_n^i, respectively, in the computer simulation. During the TC and at the early stage of the SC, these data are almost the same as above. After that, the desired relative phase gradually decreased and approached to the actual one due to the modulation of interlimb coordination. On the other hand, the actual relative phase gradually increased to approach to the desired one due to the modulation of intralimb coordination. After sufficient steps, the difference between the actual and desired relative phases vanished while reducing the potential functions V_n and U_n^i. The experimental results are shown in Figs. 7**B**, **D**, **F**, and **H**, which show similar trends to the simulation results. In this case, the early and late adaptations are also generated and the change of the interlimb coordination pattern during the late adaptation shows similar trend to that of humans (Fig. 1).

VI. Conclusion

In this paper, we investigated the adaptive locomotor behavior of a biped robot on a splitbelt treadmill by using computer simulations and robot experiments. We newly incorporated learning systems of the relative phase between the oscillators and foot-landing phases to our previous CPG-based locomotion control system and showed gradual modulations like the late adaptation in human splitbelt treadmill walking.

We proposed two types of learning systems; one is related to the interlimb coordination and the other is foot-landing phase related to the intralimb coordination. When we used only the modulation of the interlimb coordination, the relative phase gets away from antiphase after the early adaptation. It is opposite trend compared with the adaptation of humans. When we used only the modulation of the foot-landing phase, the relative phase entirely returned to antiphase. This is also slightly different from the adaptation in humans. However, by using both learning systems, the result showed a similar trend to that of humans. This is because the two modulations worked together in a way that the modulation of the interlimb coordination pattern moved the relative phase away from antiphase and the modulation of the foot-landing phase attracted the relative phase towards antiphase. As a result, the relative phase converged to some intermediate value between the antiphase and the relative phase just after the early adaptation. This result suggests that both the modulations of the interlimb coordination pattern

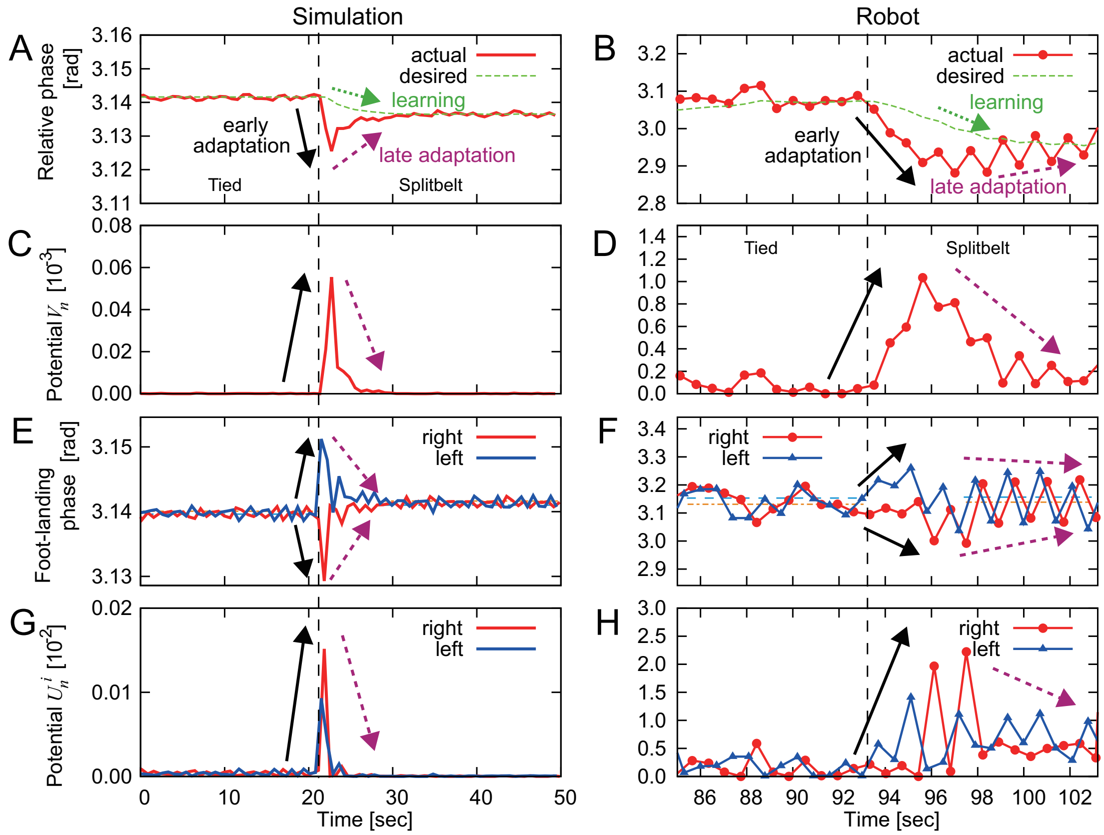

Fig. 7. Result with modulation of interlimb coordination and foot-landing phase. Relative phase between the oscillators (**A**: Simulation, **B**: Experiment), the potential function V_n (**C**: Simulation, **D**: Experiment), the foot-langing phases (**E**: Simulation, **F**: Experiment), and the potential function U_n^i (**G**: Simulation, **H**: Experiment)

and individual control of each leg contribute to generating adaptive behaviors in the late adaptation and are necessary for adaptive locomotion. Our results might contribute to understanding of the adaptation mechanism in human splitbelt treadmill walking and to guiding principle for designing a control system of biped robots. In the future, we would like to further improve our robot and control system to elucidate human's control mechanism of adaptive locomotor behavior.

Acknowledgments

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