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Adaptive splitbelt treadmill walking of a biped robot using nonlinear oscillators with phase resetting

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Abstract To investigate the adaptability of a biped robot controlled by nonlinear oscillators with phase resetting based on central pattern generators, we examined the walking behavior of a biped robot on a splitbelt treadmill that has two parallel belts controlled independently. In an experiment, we demonstrated the dynamic interactions among the robot mechanical system, the oscillator control system, and the environment. The robot produced stable walking on the splitbelt treadmill at various belt speeds without changing the control strategy and parameters, despite a large discrepancy between the belt speeds. This is due to modulation of the locomotor rhythm and its phase through the phase resetting mechanism, which induces the relative phase between leg movements to shift from antiphase, and causes the duty factors to be autonomously modulated depending on the speed discrepancy between the belts. Such shifts of the relative phase and modulations of the duty factors are observed during human splitbelt treadmill walking. Clarifying the mechanisms producing such adaptive splitbelt treadmill walking will lead to a better understanding of the phase resetting mechanism in the generation of adaptive locomotion in biological systems and consequently to a guiding principle for designing control systems for legged robots.

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1 Introduction

Humans and animals are endowed with adaptive locomotion in diverse environments by cooperatively and skillfully manipulating their complicated and redundant musculoskeletal systems. In robotics research, interest in the study of legged robots has been growing. Unlike humans and animals, legged robots still have difficulties in achieving adaptive behaviors in various environmental situations. To overcome such difficulties, clarifying the mechanisms for producing adaptive functions in biological systems and constructing design principles to generate the adaptability in robotic systems are crucial issues.

In adaptive locomotor behavior, the relationship between leg movements, such as interlimb coordination, is an important factor. To investigate the mechanism controlling the interlimb coordination during walking, a special device, a splitbelt treadmill, has been used [11, 24, 29, 38, 48, 49]. The treadmill is equipped with two parallel belts. Each belt has its own motor, and thus the speeds can be controlled independently. The belts are controlled to have the same speed (tied configuration) and different speeds (splitbelt configuration) to examine how humans and animals adapt to varying environments.

Since locomotion is a well-organized motion generated through dynamic interactions between the body, the nervous system, and the environment, neuro-mechanical interactions are crucial to create adaptive locomotion. To produce adaptability in various environments, the physiological concept of a central pattern generator (CPG) has been often used in the locomotion control of legged robots [16, 22, 23, 25, 27, 30–32, 44]. In our previous work, we constructed a locomotion control system using nonlinear oscillators based on this concept [1, 2]. We incorporated a phase resetting mechanism to modulate the locomotor behavior in response to sensory information based on the physiological evidence [14, 26, 40, 42] and demonstrated the adaptability of locomotion to perturbations and environmental changes, such as slopes.

Robots are effective tools for testing locomotor mechanisms with real-world dynamic characteristics [12, 22, 23, 25, 35, 39]. Otoda *et al.* [34] proposed an adaptation model for human splitbelt treadmill walking and investigated using a two-dimensional biped robot. They produced adaptive walking of the robot on a splitbelt treadmill by incorporating the gain adjustment of the joint feedback control. In the present study, we designed a biped robot and splitbelt treadmill and used our developed locomotion control system. We investigated the adaptability during the splitbelt treadmill walking by focusing on the functional roles of phase resetting. In addition, we measured human splitbelt treadmill walking to evaluate the adaptability in the robot. Clarifying the mechanisms producing such adaptive splitbelt treadmill walking will lead to a better understanding of the phase resetting mechanism in the generation of adaptive locomotion in biological systems and consequently to a guiding principle for designing control systems for legged robots.

This paper is organized as follows: Section 2 introduces our experimental setup including the robot, splitbelt treadmill, and measurement of human splitbelt treadmill walking, and Section 3 addresses the locomotion control system. Section 4 shows the experimental results and Section 5 presents the discussion and conclusion.

2 Experimental setup

2.1 Biped robot

We used a biped robot (Figs. 1**A** and **B**), which consists of a trunk composed of two parts, a pair of arms composed of two links, and a pair of legs composed of five links [5]. Each link is connected to the others through a rotational joint with a single degree of freedom. Each joint is controlled by a motor, encoder (Re-max 24, Maxon motor) through a timing belt and pulleys (gear ratio 3:1) and a harmonic drive gear (gear ratio 100:1).

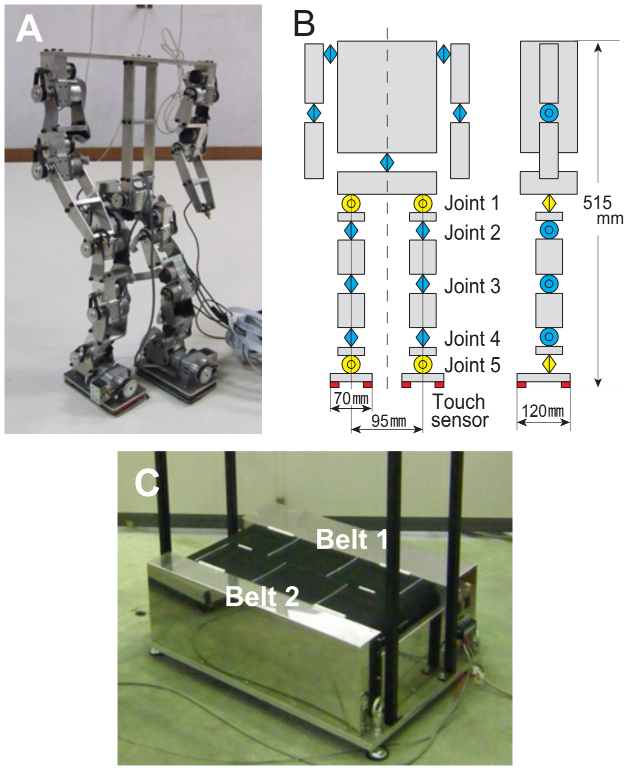

Fig. 1 Experimental devices. **A**: biped robot, **B**: schematic model of the robot, and **C**: splitbelt treadmill for the robot.

Table 1 Physical parameters of the biped robot

Link	Mass [kg]	Length [cm]
Trunk	1.42	27.2
Arm	0.53	22.2
Leg	1.40	24.3
Total	5.28	51.5

Four touch sensors are attached to the corners of the sole of each foot.

The left and right legs are enumerated as Leg 1 and 2, respectively. The joints of the legs are numbered as Joint 1-5, beginning at the trunk. To describe these configurations, we introduce the angle θ_j^i ($i = 1, 2$, $j = 1, \ldots, 5$), which is the rotation angle of Joint j of Leg i. Table 1 shows the physical parameters of the robot.

Electric power is externally supplied and the robot is controlled by an external host computer (Intel Pentium 4, 2.8 GHz, RT-Linux), which calculates the desired joint motions and applies the oscillator phase dynamics in the locomotion control system (see Section 3). The system receives the command signals at intervals of 1 ms. The robot is connected with the electric power unit and the host computer by cables that are slack and held up during the experiment to avoid influencing the walking behavior.

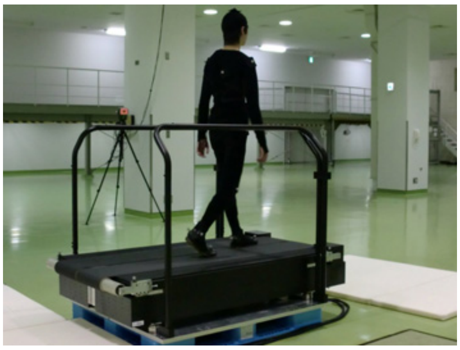

Fig. 2 Measurement of human splitbelt treadmill walking

2.2 Splitbelt treadmill for the robot

We developed the splitbelt treadmill, which has two parallel belts (Belts 1 and 2) and two motors with encoders (Fig. 1**C**). Therefore, we can control each belt speed independently. The width of each belt is 15 cm and the distance between the rotation axes is 64 cm. The robot walks on this treadmill under various speed conditions.

2.3 Measurement of human splitbelt treadmill walking

To investigate the adaptive functions embedded in human splitbelt treadmill walking, we measured the kinematics of a human walking on a splitbelt treadmill. The participants, who were three healthy men (ages: 22-24, weights: 51-74 kg, and heights: 163-170 cm), walked on a splitbelt treadmill (ITR3017, Bertec Corporation) and their motions were measured with a motion capture system (Digital RealTime System, Motion Analysis Corporation) (Fig. 2). The participants gave informed consent prior to data collection according to the procedures of the Ethics Committee of Doshisha University. Reflective markers were attached to skin of the participants over the following body landmarks on both hemibodies: ear tragus, upper limit of the acromion, greater trochanter, lateral condyle of the knee, lateral malleolus, second metatarsal head, and heel [18]. The sampling rate was 500 Hz. Motion was recorded for the tied configuration at 3.0 km/h for both belts and the splitbelt configurations at 3.0 km/h for the right-side belt and 3.5 to 7.0 km/h incremented by 0.5 km/h for the left-side belt. Recording started after the participants had been walking on the treadmill long enough to settle into a regular pattern of movement for each speed condition of the splitbelt.

Humans modulate the spatiotemporal patterns of their leg movements to adapt to their environment, which, in this case, was the splitbelt treadmill. Particularly, the relative phase between the leg movements and the duty factors of the legs are modulated depending on the speed condition [11,29,38]. In the present study, we focused on these adaptations. We calculated the relative phase from the measured timings of the foot-contact of the legs ((foot-contact time of slow leg − foot-contact time of fast leg)/gait cycle) and calculated the duty factors from the ratio between the foot-contact duration and the gait cycle.

3 Locomotion control system for the robot

3.1 CPG-based oscillator network model

Physiological studies have shown that the CPG in the spinal cord strongly contributes to rhythmic limb movement, such as locomotion [19, 33, 43]. The organization of the CPG remains largely undefined, although various CPG models have been proposed [21, 28]. Physiological findings suggest that the CPG consists of hierarchical networks composed of a rhythm generator (RG) and pattern formation (PF) networks [10, 26, 40, 41]. The RG network generates the basic rhythm and alters it by producing phase shifts and rhythm resetting in response to sensory afferents and perturbations (phase resetting). The PF network shapes the rhythm into spatiotemporal patterns of motor commands. That is, the CPG separately controls the locomotor rhythm and the motor commands in the RG and PF networks, respectively.

In this paper, we used the oscillator network model (Fig. 3), based on the two-layer hierarchical network model composed of the RG and PF networks [1, 2, 4, 5, 7], to control our robot. The RG model produces the rhythm information for locomotor behavior using phase oscillators and regulates the rhythm information by phase resetting in response to touch sensor signals. To produce the joint movements, the PF model generates motor torques based on the rhythm information from the RG model. The following sections explain the detail of the oscillator network model.

3.2 Rhythm generator (RG) model

The RG model produces the rhythm information for locomotor behavior through interactions of the robot mechanical system, the oscillator network system, and the environment. We used four simple phase oscillators (Leg 1, Leg 2, Trunk, and Inter oscillators), which produce the basic rhythm and phase information for locomotion based on command signals related to the locomotion speed. The oscillators also receive touch sensor

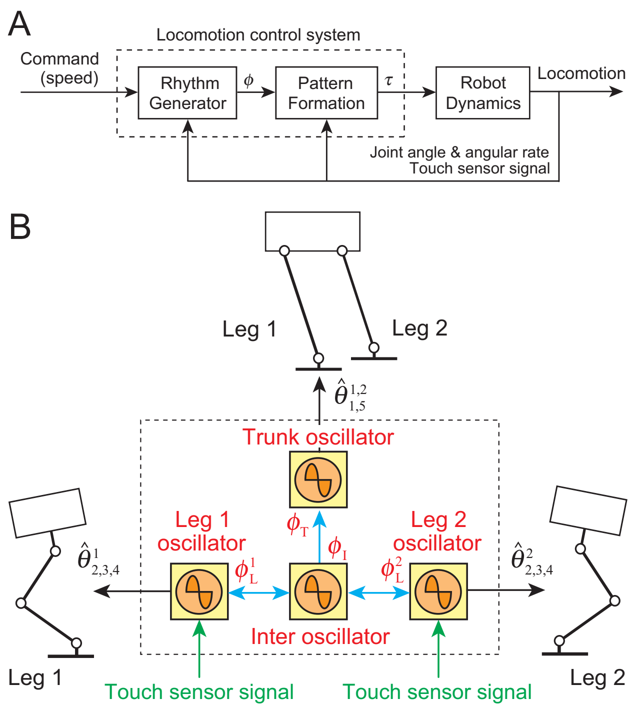

Fig. 3 Locomotion control system. **A**: two-layer hierarchical network model composed of a rhythm generator (RG) and pattern formation (PF) models, **B**: phase oscillators for producing locomotor rhythm and motor commands. The blue arrows indicate interactions among the oscillators. The oscillator phases are modulated by phase resetting based on touch sensor signals (green arrows). The oscillator phases determine the leg kinematics (black arrows).

signals to modulate the rhythm and phase information by phase resetting.

We denote the phases of Leg i, Trunk, and Inter oscillators by $\phi_{\rm L}^i$, $\phi_{\rm T}$, and $\phi_{\rm I}$ ($i=1,2$), respectively, as given by the following dynamics

$$\begin{aligned} \dot{\phi}_{\rm I} &= \omega + g_{1\rm I} \\ \dot{\phi}_{\rm T} &= \omega + g_{1\rm T} \\ \dot{\phi}_{\rm L}^i &= \omega + g_{1\rm L}^i + g_{2\rm L}^i \quad i=1,2 \end{aligned} \tag{1}$$

where ω is the basic oscillator frequency that is the same value for all the oscillators, $g_{1\rm I}$, $g_{1\rm T}$, and $g_{1\rm L}^i$ ($i=1,2$) are functions related to the interlimb coordination pattern (see Section 3.4), and $g_{2\rm L}^i$ ($i=1,2$) is a function related to the phase and rhythm modulation in response to the touch sensor signals based on the phase resetting mechanism (see Section 3.5).

3.3 Pattern formation (PF) model

Physiological studies revealed that spinocerebellar neurons receive sensory signals from proprioceptors and cutaneous receptors and then encode the global information of the limb kinematics, such as the length and orientation of the limb axis [9, 36, 37]. We used the PF model to determine these global parameters of the leg kinematics based on the oscillator phases and produced motor torques to establish the desired kinematics.

Locomotion in humans and animals involves moving the center of mass forward. To achieve this, they move the swing leg forward. When the leg touches the ground, it supports the body and generates a propulsive force from the ground. We designed the simple leg kinematics of the swing and stance phases in reference to the length and orientation of the limb axis in the pitch plane (Fig. 4). The swing phase is composed of the simple closed curve of Joint 4 (ankle pitch joint), which includes an anterior extreme position (AEP) and a posterior extreme position (PEP). It starts from the PEP and continues until the foot touches the ground. The stance phase consists of a straight line from the landing position (LP) to the PEP. During this phase, the foot moves in the opposite direction to the trunk. The trunk travels in the walking direction while the foot is in contact with the ground. In both the swing and stance phases, the angular movement of Joint 4 is designed so that the foot is parallel to the line that connects points AEP and PEP. We denote D as the distance between points AEP and PEP. We denote the swing and stance phase durations by $T_{\rm sw}$ and $T_{\rm st}$, respectively, for the case that the foot touches the ground at the AEP (LP = AEP). The duty factor β, which is the ratio between the stance phase and the gait cycle, the basic frequency ω in (1), the stride length S, and the locomotion speed v are then given by

$$\begin{aligned} \beta &= \frac{T_{\rm st}}{T_{\rm sw}+T_{\rm st}} \\ \omega &= \frac{2\pi}{T_{\rm sw}+T_{\rm st}} \\ S &= \frac{T_{\rm sw}+T_{\rm st}}{T_{\rm st}} D \\ v &= \frac{D}{T_{\rm st}} \end{aligned} \tag{2}$$

The trunk angle $\psi_{\rm H}$ is measured from the line perpendicular to the line connecting the AEP and the PEP. The two trajectories for the swing and stance phases provide the desired motion $\hat{\theta}_j^i$ ($i=1,2,\ j=2,3,4$) of Joint j (hip, knee, and ankle pitch joints) of Leg i by the function of phase $\phi_{\rm L}^i$ of Leg i oscillator, where we use $\phi_{\rm L}^i=0$ at the PEP and $\phi_{\rm L}^i=\phi_{\rm AEP}(=2\pi(1-\beta))$ at the AEP.

To increase the stability of bipedal locomotion in three-dimensional space, we used roll joints in the legs. We designed the desired motions $\hat{\theta}_j^i$ ($i=1,2,\ j=1,5$) of Joints 1 and 5 (hip and ankle roll joints) of Leg i by

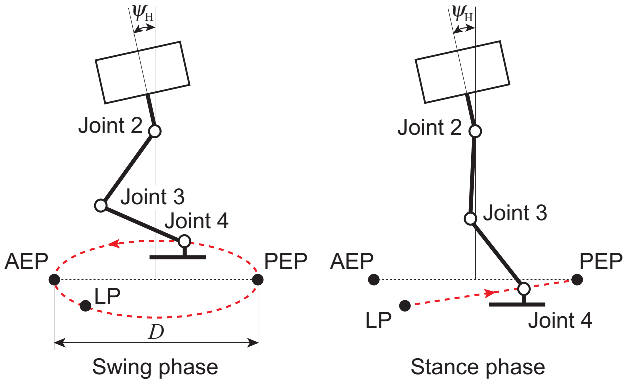

Fig. 4 Desired leg kinematics composed of the swing and the stance phases. When the foot lands on the ground, the trajectory changes from the swing to the stance phase. When the foot reaches point PEP, the trajectory moves into the swing phase.

the functions of phase ϕ_{T} of Trunk oscillator by

$$\hat{\theta}_1^i = R\cos(\phi_{\mathrm{T}} + \varphi)$$
$$\hat{\theta}_5^i = -R\cos(\phi_{\mathrm{T}} + \varphi) \tag{3}$$

where R is the amplitude of the roll motion and φ determines the phase relationship between the leg movements in the pitch and roll planes.

Since this study focused on the adaptability of leg movements during splitbelt treadmill walking, we did not use the waist and arm movements during walking. To achieve the desired joint motions, the PF model produced motor torques based on proportional-derivative (PD) feedback control by using high-gain feedback gains by

$$\tau_j^i = -\kappa_j^i(\theta_j^i - \hat{\theta}_j^i(\phi_i)) - \sigma_j^i\dot{\theta}_j^i, \quad i = 1, 2 \; j = 1, \dots, 5 \tag{4}$$

where τ_j^i $(i = 1, 2,\ j = 1, \dots, 5)$ is the torque at Joint j of Leg i and κ_j^i and σ_j^i $(i = 1, 2,\ j = 1, \dots, 5)$ are the gain constants.

3.4 Phase modulation based on the interlimb coordination pattern

The aim of this paper is to describe how our robot creates adaptive walking through dynamical interactions among the robot mechanical system, the oscillator network system, and the environment under various speed conditions of the splitbelt. In the generation of adaptive walking on a splitbelt treadmill, the interlimb coordination is a crucial factor [11, 29, 38]. Since the corresponding oscillator phase determines the desired leg kinematics, the interlimb coordination pattern of our robot is represented by the phase relationship, that is, the relative phase between the leg oscillators. Functions $g_{1\mathrm{I}}$, $g_{1\mathrm{T}}$, and $g_{1\mathrm{L}}^i$ in (1) modulate this interlimb coordination and are given as follows by using the relative phase between the oscillators based on Inter oscillator,

$$g_{1\mathrm{I}} = -\sum_{i=1}^{2} K_{\mathrm{L}} \sin(\phi_{\mathrm{I}} - \phi_{\mathrm{L}}^i + (-1)^i\pi/2)$$
$$g_{1\mathrm{T}} = -K_{\mathrm{T}} \sin(\phi_{\mathrm{T}} - \phi_{\mathrm{I}})$$
$$g_{1\mathrm{L}}^i = -K_{\mathrm{L}} \sin(\phi_{\mathrm{L}}^i - \phi_{\mathrm{I}} - (-1)^i\pi/2) \quad i = 1, 2 \tag{5}$$

where K_{L} and K_{T} are gain constants. These interactions are shown by the blue arrows in Fig 3**B**. Depending on the gain parameter K_{L}, these functions move the phase relationship between the legs into the desired state in which both legs move in antiphase with each other; $\phi_{\mathrm{L}}^1 - \phi_{\mathrm{L}}^2 = \pi$. Therefore, when we use a large value for K_{L}, $\phi_{\mathrm{L}}^1 - \phi_{\mathrm{L}}^2 = \pi$ is satisfied. In contrast, when we use a small value for K_{L}, the relative phase between the leg oscillators is shifted from antiphase through the phase regulation by the phase resetting shown below.

3.5 Phase modulation based on phase resetting

Although the CPG can produce oscillatory signals even in the absence of rhythmic input and proprioceptive feedback, it must use sensory feedback to create adaptive and effective locomotor behavior. For example, spinal cats produce locomotor behaviors on a treadmill and their gait changes depending on the belt speed [17, 33]. This result suggests that the tactile sensory information between their feet and belt influences the locomotion phase and its rhythm generated by the CPG [15]. Physiological studies have shown that the locomotion rhythm and its phase are modulated by producing phase shift and rhythm resetting based on sensory afferents and perturbations (phase resetting) [13, 14, 20, 26, 42]. In addition, the functional roles of phase resetting in the generation of adaptive walking have been investigated using neuromusculeskeletal models [3, 6, 8, 45–47].

We modulated the locomotion rhythm and its phase based on the phase resetting mechanism in response to touch sensor signals in order to create adaptive locomotor behavior through dynamic interactions between the robot mechanical system, the oscillator network system, and the environment. Function $g_{2\mathrm{L}}^i$ in (1) corresponds to this modulation. When Leg i lands on the ground, phase ϕ_{L}^i of Leg i oscillator is reset to ϕ_{AEP} $(i = 1, 2)$. Therefore, function $g_{2\mathrm{L}}^i$ is written by

$$g_{2\mathrm{L}}^i = (\phi_{\mathrm{AEP}} - \phi_{\mathrm{L}}^i)\delta(t - t_{\mathrm{land}}^i) \quad i = 1, 2 \tag{6}$$

where t_{land}^i is the time when Leg i lands on the ground $(i = 1, 2)$ and $\delta(\cdot)$ denotes Dirac's delta function. Note that the touch sensor signals not only modulate the locomotor rhythm and its phase but also switch the leg motions from the swing phase to the stance phase, as described in Section 3.3 (this does not induce a discrete change in the desired leg kinematics). Also note that this phase resetting does not work for Trunk and Inter oscillators, but only for the leg oscillators.

3.6 Parameter determination

The locomotion control system has the following parameters: D, T_{sw}, and T_{st} to determine the locomotion speed (2), ψ_{H}, R, and φ to determine the leg movements in the pitch (Fig. 4) and roll plane (3), and K_{T} and K_{L} to determine the strength of the interaction among the oscillators (5). In particular, the synchronization of the roll and pitch motions during locomotion is crucial to produce stable walking. We used R and φ for the roll motion and ψ_{H} for the pitch motion as tuning parameters [1]. Since K_{L} is crucial to control the interlimb coordination pattern, we investigated the roles of this parameter in the generation of adaptive walking (see Section 4.3). It should be noted that this paper does not focus on the optimality of these parameters, but the emergence of adaptive functions during locomotion through interactions of the robot mechanical system, the oscillator network system, and the environment.

4 Results

4.1 Generation of walking under various speed conditions

To investigate how our robot establishes adaptive walking on the splitbelt treadmill, we used two conditions for the speeds of the left-side belt v_1 and the right-side belt v_2: 1. a tied configuration, $v_1 = v_2$, and 2. a splitbelt configuration, $v_1 > v_2$, similarly to the measurement of human splitbelt treadmill walking. We examined only the configuration ($v_1 > v_2$) because the robot mechanical system has bilateral symmetry. We used the following parameters, which are independent of the speed conditions of the splitbelt: $D = 2.5$ cm, $T_{\mathrm{sw}} = 0.35$ s, $T_{\mathrm{st}} = 0.35$ s, $R = 3°$, $\varphi = -170°$, $\psi_{\mathrm{H}} = 5°$, $K_{\mathrm{T}} = 10$, and $K_{\mathrm{L}} = 1.0$. Given these parameters, $\beta = 0.5$, $S = 5$ cm, and $v = 7.1$ cm/s in (2). To clearly see the differences among various speed conditions, the robot first walked in the tied configuration. After the robot established steady walking, we changed the speed condition of the treadmill from the tied to the splitbelt configuration and examined how the robot adapted to the changed environment.

When we did not use phase resetting, the robot easily fell down. However, the robot with phase resetting achieved steady and straight walking on the splitbelt treadmill without changing the control parameters, indicating that the robot established dynamically stable walk due to phase resetting. One foot of the robot contacted only the ipsilateral belt during locomotion, even when one belt speed was 2.0 times faster than the other belt speed ($v_1 = 9.3$, $v_2 = 4.6$ cm/s, see supplementary movie). When the speed discrepancy between the belts was larger than this, the robot did not fall down but it was difficult for it to establish a straight walk for a long time.

4.2 Adaptive behaviors in splitbelt treadmill walking of human and robot

Humans generate adaptive walking on a splitbelt treadmill, because they can change both the relative phase between leg movements and the duty factors depending on the speed condition [11,29,38]. We measured human splitbelt treadmill walking, as shown in Fig. 5. This figure shows the relative phase and the duty factors for various speed conditions, where the data points and error bars correspond to the means and standard deviations of over 50 gait cycles. Although the data shown were obtained from one participant, the other participants showed similar trends. As the speed discrepancy between the belts increased, the relative phase shifted from antiphase and the duty factors on the fast belt decreased whereas the duty factors on the slow belt increased.

To investigate why our robot generated steady walking on a splitbelt treadmill, as shown in the previous section, we examined the relative phase between the leg oscillators $\phi_{\mathrm{L}}^1 - \phi_{\mathrm{L}}^2$ and the duty factors of the legs. Figure 6 shows the representative result after we changed the speed condition from the tied configuration ($v_1 = v_2 = 6.9$ cm/s) to the splitbelt configuration ($v_1 = 8.5$, $v_2 = 5.4$ cm/s). For the tied configuration shown in Fig. 6**A**, although the relative phase fluctuates discretely due to phase resetting, it remains approximately π rad. This means that the two legs moved in antiphase with each other during locomotion. However, for the splitbelt configuration, the average of the phase difference slightly shifted from π rad, indicating that the phase relationship between the leg movements changed from antiphase due to the discrepancy between the belt speeds. Figure 6**B** shows the duty factors of the legs during locomotion. Although the legs have almost the same values in the tied configuration, the values are slightly different for the splitbelt configuration.

To more clearly see these effects, we conducted thorough investigations using various conditions of belt speeds.

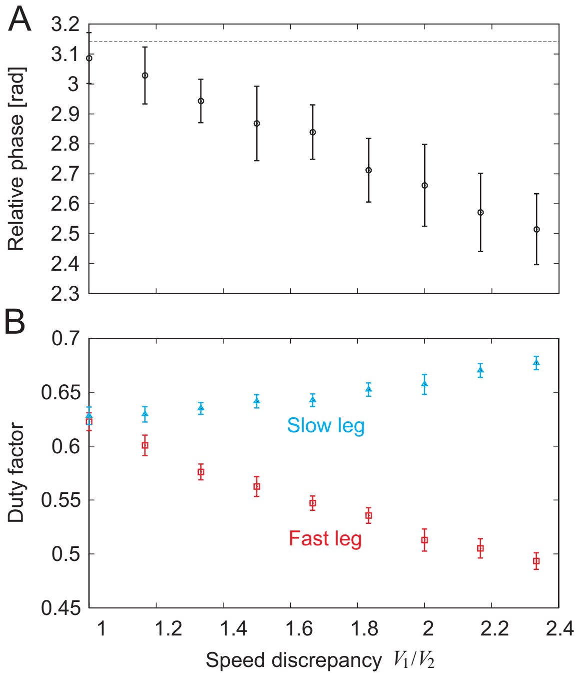

Fig. 5 Adaptation in human splitbelt treadmill walking. **A**: relative phase between the leg movements, and **B**: duty factors. V_1 and V_2 are the speeds of the left-side and right-side belts, respectively.

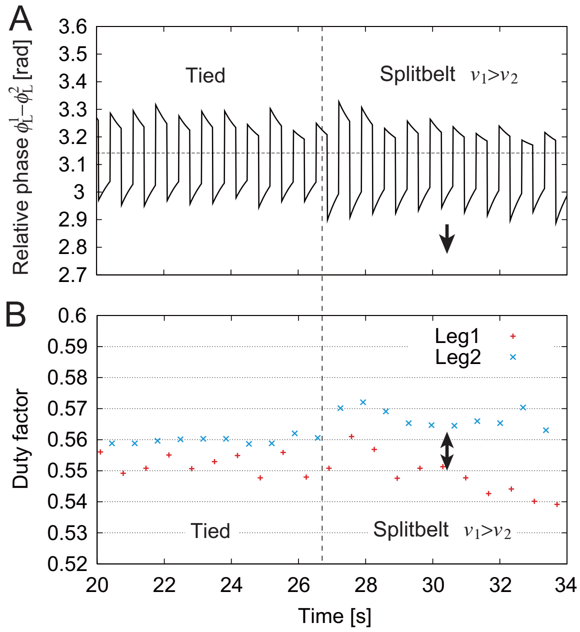

Fig. 6 Changes in relative phase and duty factors by changing the speed condition from the tied configuration ($v_1 = v_2$) to the splitbelt configuration ($v_1 > v_2$). (**A**): relative phase $\phi_L^1 - \phi_L^2$, and (**B**): duty factors. The speed condition changes are denoted by the vertical dotted line.

Figure 7 shows the changes of the relative phase between the leg oscillators from the tied configuration to the splitbelt configuration (**A**) and the changes of the duty factors (**B**) due to the speed discrepancy between the belts. The values are the averages over five gait cycles for each trial. The data points and error bars correspond to the means and standard deviations of the five experiments. This figure clearly shows that the relative phase shifted from π rad and that the duty factors changed depending on the speed discrepancy between the belts. These trends are similar to those observed in human splitbelt treadmill walking (Fig. 5).

4.3 Contribution of phase modulations based on phase resetting and interlimb coordination pattern

The relative phase between the leg oscillators is determined by the interaction among the oscillators (5) and the phase regulation by the phase resetting (6). When we use neither (5) nor (6), the relative phase never changes from the initial value. When we use a large value for the gain parameter K_L in (5), the relative phase hardly shifts from antiphase. In contrast, when we use a small value for K_L, the relative phase can shift from antiphase. That is, the relative phase depends on the relationship between the interaction among the oscillators (5) and the phase regulation by phase resetting (6).

To investigate this effect on the production of adaptive splitbelt treadmill walking, we used various values for K_L and examined how much belt speed discrepancy the robot can adapt to for each K_L. We used 0.5 to 2.5 incremented by 0.5 for K_L and four splitbelt configurations, (v_1, v_2)=$(7.7, 6.2)$, $(8.5, 5.4)$, $(9.3, 4.6)$, and $(10.1, 3.8$ cm/s). We used the same values for the parameters of the locomotion control system as in the previous sections except for K_L. We considered a trial to be successful if the robot walked in a straight line for 15 steps in the manner that one foot contacts only the ipsilateral belt during walking after the configuration changes from the tied to the splitbelt configuration. For each K_L and splitbelt configuration, we performed the robot experiment five times and examined the success rate. Figure 8 shows the result. The larger the speed discrepancy of the belts, the lower the success rate was for each K_L. The success rate depended on K_L, and we obtained the best success rate for $K_L = 1.0$.

Next, to investigate why the success rate depended on K_L, as shown in Fig. 8, we examined the changes of the relative phase between the leg oscillators and the duty factors from the tied to the splitbelt configuration for some values of K_L. The changes were calculated by averaging five gait cycles for each trial, as in Fig. 7.

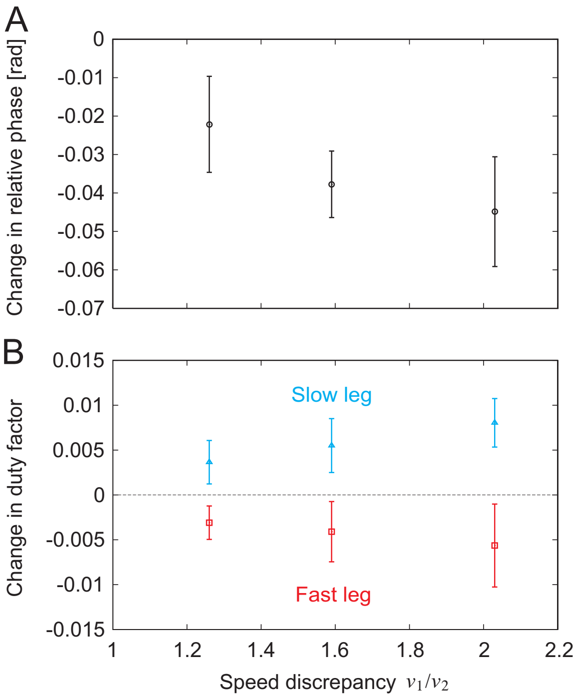

Fig. 7 Changes from the tied configuration to the splitbelt configuration versus the discrepancy between the belt speeds v_1/v_2. (**A**): relative phase between the leg oscillators, and (**B**): duty factors. The data points and error bars correspond to the means and standard deviations of five experiments.

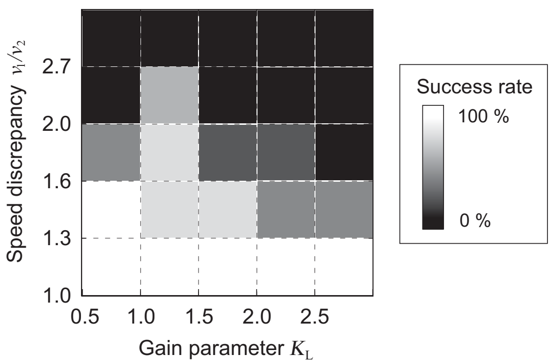

Fig. 8 Success rate of splitbelt treadmill walking for various speed conditions and values of K_{L}. The lower left corner of each box corresponds to the axis value.

Figure 9 shows the changes in the relative phase (**A**) and the duty factors (**B**), for $K_{\mathrm{L}} = 0.5, 1.0$, and 1.5, where $v_1 = v_2 = 6.9$ cm/s for the tied configuration, and $v_1 = 7.7$ and $v_2 = 6.2$ cm/s for the splitbelt configuration. The larger the value we used for K_{L}, the smaller were the changes of the relative phase and the duty factors. When we used a large value for K_{L}, the interaction among the oscillators (5) remained strongly in the relative phase π rad, and the relative phase did not vary from π rad, even with the modulation of the

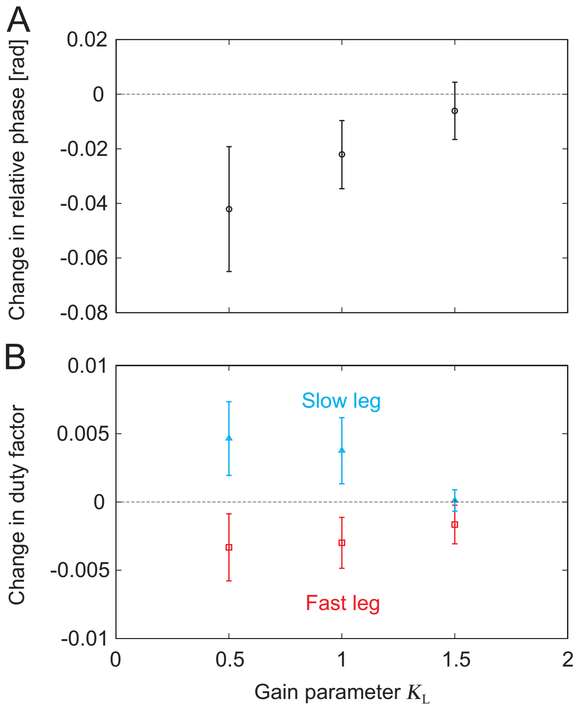

Fig. 9 Changes from the tied configuration to the splitbelt configuration for $K_{\mathrm{L}} = 0.5, 1.0$, and 1.5 with $v_1 = 7.7$ and $v_2 = 6.2$ cm/s. (**A**): relative phase between the leg oscillators, and (**B**): duty factors. The data points and error bars correspond to the means and standard deviations of five experiments, respectively.

phase resetting. At the same time, the leg movements were constrained to be antiphase and the duty factors scarcely changed. Hence, it was difficult for the robot to walk in a straight line in the environment that the belt speeds are different. When we used a small value for K_{L}, the interaction among the oscillators (5) became smaller, and the relative phases were allowed to vary from π rad due to phase resetting (6). The relative phase between the leg movements shifted from antiphase and the duty factors changed greatly. However, the fluctuation became large and decreased the stability for walking in a straight line.

5 Discussion

In general, environmental variations, such as the speed discrepancy between the belts, decreases the locomotion stability of the biped robot, unless the robot changes the control strategy or control parameters to cope with such variations. However, our robot established stable walking without changing the control strategy and parameters, despite a large discrepancy between the belt speeds. Instead, the relative phase between the leg movements shifted from antiphase and the duty factors

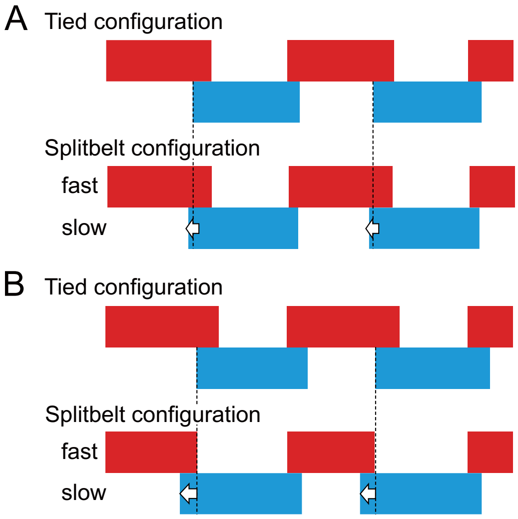

Fig. 10 Foot patterns of tied and splitbelt configurations. (**A**): robot with $v_1 = 8.5$ and $v_2 = 5.4$ cm/s, and (**B**): human with $V_1 = 7.0$ and $V_2 = 3.0$ km/h. The bold lines indicate the foot-contact duration.

of the legs varied depending on the speed discrepancy between the belts (Figs. 6 and 7). This is because the speed discrepancy between the belts caused changes in the locomotion dynamics. More specifically, it yielded changes in the timing of the foot contact for each leg. For example, since the stance leg on the belt with a faster speed is pulled more backward than the contralateral leg, the robot falls forward and the foot contacts of the contralateral leg occur earlier. Such temporal asymmetry shifts the relative phase of the leg oscillators due to phase resetting and modulates the phase relationship between the leg movements, and therefore creates spatial asymmetry of the locomotor behaviors. These locomotor behaviors can be verified from the changes in the foot patterns (Fig. 10). Human splitbelt treadmill walking showed similar trends. These temporal and spatial asymmetries reflect the adaptability achieved during splitbelt treadmill walking. This adaptability in our robot is not a characteristic that we specifically designed, but it emerged through the dynamic interactions of the robot mechanical system, the oscillator control system, and the environment. When the robot movements are completely predetermined, as in the case without phase resetting (Section 4.1), the robot cannot establish such adaptability and easily falls down.

Although physiological evidence has shown that the locomotor rhythm and its phase are modulated by producing a phase shift and rhythm resetting based on sensory afferents and perturbations [13, 14, 26, 42], such rhythm and phase modulations in phase resetting have for the most part been investigated for fictive locomotion in cats, and their functional roles during actual locomotion remain largely unclear. Simulation studies with neuromusculeskeletal models of biological systems have shown the functional roles of phase resetting in the generation of adaptive walking [3, 6, 8, 45–47]. Our results regarding the improvement of the adaptability in locomotion through temporal modulation by phase resetting, as obtained in our robot experiments, are consistent with the simulation results of biological systems.

To create adaptive splitbelt treadmill walking, the controls of the locomotor rhythm and its phase for each leg as well as the relative phase between the legs are crucial. Our results show that the phase regulation by the interaction among the oscillators and the phase resetting should be well-balanced (Figs. 8 and 9), which is the same as our previously reported simulation result of a physiologically based model of human walking [3].

So far, phase resetting has been demonstrated to be useful in the generation of adaptive locomotion of biped robots to perturbations and environmental changes, such as slopes [1, 2, 5, 30–32]. Our results show that phase resetting contributes to the special environment of the splitbelt treadmill without incorporating special techniques. This further clarifies the usefulness of phase resetting in the generation of adaptive locomotion of legged robots and can lead to further progress in the design of a locomotion control system.

To clearly investigate the adaptive functions of phase resetting in splitbelt treadmill walking, we used simple robot kinematics and a simple control strategy. We did not use any vision or gyro sensors to regulate postural behaviors. We used only touch sensors to recognize the environmental situation and to modulate the robot movements. Therefore, the adaptability of our control system is limited. However, the shifts of the relative phase between leg movements and the modulations of the duty factors of the legs were observed during human splitbelt treadmill walking (Fig. 5), and our results suggest that our simple dynamic model using the robot with the oscillator control system reflects the essence of the ability to produce adaptive locomotor behaviors.

Although we investigated steady walking behaviors on the splitbelt treadmill, two types of adaptation can be found in human splitbelt treadmill walking when switching the configurations of the splitbelt [11, 29, 38]. One is early adaptation, which quickly modulates the locomotor behavior to adapt to the changed environment. The other is late adaptation, which slowly modulates the locomotor behavior through learning to produce a new pattern and induces aftereffects. Since we did not incorporate any learning mechanism in our locomotion control system, our robot does not produce such slow adaptation and aftereffects. In the future, we intend to improve our locomotion control system to investigate this adaptation mechanism in human splitbelt treadmill walking and to produce further design principles for the control systems of legged robots.

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