Split-Belt Adaptation Model of a Decerebrate Cat Using a Quadruped Robot with Learning

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Abstract. We propose a model connecting body dynamics and sensor feedback to investigate gait adaptation mechanisms of decerebrate cats in split-belt waking. In our previous studies, we proposed a leg controller using leg loading/unloading for the leg phase transition of a quadruped robot: "Kotetsu." The purpose of this study is to make a model of split-belt gait adaptation in spinal cats and decerebrate cats to refer to biological knowledge and to evaluate the validity of those models using Kotetsu. We construct the spinal cat model integrating our leg controller with Frigon's spinal cord model. Also, we employ motor learning in the cerebellum by long-term depression for the decerebrate cat model. As the results of experiments, we show that early adaptation in the split-belt walking is obtained by the stance-to-swing leg phase transition mechanism in the spinal cat model. We also show that late adaptation in split-belt walking is obtained by motor learning as the step distance adjustment in the decerebrate cat model. The validity of those models is evaluated by comparing durations of forelegs bi-support phases and duty ratios in the transition from tied-belt to split-belt walking between decerebrate cats and Kotetsu with the decerebrate cat model.

Keywords: Split-belt walk · Decerebrate cat model · Quadruped robot

1 Introduction

1.1 Walking of a Decerebrate Cat on a Split-Belt Treadmill

Animals and humans change the gait and adapt to perturbations while walking. In spite of such evidence, detailed mechanisms of such gait adaptation have not yet been clarified. To investigate such adaptation mechanisms, experiments to make animals [1–4] and humans walk on split-belt[1] treadmills were much

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[1] The situation of different belt speed in left and right is named split-belt; that of the same belt speed is named tied-belt. A leg on the fast belt or the slow belt is named fast-leg or slow-leg (normal-leg), respectively.

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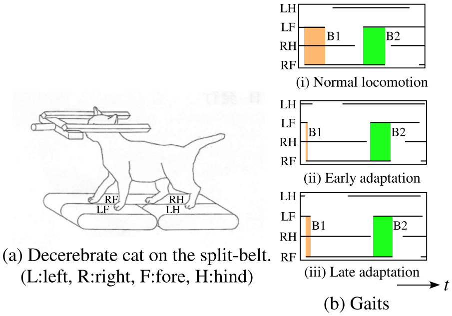

(a) Decerebrate cat on the split-belt. (L:left, R:right, F:fore, H:hind)

(i) Normal locomotion

(ii) Early adaptation

(iii) Late adaptation

(b) Gaits

	leg	duty ratio
Normal	LF	0.70
	RF	0.68
Early adaptation	LF	0.45
	RF	0.72
Late adaptation	LF	0.47
	RF	0.73

(c) Duty ratios

Fig. 1. (a) A decerebrate cat in split-belt walking, which was revised by authors from [3]. (b) gait diagrams and (c) duty ratios of a decerebrate cat on tied-belt: (i) and on split-belt:(ii), (iii). The x-axis of the gait diagram means time t. The gait diagrams were revised by authors from [1,5]. The values of duty ratio were measured based on those gait diagrams dividing the stance phase by the total phase by authors.

conducted. Especially, to investigate the role of the cerebellum in gait adaptation of quadrupedal animals, Yanagihara et al. [1–3] conducted experiments where decerebrate cats walked on split-belt treadmills and proposed a motor learning paradigm such that the cerebellum induces adaptive coordination among limbs in case of the perturbation to one forelimb. In the experiment [1], decerebrate (thalamic) cats[2] walked on a split-belt treadmill shown in Fig. 1-(a) where the LF belt speed was 61 [cm/s] and the other belt speed was 36 [cm/s]. As a result, the gait was changed and became stable according to the time course.

Usually, such experiments are explained using three stages. The first stage corresponds to walking on the tied-belt treadmill initially, and it is also called "normal locomotion." The second stage corresponds to the time course for a while after the change to walking on the split-belt treadmill (perturbation). And the change of the gait induced in this stage is named "early adaptation." The third stage corresponds to the time course sufficient for stabilizing the gait after the perturbation, and the change of the gait induced in this stage is named "late adaptation" [6]. In Fig. 1-(b) & (c), the gait and duty ratios in each stage are shown. Exchanging leg loading between forelegs is performed in bisupport phases, of which sufficient duration is important for the smooth exchange of leg loading [3]. We call the bisupport phase starting on touch down (TD) of RF and terminating on lift off (LO) of LF as "B1," and the bisupport phase starting on TD of LF and terminating on LO of RF as "B2." In Fig. 1-(b), the difference between durations of B1 and B2 is obvious in split-belt walking (ii&iii). In Fig. 1-(c), the duty ratio of each leg changes in each stage. The duration of the stance phase, the swing phase and the step cycle of LF and RF in each stage [1] are shown in Fig. 2.

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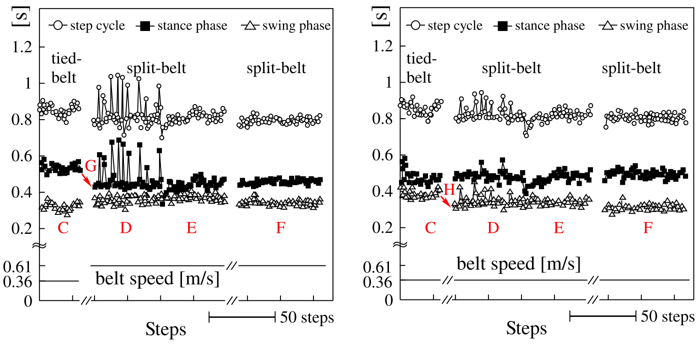
[2] A cat disconnected from upper central nerves with remaining locomotor regions at the sub-thalamic (SLR), cerebellum (CLR) and mesencephalic (MLR) is called a "thalamic cat." On the other hand, a cat disconnected from upper central nerves, including the cerebellum and brain stem, is called a "spinal cat.".



(a) LF (left fore leg)

(b) RF (right fore leg)

Fig. 2. The duration of the stance phase, the swing phase and the step cycle of LF and RF in walking of a decerebrate cat (revised by authors from [1]). In both diagrams, (C) a cat walked on a tied-belt. (D) & (E) a cat walked on split-belt in the first trial. (F) a cat walked on split-belt in the third trial. At the beginning of split-belt walking, durations of the stance phase of LF and the swing phase of RF quickly decreased (G) and (H), respectively. Fluctuations of durations were very large in (D), still not small in (E) and small in (F). The gaps in steps meant standing for approx. 20[min].

The characteristics of each stage are summarized as follows.

(i) normal locomotion
The duration of B1 and B2 in Fig. 1-(b) and step cycle durations of LF and RF in Fig. 2-(C) are almost equal.

(ii) early adaptation
As shown in Fig. 2-(G) & (H), durations of the stance phase of LF and the swing phase of RF clearly decrease immediately after the perturbation, respectively. For approx. 50[steps] after the perturbation in (D), fluctuations of those durations and the duration of the step cycle of both legs are very large. As a result, fluctuations of bisupport phase durations (B1 and B2) increases[3] [3]. For the next approx. 50[steps] in (E), such early adaptation that all indexes converge into approx. constant values appear. Although fluctuations of all indexes are still not small, the duty ratio of fast-leg (LF) much decreases, and the duty ratio of slow-leg (RF) increases a little in Fig. 1-(c). While comparing durations of B1 and B2 in the second stage with those in the first stage in Fig. 1-(b), the duration of B2 is approx. equal, but the duration of B1 in early adaptation is extremely short. This extremely short duration of B1 means that exchanging leg loading from LF to RF is not sufficient, and walking is unstable.

(iii) late adaptation
As shown in Fig. 2-(F), fluctuations of all indexes become small as a result of late adaptation after the sufficient time course. Although durations of the

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[3] The range of bisupport phase after the perturbation is more than five times it in normal locomotion.

stance phase of LF and the swing phase of RF in (F) are a little different from those in (E), duty ratios of LF and RF at late adaptation are approx. equal to those at early adaptation (Fig. 1-(c)). In spite of such equality of duty ratios, since the relative phase between LF and RF is adjusted in late adaptation, the duration of B1 at late adaptation becomes larger than the one at early adaptation (Fig. 1-(b)). It means that exchanging leg loading from LF to RF becomes a little smooth, and walking is stable under the perturbation.

Let us describe more details about the duration of B1 considering the leg phase duration, the step cycle, and the relative phase in forelimbs. Immediately after the perturbation at the beginning of early adaptation, the duration of the stance phase of LF (fast-leg) decreases due to the direct perturbation from the fast-belt. Besides, the duration of the swing phase of RF (slow-leg) also decreases in spite of no direct perturbation from the fast-belt. As a result, although there exit large fluctuations immediately after the perturbation, the step cycle difference between LF and RF become small (Fig. 2-(E)), and the duration of B1 is not sufficient but at least kept. This adaptation enables split-belt walking to continue even though it is unstable. In addition, in the second half of early adaptation, fluctuations become less. This means that the quick contralateral coordination mechanism between left and right legs does exist in early adaptation.

In late adaptation, since durations of the stance phase and the swing phase of LF and RF are a little adjusted from those in early adaptation, the step cycle difference between LF and RF becomes approx. zero (Fig. 2-(F)). Also, the relative phase between LF and RF is adjusted properly, and the duration of B1 is sufficiently kept. This adaptation enables stable split-belt walking to continue. This means that the delayed learning mechanism does exist in late adaptation [1]. In the case of split-belt walking of a decerebrate cat with long-term depression in the cerebellum being inhibited chemically, early adaptation appears with many large fluctuations, but late adaptation does not appear. This means that the cerebellum plays a key role in such learning functions [3]. Given that the dynamics of walking, these adaptations are specific to quadrupedal walking.

1.2 Proposal of the Gait Adaptation Model of a Decerebrate Cat

In this study, we aim at the constructive model[4] of gait adaptation in split-belt walking of a decerebrate cat. The constructive model can explain the mechanism of gait generation and adaptation as the physical phenomenon while connecting the embodiment and sensor feedback. As one of such constructive models for gait generation and adaptation of a quadruped, we proposed the method [7] using leg loading and unloading for the swing-to-stance and stance-to-swing leg

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[4] In the constructive model, the dynamics of a single element and dynamics between elements are defined. As a result of simulations or experiments of the interaction between those elements and the environment, we might be able to understand the underlying mechanisms of the non-linear dynamic system constructively.

phase transitions, respectively. On the other hand, Frigon et al. [4] carried split-belt walking experiments with hind legs of a spinal cat and proposed the leg phase transitions model at the spinal cord. In this paper, we employ Frigon's model into our method and construct the spinal cat model for early adaptation. In addition, to show that motor learning is necessary to adapt to split-belt in quadruped walking, we employ the learning function at the cerebellum into the spinal cat model and construct the decerebrate cat model for late adaptation.

As one of the related studies, Fujiki and Aoi et al. [6] proposed such learning model at the cerebellum as adjusting the amount of the phase resetting on TD of each leg, and realized gait adaptation in split-belt walking of a biped robot in simulations and experiments. The target of this study is the pattern adaptation in the non-linear dynamic system, and it is the constructive model with the embodiment in the sense that is mathematically dealing with dynamics of the relative phase between legs. Therefore, it is "the robot controlling model described as the non-linear dynamic system."

On the other hand, we explicitly describe the leg phase transition based on sensor information. Therefore, it is "the model much close to robotics described as the sensory-motor system" in the sense that dynamics of the relative phases among legs emerges through the interaction between the body and environment [7,8]. While using such a model, we aim at constructively clarifying the relation among the embodiment, sensor feedback and motor learning in split-belt walking of a decerebrate cat.

1.3 Indexes and Values of Parameters

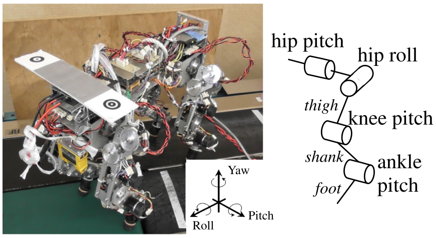
Indexes and abbreviations and values of parameters in experiments are shown in Table 1 and 2, respectively. The leg index i is often eliminated if it is obvious. The hat ˆ, the bar ¯ and the tilde ˜ symbols are respectively used to represent the nominal, the measured and the reference values of a single variable.

Table 1. Indexes and abbreviations in this paper.

$L*, R*$	Left, right
$*F, *H$	Fore, hind
i	Leg index $\in \{LF, RF, LH, RH\}$
sw, st	Swing, stance
lp	Leg phase index $\in \{sw, st\}$
$cntr$	Contralateral
LO, TD	Lift off, touch down
$STPD$	Step distance

Table 2. Values of parameters used in experiments ($\hat{\phi}_{PEP} = 2\pi(= 0)$, $\hat{\phi}_{AEP} = 2\pi(1 - \hat{\beta})$, $\dot{\phi} = 2\pi(1 - \hat{\beta})/\hat{T}_{sw}$).

$\hat{T}_{sw}$ [s] 0.20	$\hat{D}$ [m] 0.03	$\hat{\chi}_{TD}$ [N] 1.9
$\hat{\beta}$ 0.7	$\hat{H}$ [m] 0.22	$\hat{\chi}_{LO}$ [N] 8
τ 0.4	ε_D [m] 0.008	



(a) On treadmill (b) Joint configuration

Fig. 3. A quadruped robot: Kotetsu

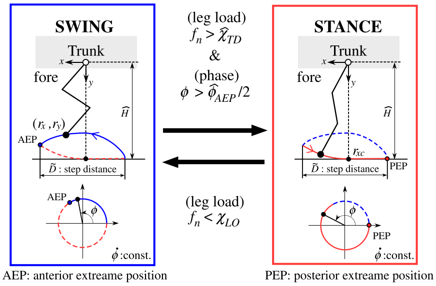


Fig. 4. Leg controller (LC)

2 Leg Controller (LC)

It is known for the stance-to-swing leg phase transition in decerebrate cats that the transition is initiated by the hip extension, and also that the stance phase is indeterminately prolonged as long as leg loading is over a given threshold. The well-known half-center model of the stance-to-swing leg phase transition at the spinal cord was proposed [9] according to such knowledge. Besides, it was shown using a computer simulation that alternative stepping of the contralateral hind legs can be generated when phase modulations based on leg unloading are used [10]. Being motivated by those half-center and sensory feedback studies, we showed in simulations [7] and experiments [8] using a quadruped (Fig. 3) that rhythmic motion of each leg (gait) is achieved as a result of the phase modulations based on leg loading and that coordinations among legs emerge allowing dynamic walking in the low- to medium- speed range. This leg controller (LC) was a simple model of the central pattern generator (CPG).

Each leg is actuated by the LC [7] shown in Fig. 4. Each LC has two leg phases, swing (sw) and stance (st), and the transfer of activity between them is regulated using sensory information related to the load supported by the leg, or leg loading. Each LC is associated with a simple oscillator with a variable phase ϕ^i of constant angular velocity $\dot{\phi}^i$, where i is the leg index. The positions of the foot at the swing-to-stance and stance-to-swing transition are named as AEP (anterior extreme position) and PEP (posterior extreme position).

Resetting of ϕ^i is employed so that $\phi^i = \hat{\phi}_{AEP}$ and $\phi^i = \hat{\phi}_{PEP}$ at the onset of stance and swing phases, respectively [6]. The leg phase transition is initiated by using the measured normal ground reaction force: f_n^i (leg loading [10]) and the force thresholds: $\hat{\chi}_{TD}$ for TD and χ_{LO}^i for LO. Those are Eq. (1) for the swing-to-stance transition, and Eq. (2) for the stance-to-swing transition.

$$f_n^i > \hat{\chi}_{TD} \;\&\; \phi^i > \hat{\phi}_{AEP}/2 \tag{1}$$

$$f_n^i < \chi_{LO}^i \tag{2}$$

3 Spinal Cat Model for the Leg Phase Transition

3.1 Frigon's Model

While referring to the half-center model of the stance-to-swing leg phase transition [9], Frigon proposed the CPG model for leg phase transitions (Fig. 5). This conceptual model involves sensor inputs such as not only the hip extension and leg loading, but also the hip flexion. Also, this model has mutual inhibition between left and right FHCs as the CIM (contralateral inhibition mechanism). Since our LC described in Sect. 2 uses leg loading/unloading as a sensor input for leg phase transitions, it is easy to construct the model integrating our LC with Frigon's spinal cord model[5]. To sum up, we call the model made up of Kotetsu and LC integrating Frigon's spinal cord model "the spinal cat model".

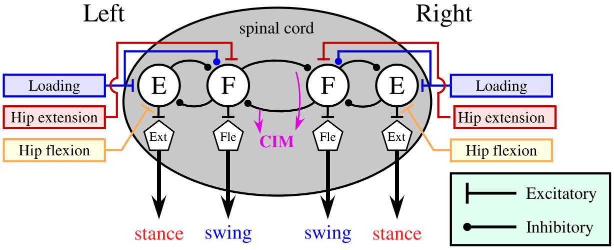


Fig. 5. Frigon's leg phase transitions model at the spinal cord (revised by authors from [4]). Each CPG on left or right is represented by the extensor half-center: EHC (E) and the flexor half-center: FHC (F). The EHC projects to the extensor motor neuron (Ext) while the FHC projects to the flexor motor neuron (Fle). Those motor neurons produce the stance phase and the swing phase, respectively. Leg loading, the hip extension and the hip flexion are feed back to the EHC and the FHC. Left and right FHCs are mutually inhibited by each other as the CIM.

3.2 Employing Frigon's Model into the LC

While referring to Frigon's model, we define χ^i_{LO} in Eq. (2),

$$\chi^i_{LO} = \begin{cases} \hat{\chi}_{LO} \cdot (r_{xc} - \bar{r}^i_x)/(\hat{D}/2) & (\text{if } lp^{cntr} = st) \\ -5 & (\text{otherwise}) \end{cases} \tag{3}$$

where $\hat{\chi}_{LO}$ and $\hat{D}$ are the nominal leg loading threshold for the stance-to-swing transition and the nominal step distance in Fig. 4, respectively. On the other hand, r_x is the x-pos. of the leg tip in the hip pitch joint coordinate (Fig. 4), $\bar{r}^i_x$ is the measured x-pos. while walking, and $r_{xc}(= 0)$ is the x-pos. right under the hip pitch joint of the leg.

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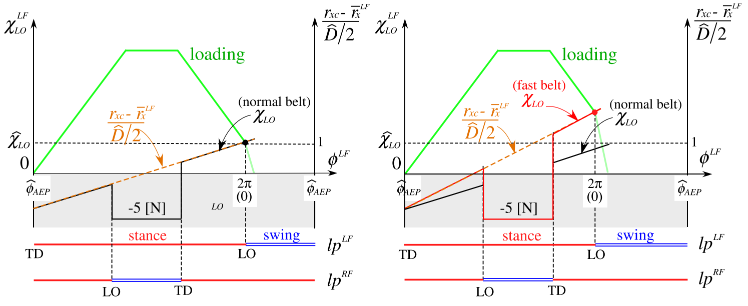
[5] Frigon proposed the model from the hindlimb adaptation of spinal cats. In this study, we discuss a mechanism considering the dynamics of quadrupedal (not hindquarters) walking. For simplicity, we apply Frigon's model to the fore and hind LCs.

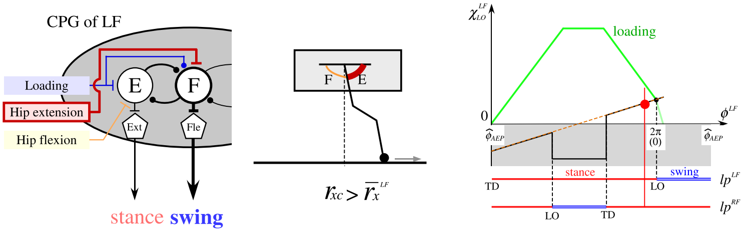


(a) normal belt (b) fast belt

Fig. 6. The mechanism of the stance-to-swing transition of LF, according to Eq. (2) & (3). RF is the contralateral leg. Black solid lines in (a) & (b) mean χ_{LO}^{LF} on the normal-belt. Red solid line in (b) means χ_{LO}^{LF} on the fast-belt. Brown broken lines in (a) & (b) mean $(r_{xc}-\bar{r}_x^i)/(\hat{D}/2)$, which is the normalizing coefficient of the right hand term in Eq. (3). Green solid lines in (a) & (b) mean expected and simplified leg loading of LF. The horizontal axis means the oscillator phase of LF: ϕ^{LF}. The origin of this axis is not zero, but $\hat{\phi}_{AEP}$. The leg phase: lp^i is the swing or the stance. In gray zone, since χ_{LO}^{LF} is negative, the stance-to-swing transition of LF never occurs. For simplicity, this figure is made with $\phi^{LF}-\phi^{RF}=\pi$ [rad], the duty ratio: $\hat{\beta}=0.75$ and $\hat{\phi}_{AEP}=\pi/2$ [rad]. (Color figure online)

In Eq. (3), if the leg phase: lp^{cntr} of the contralateral leg for the i-th leg is stance, $\hat{\chi}_{LO}$ is modulated using the coefficient: $r_{xc}-\bar{r}_x^i$ normalized by $\hat{D}/2$. This modulation corresponds with sensor inputs such as the hip extension and flexion in Frigon's model. On the other hand, while $lp^{cntr}=sw$, χ_{LO}^i is negative, and the stance-to-swing transition is prohibited as the CIM. While combining Eq. (3) with Eq. (2), we can integrate sensory inputs (leg loading, the hip extension and the hip flexion) in Frigon's model into the simple equations.

By using Fig. 6-(a), we explain how χ_{LO}^{LF} changes during the stance phase of LF in tied-belt walking while considering the leg phase of the contralateral leg: RF. Due to $r_{xc}<\bar{r}_x^{LF}$ in the 1st half of the stance phase, the coefficient: $(r_{xc}-\bar{r}_x^{LF})/(\hat{D}/2)$ (brown broken line) is negative. However, the coefficient in the 2nd half of the stance phase increases according to backward motion. Although χ_{LO}^{LF} (black solid line) is negative while $lp^{RF}=sw$, it becomes positive after TD of RF and gets close to leg loading (green solid line). After a short while, Eq. (2) gets satisfied, and the leg phase transits from the swing to the stance. Besides, in Fig. 6-(b), while assuming no slip between the belt and the leg tip, since $\bar{r}_x^{LF}$ on the fast belt moves backwards faster than that on the normal belt, χ_{LO}^{LF} draws the red line in Fig. 6-(b), and the stance-to-swing phase transition of LF is advanced in split-belt walking. As a result, the duration of the stance phase and the duty ratio decrease. Since the spinal cat model using the LCs with Eq. (3) involves the leg phase transition mechanism similar to the one of Frigon's model, and can deal with the advanced stance-to-swing phase transition of fast-leg, we consider this spinal cat model is most appropriate as the constructive model for early adaptation in split-belt walking of a decerebrate cat.



(a) Frigon's CPG model (b) Hip extension (c) Spinal cat model

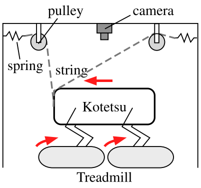
Fig. 7. This figure shows the corresponding at the last stage in the stance phase of LF among (left): the Frigon's model, (middle): the leg tip position with the states of flexor and extensor muscles of the hip joint, and (right): the relationship between the oscillator phase of the LC: ϕ^{LF} (the horizontal axis) and the leg loading threshold: χ_{LO}^{LF} (the vertical axis) in the spinal cat model. The bold line in (left) means that the sensor input is active. The bold line in (middle) means that the muscle (extensor: E) is contracted. The ● in (right) means that the value of χ_{LO}^{LF} at the current oscillator phase.

By using the last stage in the stance phase of LF in Fig. 7, we describe the relation between Frigon's model at the spinal cord and our spinal cat model more in details. Since leg loading is low, the depression to the FHC decreases. In addition, since the hip extension of LF is high, the excitation to the FHC increases. Therefore, the activity of the FHC increases, and the activity of the EHC decreases. That is, the flexor and extensor motor neurons are activated and inactivated, respectively. This leads to the stance-to-swing transition. Since the CIM never works due to $lp^{RF} = st$ in Eq. (3), χ_{LO}^{LF} increases according to the decrease of $\bar{r}_x^{LF}$ by backward motion of LF. In addition, leg loading of LF decreases due to the leg load transition from left to right due to rolling motion. Therefore, Eq. (2) for the stance-to-swing transition gets satisfied. Consequently, the stance-to-swing transition is induced in both models after a short while.

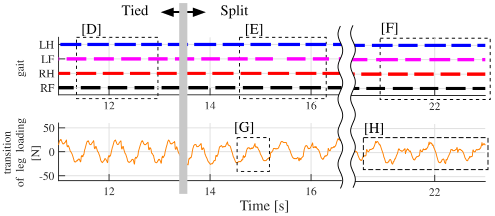
3.3 Split-Belt Walking with the Spinal Cat Model

In all experiments of this study shown in Fig. 8-(a), we start from tied-belt (speed: 13.2 [cm/s]), and then change to split-belt (speed of LF belt: 21.6 [cm/s], and speed of other belts not changed). Since the speed of LF belt is changed manually, the controller never detects the exact time of change. Therefore, the vision system over the treadmill is tracking two marks on Kotetsu while walking, detects the approx. time of change by human's hiding a mark and records it. Also, the front of the body of Kotetsu on the treadmill is constrained by two strings to use the similar constraint with a decerebrate cat as shown in Fig. 1-(a). However, the influence of the constraint by strings to rolling motion is little and Kotetsu can exchange leg loading between LF and RF smoothly.

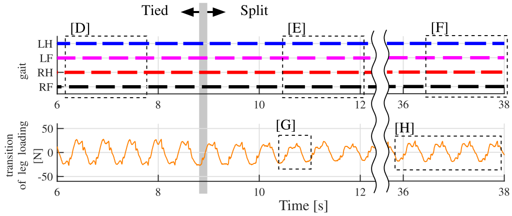
Results of split-belt walking using the spinal cat model are shown in Fig. 8-(b). In tied-belt walking, the stable walk gait appears at [D]. However, just after a change to split-belt walking, the walking gait is much unstable at [E]. Let us consider this unstable walk gait of the spinal cat model in Sect. 4.2.



(a) Kotetsu on split-belt



(b) Split-belt walking with the spinal cat model



(c) Split-belt walking with the decerebrate cat model

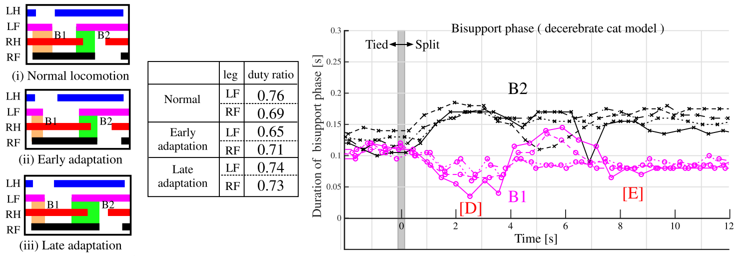
Fig. 8. Experimental setup: (a). Results of split-belt walking experiments with the spinal cat model: (b) and with the decerebrate cat model: (c). Bottom: the transition of leg loading between LF and RF calculated by $\bar{f}_n^{RF} - \bar{f}_n^{LF}$. Gait on tied-belt: [D]. Gait after the switchover from tied to split (early adaptation): [E]. Gait on split-belt (late adaptation): [F]. Transition of leg loading after the switchover from tied to split: [G]. Transition of leg loading on split-belt: [H].

4 Decerebrate Cat Model with Learning for Late Adaptation

4.1 Employing Step Distance Adjustment into the Spinal Cat Model

Yanagihara et al. showed that nitric oxide (NO) in the cerebellum plays a key role in motor learning, and that late adaptation in split-belt walking of decerebrate cats is the result of long-term depression in cerebellar Purkinje cells [3]. When a decerebrate cat receives the perturbation in split-belt walking, it is observed that the probability of occurrence of climbing fiber responses during such perturbed locomotion is higher than that during unperturbed locomotion, especially much higher in the second half of the swing phase [2].

In this study, we consider the step distance (STPD) as an adjustable motion parameter in the swing phase and propose the decerebrate cat model. We employ the STPD adjustment: Eq. (4) for the leg: i, and use the leg loading threshold: Eq. (5) for the stance-to-swing phase transition rather than Eq. (3). This means that we add the motion learning function for late adaptation in split-belt walking into the spinal cat model described in Sect. 3. We call this "the decerebrate cat model."



	leg	duty ratio
Normal	LF	0.76
	RF	0.69
Early adaptation	LF	0.65
	RF	0.71
Late adaptation	LF	0.74
	RF	0.73

(a) Gaits (b) Duty ratios (c) Durations of bisupport phases (B1 & B2)

Fig. 9. (a) Gaits of Kotetsu on tied-belt: (i) and on split-belt: (ii) and (iii) with the decerebrate cat model. (b) Duty ratios corresponding with (a). (c) The durations of bisupport phase B1 and B2 in 5 times experiments of split-belt walking of Kotetsu with the decerebrate cat model. [D]: Early adaptation. [E]: Late adaptation.

$$\tilde{D} = \begin{cases} \tau\bar{D}^i - (1-\tau)\tilde{D}^i[n-1] & (\text{if } |\bar{D}^i - (1-\tau)\tilde{D}^i[n-1]| > \varepsilon_D) \\ \tilde{D}^i[n-1] & (\text{otherwise}) \end{cases} \tag{4}$$

$$\chi^i_{LO} = \begin{cases} \hat{\chi}_{LO} \cdot (r_{xc} - \bar{r}^i_x)/(\tilde{D}/2) & (\text{if } lp^{cntr} = st) \\ -5 & (\text{otherwise}) \end{cases} \tag{5}$$

In Eq. (4) and Eq. (5), $\tilde{D}^i[n]$ means the reference value of the STPD at the swing and stance phases of the n-th step ($\tilde{D}^i[1] = \hat{D}$). On the other hand, $\bar{D}^i$ means the measured value of the STPD at the stance phase of the $(n-1)$-th step. When the absolute subtraction between measured and reference values is larger than the threshold: ε_D, the calculation for adjustment is done. The constant value: τ for adjusting the learning speed is set as a little bit small ($\tau = 0.4$), but the learning speed is much faster than the one in case of decerebrate cats.

4.2 Split-Belt Walking with the Decerebrate Cat Model

The results of experiments of split-belt walking of Kotetsu using the decerebrate cat model are shown in Fig. 8-(c) and Fig. 9.

Since we are using the very simple decerebrate cat model, its behavior should be very similar to that of the spinal cat model until motor learning functions start to work. When we compare Fig. 8-(b) & (c) just after the change to split-belt walking, the transition of leg loading between LF and RF is perturbed at [G], gait gets unstable at [E] in both cases. Such behavior corresponds to early adaptation in decerebrate cats shown in Fig. 9. In the early adaptation of the decerebrate cat model, the duration of B1 is short at (ii) in Fig. 9-(a) and at [D] in Fig. 9-(c). Let us consider what is happening using Fig. 8-(c). About gaits shown at [E], the duration of the stance phase of LF: T^{LF}_{st} quickly decreases due to the early stance-to-swing transition of LF while being pulled backwards by fast-belt as described in Sect. 3.2. Simultaneously, the duration of the swing phase of RF: T^{RF}_{sw} quickly decreases. As a result, the duty ratio of RF quickly increases a little in Fig. 9-(b), and the duration B1 still remains and contributes to the transition of leg loading from LF to RF even not so sufficient. Since similar results about durations of B1 and B2 and duty ratios at early adaptation with those at early adaptation in Fig. 1 are obtained in experiments using the decerebrate cat model, we can consider that early adaptation is induced at the spinal cord of a decerebrate cat [6].

While keeping split-belt walking, the STPD of LF is adjusted by learning functions in Eq. (4). Consequently, adjustment of the relative phase between LF and RF is carried out by learning functions at the cerebellum, leg loading between LF and RF is exchanged smoothly at [H] in Fig. 8-(c), and the stable gait in split-belt walking different from the gait in tied-belt walking is induced as a result of late adaptation at [F] in Fig. 8-(c). In the late adaptation of the decerebrate cat model, the duration of B1 is prolonged at (iii) in Fig. 9-(a) and at [E] in Fig. 9-(c). But the duration of B2 is also prolonged at (iii) in Fig. 9-(a). Such difference from the result of a decerebrate cat, including the duration of the swing/stance phases should be fixed in our next study.

5 Conclusion

We constructed the spinal cat model integrating our previous leg controller with Frigon's spinal cord model, and the decerebrate cat model adding motor learning function at the cerebellum. We showed by experiments that early adaptation was obtained in the spinal cat model, and late adaptation was obtained by motor learning as the step distance adjustment in the decerebrate cat model. The validity of those models was evaluated by comparing durations of forelegs bisupport phases and duty ratios between decerebrate cats and a quadruped robot with the decerebrate cat model. It does not necessarily mean that this is how the control in the biological system works, but we confirmed that the basis of proposal model concepts could explain the adaptation of split-belt walking.

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