Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts

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Adaptive Dynamic Walking of a Quadruped Robot on Natural Ground Based on Biological Concepts

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Keywords

legged locomotion, quadruped, biologically inspired robot, adaptive walking on irregular terrain, neural system model, central pattern generator (CPG), reflex

We report our study to make a quadruped robot walk with medium forward speed on irregular terrain in outdoor environment using a neural system model. We propose the necessary conditions for stable dynamic walking on irregular terrain in general, and we design the neural system by comparing biological concepts with those necessary conditions described in physical terms. PD-controller at joints constructs the virtual spring-damper system as the visco-elasticity model of a muscle. The neural system model consists of a CPG (central pattern generator), responses and reflexes. A response directly and quickly modulates the CPG phase, and a reflex directly generates joint torque. The state of the virtual spring-damper system is switched based on the CPG phase. In order to make a self-contained quadruped called Tekken2 walk on natural ground, we newly develop several reflexes and responses in addition to those developed in our previous studies. A flexor reflex prevents a leg from stumbling on small bumps and pebbles. A sideway stepping reflex stabilizes rolling motion on a sideway inclined slope. A corrective stepping reflex/response prevents a robot from falling down in case of loss of ground contact. A crossed flexor reflex helps a swinging leg keep enough clearance of the toe to the ground. We validate the effectiveness of the proposed neural system model control and especially newly developed reflexes and responses by indoor and outdoor experiments using Tekken2. A CPG receives sensory feedback as a result of motions induced by reflexes, and changes the period of its own active phase. Since a CPG has the ability of mutual entrainment with pitching motion of legs and rolling motion of the body in addition, the consistency between motion of a leg temporally modified by a reflex and motions of other legs are maintained autonomously. As results, it is shown that

CPGs can be the center of sensorimotor coordination, and that the neural system model simply defining the relationships between CPGs, sensory input, reflexes and mechanical system works very well even in complicated tasks such as adaptive dynamic walking on unstructured natural ground.

1 Introduction

Most studies on legged robots were biologically inspired to some extent in mechanical design, control, navigation and so on. Especially, not static walking but dynamic walking and running of animals and humans attracted several robotics researchers in 1980' (Miura and Shimoyama 1984; Raibert 1986; Kimura *et al* 1990; Sano and Furusho 1990). Since 1990', several studies on running (Hodgins and Raibert 1991), and dynamic walking of biped robots (Yamaguchi, Takanishi and Kato 1994; Kajita and Tani 1996; Hirai *et al* 1998; Chew, Pratt and Pratt 1999; Yokoi *et al* 2004) and quadruped robots (Yoneda, Iiyama and Hirose 1994; Buehler *et al* 1998) on irregular terrain had been carried out. However, most of those studies assumed that the structure of the terrain was known, even though the height of the step or the inclination of the slope was unknown. In 2000', several hexapod robots (Saranli, Buehler and Koditschek 2001; Quinn *et al* 2001; Cham, Karpick and Cutkosky 2004) realized high-speed mobility over irregular terrain with appropriate mechanical compliance of the legs. The purpose of our study is to realize high-speed mobility on irregular terrain in outdoor environment with less knowledge about terrain using a mammal-like quadruped robot, the dynamic walking of which is less stable than that of hexapod robots, by referring to the well-known abilities of animals to autonomously adapt to their environment.

As many biological studies of motion control progressed, it has become generally accepted that animals' walking is mainly generated at the spinal cord by a combination of a CPG (central pattern generator) and reflexes receiving adjustment signals from a cerebrum, cerebellum and brain stem (Grillner 1981; Cohen and Boothe 1999). A great deal of the previous research on this attempted to generate walking using a neural system model, including studies on dynamic walking in simulation (Taga *et al* 1991; Taga 1995; Ijspeert 2001; Tomita and Yano 2003) and real robots (Kimura *et al* 1999, 2001; Berns *et al* 1999; Tsujita, Tsuchiya *et al* 2001; Lewis *et al* 2003). But autonomously adaptive dynamic walking on irregular terrain was rarely realized in those earlier studies except for our studies using quadruped robots called "Patrush" (Kimura *et al* 1999, 2001) and "Tekken1" (Fukuoka, Kimura and Cohen 2003a).

Since Tekken1 was not self-contained (power autonomous), we developed a self-contained quadruped robot called "Tekken2" for outdoor experiments. We had already realized adaptive walking on natural ground using Tekken2, and very briefly reported the design concepts of mechanical and neural systems of Tekken2 (Kimura and Fukuoka 2004). In that report, it was mentioned that there existed a slope of 3 (deg) at most, bumps of 1 (cm) in height and small pebbles everywhere even on a paved road, and that we had to develop additional sensor based adaptation methods for outdoor experiments. In this article, we describe the details of newly developed sensor based adaptation methods and experimental results of adaptive dynamic walking on natural ground using Tekken2 (Figure 1).

A CPG receives sensory input as resultant motions of reflexes and changes the period of its own active phase. Since a CPG has the ability of mutual entrainment with the pitching motion of legs and the rolling motion of the body, the consistency between the motion of a leg temporally modified by a reflex and the motions of the other legs are maintained autonomously. As results, it is shown that CPGs can be the center of sensorimotor coordination, and that the neural system model simply defining the relationships between CPGs, sensory input, reflexes and mechanical system works very well even in complicated tasks such as adaptive dynamic walking on unstructured natural ground.

(a) (b)

Figure 1: Photos of walking of Tekken2 on natural ground. The cable is just to prevent Tekken2 from damage in case of emergency, and usually slack. The average walking speed was approx. 0.7 (m/s).

2 Considerations for Adaptive Walking

Before design and implementation of the neural system model, let us briefly describe the considerations necessary for adaptive walking on irregular terrain. In this article, we define a "reflex" as joint torque generation based on sensor information and a "response" as CPG phase modulation through sensory feedback to a CPG.

2.1 Legged Locomotion Control Methods

Jindrich and Full (2002) mentioned that two general methods are available to maintain stability during legged locomotion. Those are:

[a] adjustment of joint torques within a single step cycle,

[b] adjustment of initial conditions of the legs at the transition from swing to stance.

We would like to add the third method:

[c] adjustment of phase (stance or swing) of a leg[1].

[1]That is, shortening or lengthening the period of a stance or swing phase of a leg in a step cycle.

Method [a] is very popular in several legged locomotion studies (Kajita *et al* 1996; Chew *et al* 1999; Yoneda *et al* 1994; Buehler *et al* 1998) including ZMP (zero moment point) based control (Yamaguchi *et al* 1994; Hirai *et al* 1998; Yokoi *et al* 2004).

Method [b] involves the adjustment of touchdown angle (stepping reflex) of a swinging leg (Miura and Shimoyama 1984; Raibert 1986; Townsend 1985; Bauby and Kuo 2000), and the switching of leg stiffness between stance and swing phases (Raibert 1986; Kimura *et al* 1990; Taga *et al* 1991; Taga 1995; Fukuoka *et al* 2003a). Since the running speed can be stabilized using the constant touchdown angle, self-stabilization of the musculo-skeletal system in running (Full *et al* 1999; Seyfarth *et al* 2002; Cham *et al* 2004; Hackert *et al* 2005; Poulakakis *et al* 2005) is also involved in [b].

As the examples of method [c], we developed a "response" as a modulation of the CPG phase (Fukuoka *et al* 2003a). Cham *et al* (2004) and Zhang *et al* (2006) also used the method [c] to stabilize running of a hexapod and a quadruped on irregular terrain, respectively.

Of course, these three methods are not completely independent. For example, the method [c] becomes more effective when the switching of leg stiffness between stance and swing phases is employed.

2.2 Stability Evaluation in Dynamic Walking

In out previous article (Fukuoka *et al* 2003a), we defined the "wide stability margin" as the shortest distance from the projected point of the center of gravity to the edges of the polygon constructed by the projected points of legs independent of their stance or swing phases (Figure 2).

Since the wide stability margin (WSM) is used not for motion planning but for motion evaluation, not ZMP but the projected point of the center of gravity is used eliminating inertia force and so on for simplicity. In such robot like Tekken which can move a swinging leg quickly enough within the short cyclic period of walking (0.2$\sim$0.4 (s)), a swinging leg can land on floor immediately if needed in Figure 2. Therefore, the WSM can be the substitution of the conventional stability margin or the ZMP margin used in order to avoid excess angular acceleration around the line connecting two supporting points. WSM is calculated using measured joint angles.

2.3 Necessary Conditions for Stable Dynamic Walking on Irregular Terrain

We had proposed the necessary conditions to keep the limit cycle for stable dynamic walking on irregular terrain[2] in our previous article (Fukuoka *et al* 2003a). We add a necessary condition [1] with regard to the walking cycle period and describe all those conditions [2]$\sim$[6] again for completeness:

[1] the period of the walking cycle should be short enough to keep high WSM while walking,

[2] It should be noted that those are not sufficient, but necessary conditions. Therefore, stable walking cannot be ensured with those conditions. When one of those conditions is not satisfied on any terrain, walking motion is disturbed and moves off from the limit cycle, and the robot may fall down at worst.

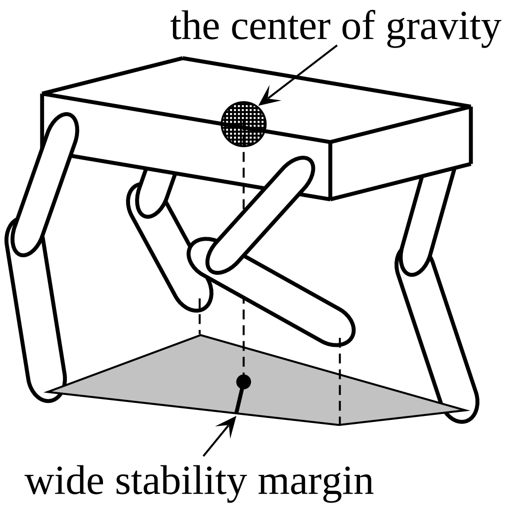

Figure 2: The definition of the wide stability margin

[2] the swinging legs should be free to move forward during the first period of the swing phase,

[3] the swinging legs should land on the ground without slipping and without large delay during the second period of the swing phase,

[4] the angular momentum of the robot during its pitching motion or rolling motion around the contact points should be kept constant at the moment of landing or leaving of legs,

[5] the phase difference between rolling motion of the body and pitching motion of the legs should be maintained regardless of a disturbance from irregular terrain, and

[6] the phase differences between the legs should be maintained regardless of delay in the pitching motion of a leg receiving a disturbance from irregular terrain.

About the condition [1], a dynamic system similar to an inverted pendulum appears in the two-legged stance phase in most of the gaits of a quadruped, and the long cyclic period makes dynamic walking be less stable mainly for the following reasons:

- The long cyclic period makes the amplitude of motion of an inverted pendulum be larger and WSM be smaller[3].
- The long cyclic period makes the influence of disturbances in a step cycle be larger and keeping the limit cycle by phase switching [4] be more difficult.

[3]For example, in a trot gait of Tekken2, a rolling motion is naturally generated although Tekken2 has no joint around the roll axis. The long cyclic period makes the amplitude of this rolling motion be larger and WSM be smaller.

[4]Exchanging of supporting legs and swinging legs (i.e. phase switching) makes the influence of disturbances in a step cycle be smaller in the next step cycle, and helps keeping the limit cycle (Miura and Shimoyama 1984).

In order to make Tekken2 walk with longer cyclic periods (slower step rates), we needs to use a walk gait[5] and larger duty factors to decrease the period in which an inverted pendulum appears. But we consider walking with short cyclic period (0.2∼0.4 (s)) using a trot gait and smaller duty factor (0.55∼0.62) for simplicity in this article.

We designed the neural system consisting of CPGs, responses and reflexes for these necessary conditions to be satisfied in order to realize adaptive walking of Tekken1 (Fukuoka *et al* 2003a). In this article, we add several reflexes and responses to make Tekken2 walk on natural ground while considering these necessary conditions.

2.4 Mechanical Design of Tekken2

In order to apply the neural system model control, the mechanical system should be well designed to have good dynamic properties (i.e. small moment of inertia, low friction, high backdrivability and so on). In addition, performance of dynamic walking such as adaptability on irregular terrain, energy efficiency, maximum speed and so on highly depends on the mechanical design. The design concepts of Tekken2 (Figure 3-(a)) are:

- high power actuators and small moment of inertia of legs for quick motion and response,
- small gear reduction ratio for high backdrivability to increase passive compliance of joints,
- small mass of the lowest link of legs to decrease impact force at collision,
- small contacting area at toes to increase adaptability on irregular terrain.

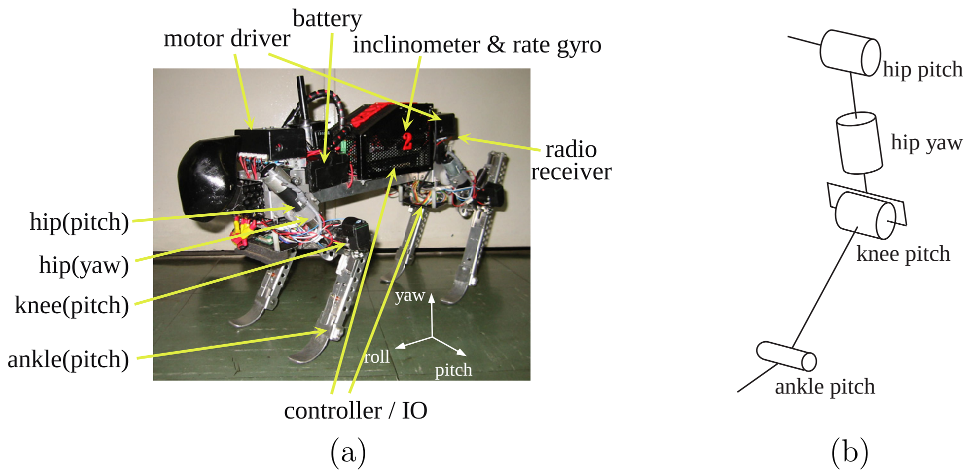

Figure 3: Self-contained quadruped robot: Tekken2 (a) and joints of a leg (b). The length of the body and a leg in standing are 30 (cm) and 25 (cm). The weight including batteries is 4.3 (kg).

[5]Diagonal legs and lateral legs are paired and move together in a trot gait and a pace gait, respectively. A walk gait is the transversal gait between the trot and pace gaits.

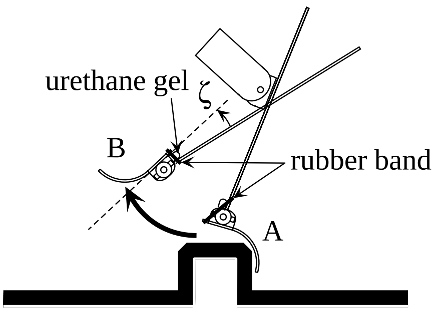

Figure 4: Passive ankle joint mechanism. A leg stumbled on an obstacle at A, and the leg was prevented from stumble passively at B.

Tekken2 has the same configuration as Tekken1 except for that the size and weight of Tekken2 are approx. 25% larger that those of Tekken1. Tekken2 has four joints on each leg (Figure 3-(b)). The hip pitch joint, knee pitch joint and hip yaw joint are activated by DC motors of 23 (W), 23 (W) and 8 (W) through gear ratio of 20, 28 and 18, respectively. The ankle joint is passive with a spring-lock mechanism (Figure 4). The walking direction can be changed by using the hip yaw joints. Two rate gyros and two inclinometers are mounted on the body in order to measure the body pitch and roll angles.

The joint angles of hip pitch, knee pitch, hip yaw and ankle pitch are expressed by θ, ϕ, ψ and ζ, respectively (see the lower part of Figure 5). In Figure 4, since the urethane gel inserted between two links is crushed elastically in a stance phase, we can detect the contact of a leg with floor by the encoder at the ankle joint. As a result, we can detect three states of a leg by measuring the ankle joint angle ζ: stance ($\zeta \leq -10(deg)$), swing in the air ($-10 < \zeta \leq 5(deg)$) and stumble on an obstacle ($\zeta > 5(deg)$). Walking speed is calculated using measured joint angles of supporting legs at every sampling time.

3 Neural System for Adaptive Walking on Irregular Terrain

The basis of the neural system of Tekken2 (the middle part of Figure 5) is same with that of Tekken1. Since we had already described the neural system consisting of CPGs and the virtual spring-damper system in our previous article (Fukuoka *et al* 2003a), we describe it briefly in Section *3.1* and Section *3.2* again for completeness. For more details, please see that article.

3.1 Rhythmic Motion by CPG

We construct the neural system centering a neural oscillator (Matsuoka 1987; Taga *et al* 1991) as a model of a CPG. A single neural oscillator (NO) consists of two mutually inhibiting neurons. Each neuron in this model is represented by the following nonlinear differential equations:

$$\tau \dot{u}_{\{e,f\}i} \quad = \quad -u_{\{e,f\}i} + w_{fe} y_{\{f,e\}i} - \beta v_{\{e,f\}i}$$

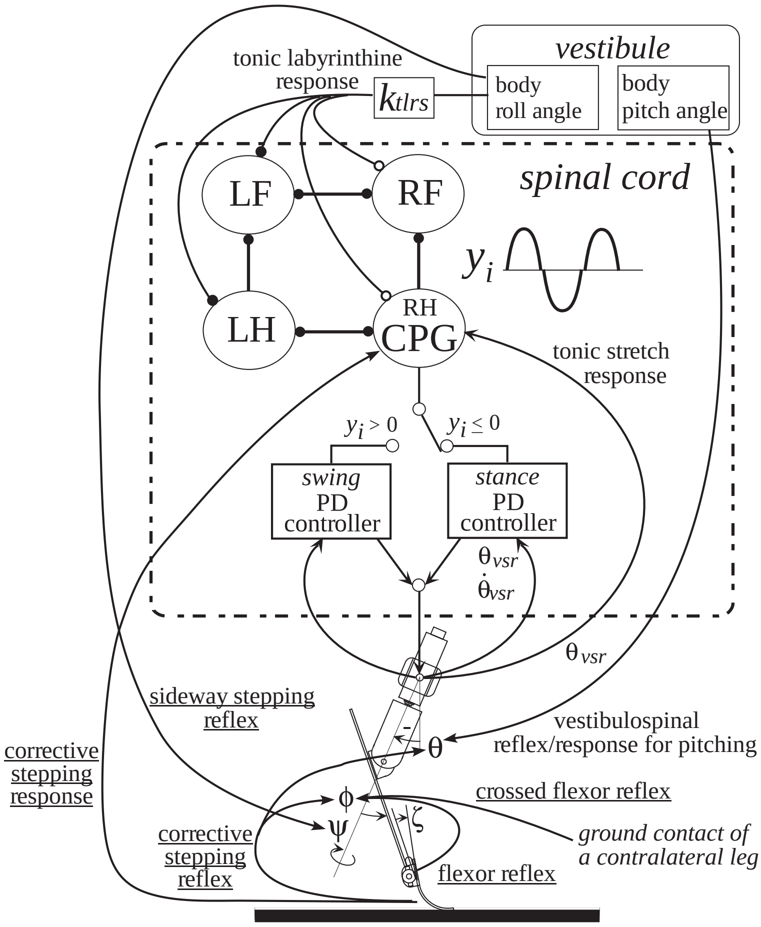

Figure 5: Control diagram for Tekken2. PD-control at the hip yaw and knee pitch joints are eliminated in this figure. The names of newly developed reflexes and responses are underlined.

$$
\begin{aligned}
& +u_0 + Feed_{\{e,f\}i} + \sum_{j=1}^{n} w_{ij} y_{\{e,f\}j} \\
y_{\{e,f\}i} &= \max\left(u_{\{e,f\}i}, 0\right) \qquad (1)\\
\tau' \dot{v}_{\{e,f\}i} &= -v_{\{e,f\}i} + y_{\{e,f\}i}
\end{aligned}
$$

where the suffix e, f, and i mean an extensor neuron, a flexor neuron, and the i-th NO, respectively. $u_{\{e,f\}i}$ is u_{ei} or u_{fi}, that is, the inner state of an extensor neuron or a flexor neuron of the i-th NO; $v_{\{e,f\}i}$ is a variable representing the degree of the self-inhibition effect of the neuron; y_{ei} and y_{fi} are the output of extensor and flexor neurons, and are input to flexor and extensor neurons with a connecting weight: w_{fe}, respectively; u_0 is an external input with a constant rate; $Feed_{\{e,f\}i}$ is a feedback signal from the robot, that is, a joint angle, angular velocity and so on; and β is a constant representing the degree of the self-inhibition influence on the inner state. The quantities τ and τ' are time constants of $u_{\{e,f\}i}$ and $v_{\{e,f\}i}$; w_{ij} is a connecting weight between neurons of the i-th and j-th NO. The subscripts $i, j = 1, 2, 3, 4$ correspond to LF, LH, RF, RH. L, R, F or H denotes the left, right, fore or hind leg, respectively.

The output of a CPG is a phase signal: y_i.

$$y_i = -y_{ei} + y_{fi} \tag{2}$$

The positive or negative value of y_i corresponds to activity of a flexor or extensor neuron, respectively.

The cyclic period of walking is mainly determined by the time constant τ of a neural oscillator. This makes it easy for the necessary condition [1] described in Section *2.3* to be satisfied. The time constant τ is changed according to the wide stability margin (WSM) while walking in order to solve the trade-off problem between the stability and the energy consumption (Fukuoka *et al* 2003a).

$$\tau = 0.12 \times WSM \;/\; w \tag{3}$$

where WSM is normalized using the body width of Tekken2 ($w = 135(mm)$) [6].

We use the following hip joint angle feedback as a basic sensory input to a CPG called a "tonic stretch response" in all experiments of this study. This negative feedback entrains a CPG with a rhythmic hip joint motion.

$$Feed_{e \cdot tsr} = k_{tsr}(\theta - \theta_0), \quad Feed_{f \cdot tsr} = -Feed_{e \cdot tsr} \tag{4}$$

$$Feed_{\{e,f\}} = Feed_{\{e,f\} \cdot tsr} \tag{5}$$

where θ is the measured hip joint angle, θ_0 is the origin of the hip joint angle in standing and k_{tsr} is the feedback gain. We eliminate the suffix i when we consider a single neural oscillator.

By connecting the CPG of each leg (Figure 5), CPGs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the CPGs of the legs results in a gait. For most of experiments, we used a trot gait[7].

3.2 Virtual Spring-damper System

We employ the model of muscle stiffness, which is generated by the stretch reflex and variable according to the stance/swing phases, adjusted by the neural system. Muscle stiffness is high in a stance phase for supporting a body against the gravity and low in a swing phase for compliance against the disturbance (Akazawa *et al* 1982). All joints of Tekken2 are PD controlled to move to their desired angles in each of three states (A, B, C) in Figure 6 in order to generate each motion such as swinging up (A), swinging forward (B) and pulling down/back of a supporting leg (C). The timing for all joints of a leg to switch to the next state are:

$A \rightarrow B$: when the hip joint of the leg reaches the desired angle of the state (A)

[6] When WSM/w is 0.5, τ becomes 0.06. This value makes the cyclic period of Tekken2 be approx. 0.3 (s).

[7] The gait in walking is shifted to a walk gait by rolling motion feedback to CPGs. Such autonomous gait transition in changing walking speed was discussed in our previous article (Fukuoka *et al* 2003a).

$B \to C$: when the CPG extensor neuron of the leg becomes active ($y \leq 0$)

$C \to A$: when the CPG flexor neuron of the leg becomes active ($y > 0$)

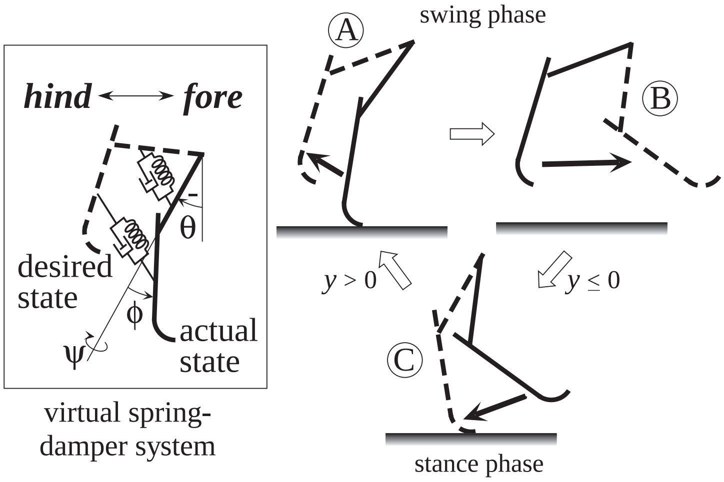

Figure 6: State transition in the virtual spring-damper system. The desired joint angles in each state are shown by the broken lines.

The desired angles and P-gain of each joint in each state are shown in Table 1. Since Tekken2 has high backdrivability with small gear ratio in each joint, PD-controller can construct the virtual spring-damper system [8] with relatively low stiffness coupled with the mechanical system. Such compliant joints of legs can improve the passive adaptability on irregular terrain.

The diagram of the pitching motion control of a leg is shown in the middle part of Figure 5. Joint torque of all joints is determined by the PD controller, corresponding to a stretch reflex at an α motor neuron in animals. The desired angle and P-gain of each joint is switched based on the phase of the CPG output: y in Eq.(2). As a result of the switching of the virtual spring-damper system and the joint angle feedback signal to the CPG in Eq.(5), the CPG and the pitching motion of the leg are mutually entrained.

3.3 Values of the Parameters in the Neural System Model

Values of parameters in the neural system were determined experimentally, and are shown in Table 2. It should be noted that values of all parameters for Tekken2 were constant in all experiments independent of terrain. In addition, values of parameters of a neural oscillator in Eq.(1) and Eq.(4) for Tekken2 were exactly same with those for Tekken1 except for θ_0 in spite of the differences (approx. 25%) of size and weight. Thus, the parameters of the neural oscillator

[8] Joints are not necessary to reach the desired angles. Usually, a CPG switches the state before reaching the desired angles. This is the reason why Tekken2 can change the walking speed by changing P-gain of the hip pitch joint in a stance phase (G_5 in Table 1).

Table 1: Desired value of the joint angles and P-gains at the joints used in the PD-controller for the virtual spring-damper system in each state. ($\theta_{C\to A}$: the hip joint angle measured at the instance when the state changes from (C) to (A). body pitch angle: the measured pitching angle of the body used for the vestibulospinal reflex. ϕ^*_{sw} means that the desired angle is calculated on-line using inverse kinematics for the height from the hip joint to the toe to be constant. v (m/s): the measured walking speed of Tekken. G_5: variable to change the walking speed. θ^*_{sw}, θ^*_{st}, ϕ^*_{st}, ψ^*, $G_1 \sim G_4$ and $G_6 \sim G_8$ are constant.)

	P control	
Angle in State	Desired Value (rad)	P-gain (Nm rad^{-1})
θ in A	$1.2\theta_{C\to A}$	G_1
θ in B	θ^*_{sw}	G_2v+G_3
θ in C	θ^*_{st}+ body pitch angle	$-G_4v$+G_5
ϕ in A & B	ϕ^*_{sw}	G_6
ϕ in C	ϕ^*_{st}	G_7
ψ in all states	ψ^*	G_8

Table 2: Values of the parameters used in experiments of Tekken2. The value of τ is typical, and actual value is determined based on Eq.(3). k_{tlrr} is the gain of a tonic labyrinthine response (Fukuoka *et al* 2003a).

Parameters	Value	Parameters	Value
u_0	1.0	ψ^*(rad)	0
τ	0.06	k_{tsr}(1/rad)	3.0
τ'	0.6	k_{tlrr}(1/rad)	2.25
β	3.0	k_{stpr}	0.9
w_{fe}	-2.0	G_1(Nm/rad)	7.0
$w_{\{13,31,24,42\}}$	-2.0	G_2(Nms/rad)	0.6
$w_{\{12,34\}}$	0	G_3(Nm/rad)	0.6
$w_{\{21,43\}}$	-0.57	G_4(Nms/rad)	1.0
θ_0(rad)	-1.06	G_5(Nm/rad)	1.5~3.0
θ^*_{sw}(rad)	-0.17	G_6(Nm/rad)	7.0
θ^*_{st}(rad)	-1.0	G_7(Nm/rad)	2.6
ϕ^*_{st}(rad)	0.61	G_8(Nm/rad)	2.0

are not highly sensitive with regard to generation of rhythmic motions of legs. The sensitivity and robustness of parameters in reflexes and responses were discussed in our previous article (Fukuoka and Kimura 2003c).

3.4 Reflexes and Responses

We use responses for direct and rapid modulation of the CPG phase, and reflexes for direct and rapid adjustment of joint torque. On the basis of biological principles and knowledge (Cohen and Boothe 1999; Ghez 1991; Gordon 1991; Grillner 1981; Ogawa *et al* 1998; Orlovsky *et al* 1999), we developed several reflexes and responses (Table 3, Figure 5) to satisfy the necessary conditions [2]∼[5] described in physical terms in Section *2.3*. These were in addition to the stretch reflex and response described in Section *3.2* and *3.1*. The necessary condition [6] can be satisfied by the mutual entrainment between CPGs and the pitching motion of legs, and the mutual entrainment among CPGs (Kimura *et al* 2001).

All responses in Table 3 are categorized as control method [c] described in Section *2.1*. Flexor, vestibulospinal and crossed flexor reflexes are categorized as control method [a]. Stepping, sideway stepping and corrective stepping reflexes are categorized as control method [b].

A stepping reflex, a vestibulospinal reflex/response, and a tonic labyrinthine response in Table 3 had been developed in Tekken1, and were described in our previous article (Fukuoka *et al* 2003a). Especially, a tonic labyrinthine response[9] (rolling motion feedback to CPGs) was important for mutual entrainment among CPGs, pitching motions of legs and rolling motion of the body. Such entrainment stabilized a walking gait, and increased the adaptability on irregular terrain (Fukuoka *et al* 2003a).

Table 3: Reflexes and responses developed on Tekken2. (The sp and sw mean the supporting leg and swinging leg, respectively. The corresponding necessary conditions are described in Section *2.3*.)

	sensed value or event	activated on	necessary conditions
flexor reflex	collision with obstacle	sw	[2]
stepping reflex	forward speed	sw	[4]
vestibulospinal reflex/response	body pitch angle	sp	[4]
tonic labyrinthine response	body roll angle	sp&sw	[3],[4],[5]
sideway stepping reflex	body roll angle	sw	[4]
corrective stepping reflex/response	loss of ground contact	sw	[3],[4]
crossed flexor reflex	ground contact of a contralateral leg	sw	[2]

About the names of reflexes, Espenschied et al. (1996) employed the swaying, elevator, step-

[9]The "tonic labyrinthine reflex" is defined in Ogawa *et al* (1998). The same reflex is called "vestibular reflex" in Ghez (1991).

ping and searching reflexes observed by Pearson et al. (1984) in a stick insect, and realized statically stable autonomous walking of a hexapod robot on rough terrain. Their elevator, stepping and searching reflexes correspond to our flexor, stepping and corrective stepping reflexes, respectively. Since we are studying a quadruped, we use the names used in biological studies of mammals as far as possible.

3.4.1 **Flexor reflex**

It is well known in biology that a stimulus on the paw dorsum in the walking of a spinal cat produces an enhanced flexion during the flexion phase of the step cycle in order to prevent it from stumbling (Forssberg *et al* 1977; Cohen and Boothe 1999). We call this the "flexor reflex", which contributes to satisfy the necessary condition [2].

In Tekken1, we had substituted the flexor reflex for the passive ankle joint mechanism with spring and lock (Figure 4) utilizing the fact that the collision with a forward obstacle occurs in the first half of a swing phase (Fukuoka *et al* 2003a). In Tekken2, although we developed the same passive ankle mechanism, it was found that the passive ankle joint was not sufficient in outdoor environment because of stumbling on small bumps and pebbles, and stumbling due to high friction on rough surfaces. Therefore, we activate a flexor reflex at the knee joint by using the following ϕ^*_{fr} instead of ϕ^*_{sw} in Table 1 in order to flex the knee joint (Figure 7-(b)) when the stumbling is detected ($\zeta > 5(deg)$, Figure 7-(a)) in the flexor neuron active phase ($y > 0$) of the CPG of a leg.

$$\phi^*_{fr} = \phi_{stmbl} + 0.7[rad] \tag{6}$$

where ϕ_{stmbl} is the knee joint angle measured at the instance of the stumbling. When the leg escapes from the stumbling (Figure 7-(c)), the passive ankle joint moves to the initial angle ($\zeta \simeq 0(deg)$) due to elasticity (32 (N/m)) of the equipped rubber, and ϕ^*_{sw} in Table 1 is used for the desired angle of PD controller.

The result of an indoor experiment is shown in Figure 8. The stumbling on a step was detected at (A), and a flexor reflex was activated at (B). In spite of this stumbling, the wide stability margin: WSM was kept relatively high ($0.4w \sim 0.5w$) while walking over a step.

3.4.2 **Sideway stepping reflex to stabilize rolling motion**

It is known that the adjustment of the sideway touchdown angle of a swinging leg is effective in stabilizing rolling motion against disturbances (Miura and Shimoyama 1984; Bauby and Kuo 2000). We call this a "sideway stepping reflex," which helps to satisfy the necessary condition [4] during rolling motion. The sideway stepping reflex is effective also in walking on a sideway inclined slope.

For example, when Tekken2 walks on a right-inclined slope (Figure 9), Tekken2 continues to walk while keeping the phase differences between left and right legs with the help of the tonic labyrinthine response. But Tekken2 cannot walk straight and shifts its walking direction to the right due to the difference of the gravity load between left and right legs. In addition, Tekken2

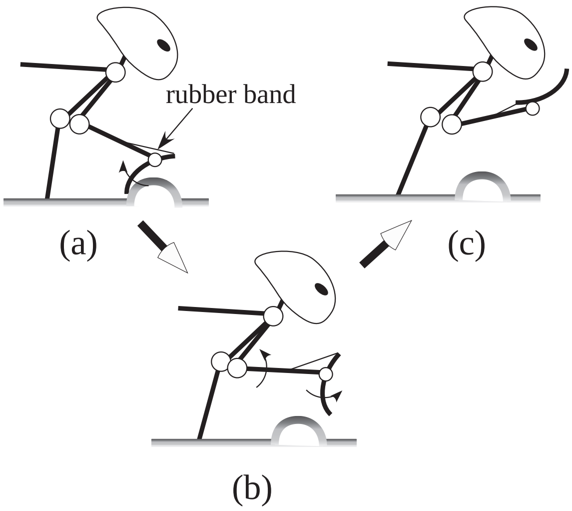

Figure 7: A flexor reflex activated on stumbling.

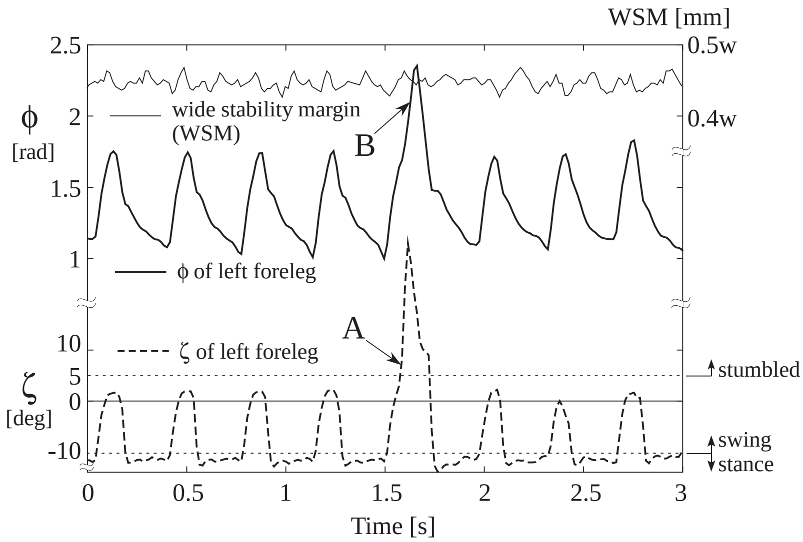

Figure 8: An experiment of walking over a step 2 (cm) in height with a flexor reflex. We use degrees only for ζ in this article.

typically falls down to the right for the perturbation from the left in the case of Figure 9-(a), since WSM is small. The sideway stepping reflex helps to stabilize the walking direction and to prevent the robot from falling down while keeping WSM large on such sideway inclined slope (Figure 9-(b)).

Since Tekken2 has no joint round the roll axis, the sideway stepping reflex is implemented as changing the desired angle of the hip yaw joint from ψ^* (Table 1) to ψ^*_{stpr} according to Eq.(7).

$$\psi^*_{stpr} = \delta(leg)\ k_{stpr} \times (\text{body roll angle}) \tag{7}$$

$$\delta(leg) = \begin{cases} 1, & \text{if } leg \text{ is a right leg;} \\ -1, & \text{otherwise} \end{cases}$$

The result of an indoor experiment is shown in Figure 10, where Tekken2 walked on the right-inclined slope (2.5∼7 (s)). In Figure 10, we can see that the body roll angle was positive (0.05∼0.2 (rad)) on the right-inclined slope:(A), and approx. 0 (rad) on flat terrain:(B),(C). The hip yaw joint of the right foreleg moved to the outside of the body (right) by 0.1∼0.2 (rad) (D) due to the sideway stepping reflex in the swing phase on the slope. On the other hand, the hip yaw joint of the left foreleg moved to the inside of the body (right) by -0.06∼-0.02 (rad) (E) due to the sideway stepping reflex in the swing phase on the slope. Consequently, Tekken2 succeeded in straight walking on the sideway inclined slope.

3.4.3 **Corrective stepping reflex and response for walking down a step**

When loss of ground contact is detected at the end of a swing phase while walking over a ditch, a cat activates corrective stepping to make the leg land at the more forward position and extend the swing phase (Hiebert *et al* 1994). We call this "corrective stepping reflex/response," which is effective for the necessary conditions [3] and [4] to be satisfied also in walking down a large step (Figure 11-(b)).

First, we define the following reference angles, θ^*_{csr} and ϕ^*_{csr}, of pitch hip and knee joints at the landing moment of a swinging leg in usual cases.

$$\theta^*_{csr} = -0.8 + (\text{body pitch angle}) \qquad \phi^*_{csr} = 1.25(rad) \tag{8}$$

If the contact to the ground of a leg is not detected ($\zeta > -10(deg)$) when the CPG extensor neuron of the leg becomes active ($y \leq 0$) and the pitch hip and knee joints reach the reference angles ($\theta \leq \theta^*_{csr}$ and $\phi \leq \phi^*_{csr}$), the corrective stepping reflex and response against loss of ground contact are activated on the leg. As the corrective stepping reflex, the hip and knee joints are PD controlled to the desired angles, θ^*_{csr} and ϕ^*_{csr}, respectively[10]. As the corrective stepping

[10]The desired angles can be adjusted according to the increased walking speed and the height of a step if those values are measured in future.

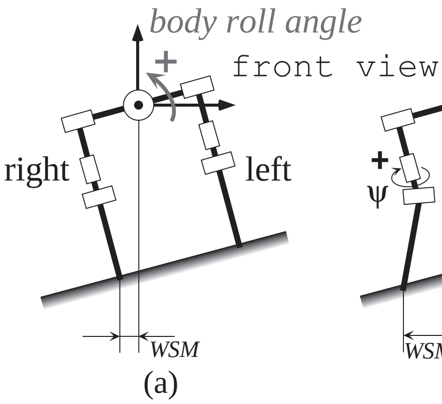

Figure 9: Walking on a sideway inclined slope without a sideway stepping reflex (a) and with it (b).

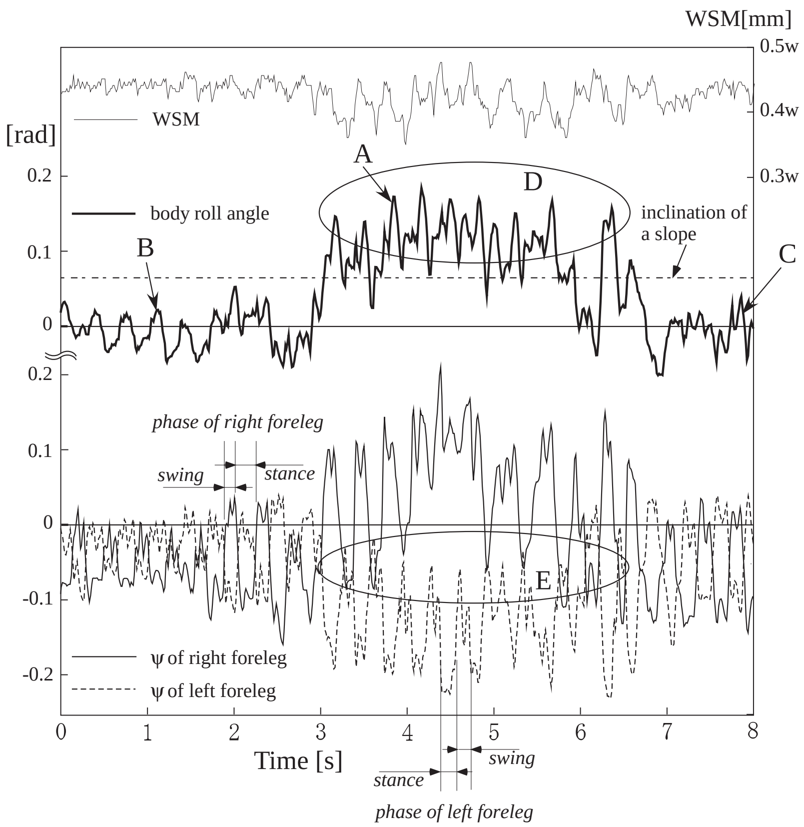

Figure 10: An experiment of walking on a right-inclined slope of 0.07 (rad) (4 (deg)) with a sideway stepping reflex.

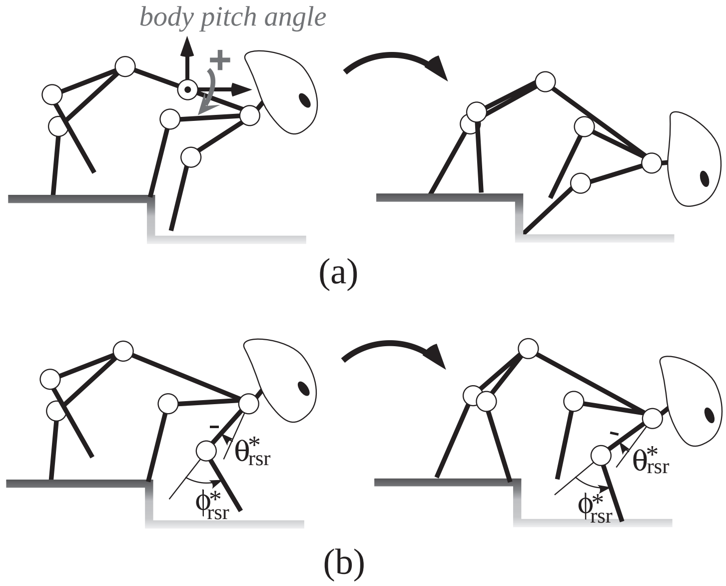

Figure 11: Walking down a step without corrective stepping:(a) and with corrective stepping:(b).

response, the following increased external input (u^*_{csr}) to the extensor neuron of the CPG for the leg is used in order to extend the stance phase.

$$u^*_{csr} = u_0 \times 2 \tag{9}$$

The results of indoor experiments are shown in Figure 12 and Figure 13, where Tekken2 walked down a step 7 (cm) in height without and with a corrective stepping reflex/response, respectively. In Figure 12, although the CPG extensor neuron of the right foreleg became active ($y \leq 0$, A) at 1.1 (s) and the state of the virtual spring-damper system was switched to a stance phase, the leg did not land on the ground (B) and the knee joint was more stretched (C). As a result, the right foreleg landed at the more backward position (D) and Tekken2 fell down at 1.4 (s) ($WSM < 0$) (Figure 11-(a)).

In Figure 13, the above described conditions to activate the corrective stepping reflex/response were satisfied at 1.05 (s) (A, B), and the hip and knee joints were PD controlled to θ^*_{csr} (C) and ϕ^*_{csr} (D), respectively. We can see that the right foreleg landed on the ground while keeping forward position of the toe (E) due to the corrective stepping reflex and the extensor neuron active phase of the CPG was extended (F) due to the corrective stepping response. As a result, the forward speed increased by lost potential energy was suppressed and Tekken2 was prevented from falling down ($WSM > 0.2w$) (Figure 11-(b)).

3.4.4 **Crossed flexor reflex**

It sometimes happens on outdoor irregular terrain that the posture of the body is significantly disturbed and a supporting leg yields excessively due to excessive gravity load to the leg (Figure

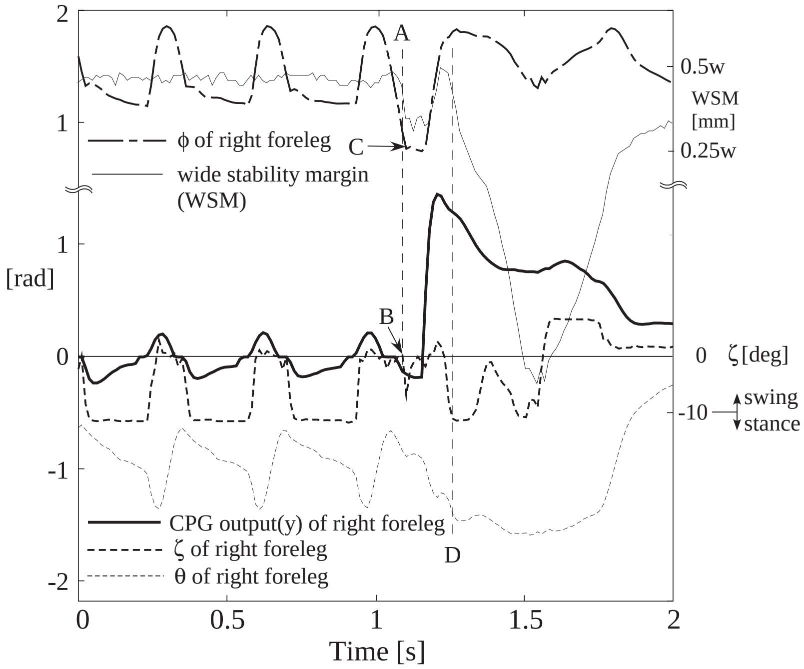

Figure 12: An experiment of walking down a step 7 (cm) in height without a corrective stepping reflex/response.

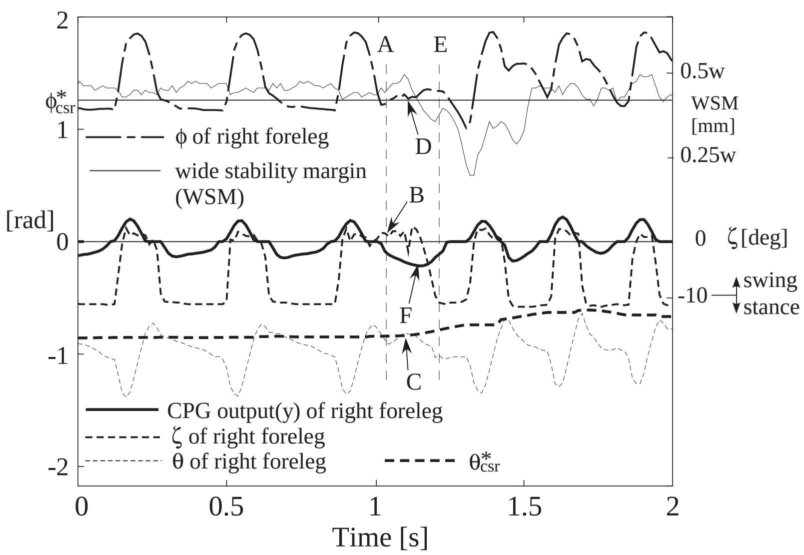

Figure 13: An experiment of walking down a step 7 (cm) in height with a corrective stepping reflex/response.

14-(a)). In such case, in order to prevent the contralateral leg from stumbling in swinging forward, it is necessary to lift the toe of the contralateral leg higher than usual (Figure 14-(b)). We call this a "crossed flexor reflex"[11] in the sense that the supporting leg is forced to flex at the moment that it needs to be extended against gravity load, and the contralateral swinging leg needs to be flexed.

In Figure 14, the height of a supporting leg from the hip joint to the toe is measured at the landing moment ($h_{sw \to st}$). As a crossed flexor reflex in Tekken2, the desired height of the contralateral swinging leg (h^*_{sw}) determined according to Eq.(10) is used for calculating ϕ^*_{sw} instead of the constant (-155 (mm)) used in Table 1, and the knee joint of the contralateral swinging leg is PD controlled to ϕ^*_{sw}.

$$h^*_{sw} = h_{sw \to st} + 39 \quad (mm) \tag{10}$$

When Tekken2 walked down a step 7 (cm) in height with a corrective stepping reflex/response as described in Section *3.4.3*, it sometimes happened that Tekken2 fell down after the right figure situation in Figure 11-(b) because of stumbling of the contralateral swinging foreleg. The result of an indoor experiment is shown in Figure 15, where Tekken2 walked down a step 7 (cm) in height with a corrective stepping reflex/response and with a crossed flexor reflex. In Figure 15, each • means $h_{sw \to st}$ of the right foreleg. The right foreleg landed on the lower ground from the upper step at (A), and $h_{sw \to st}$ was already larger than the usual desired height of the toe (-155 (mm)). In such case, the contralateral left foreleg might stumble on the ground in the next swinging phase if the usual desired height of the toe was used. But, by using h^*_{sw} (B), the left foreleg could swing forward while keeping enough clearance of the toe to the ground (C). The crossed flexor reflex helps to satisfy the necessary condition [2].

4 Outdoor Experiments

On natural ground, there existed scattered pebbles and grasses, hollows and slippery surfaces everywhere. With all reflexes and responses described in Section *3.4*, Tekken2 successfully maintained stable walking on several types of natural ground with slopes of 14 (deg) at most in pitch inclination and 6 (deg) at most in roll inclination, pebbles with a diameter of 30 (mm) at most and scattered fallen leaves. Snapshots of those experiments are shown in Figure 1.

The typical result of outdoor experiments is shown in Figure 16. Tekken2 started walking at 0 (s) and walked with speed of 0.7 (m/s) on average and 0.95 (m/s) speed at most. We can see that the body pitch angle was shifted to negative for 3∼12 (s), where Tekken2 walked up slopes of 10 (deg) on average in pitch inclination. The body roll angle was shifted to positive for 6∼12 (s), where Tekken2 successfully walked over right-inclined slopes of 5 (deg) on average with the sideway stepping reflex. The body was significantly inclined to right for the period (A), which

[11]A "crossed extension reflex" is observed in animals, where a flexion reflex on the stimulated leg causes a extension reflex on the contralateral leg (Gordon 1991). A "crossed flexor reflex" is newly defined by authors.

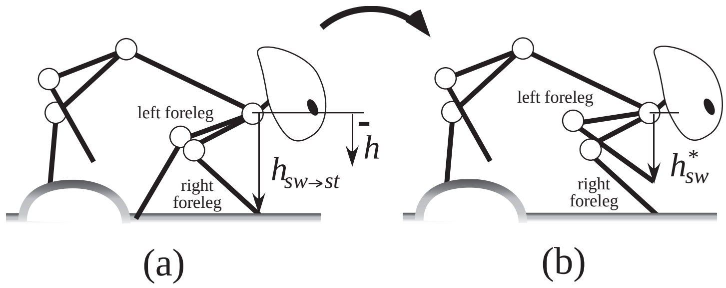

Figure 14: Crossed flexor reflex.

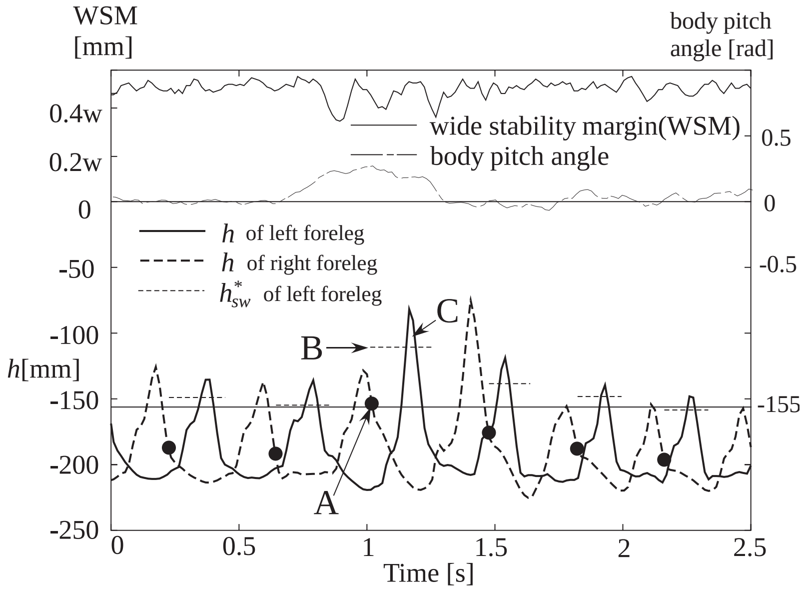

Figure 15: An experiment of walking down a step 7 (cm) in height with a crossed flexor reflex in addition to a corrective stepping reflex/response.

resulted in pitching of the body with 0.2 (rad) amplitude, and WSM became small (0.2w∼0.3w) at worst. We can see on the left foreleg that detection of loss of ground contact (B) activated the corrective stepping reflex (C) and detection of stumbling (D) activated the flexor reflex (E). The corrective stepping reflex was activated also at (F), (G) and (H). The flexor reflex was activated also at (I). We can see on the left foreleg that the crossed flexor reflex was activated at (K), (L) and (M) in order to prevent the leg from stumbling by keeping enough clearance of the toe. But in spite of the crossed flexor reflex, the left foreleg stumbled on the ground and the flexor reflex was activated at (J). This meant that the flexor reflex complemented the crossed flexor reflex for adaptive walking on irregular terrain.

Consequently, we demonstrated that the reflexes and the responses newly developed in this article were effective to prevent Tekken2 from falling down and allowed Tekken2 to maintain stable walking on natural ground.

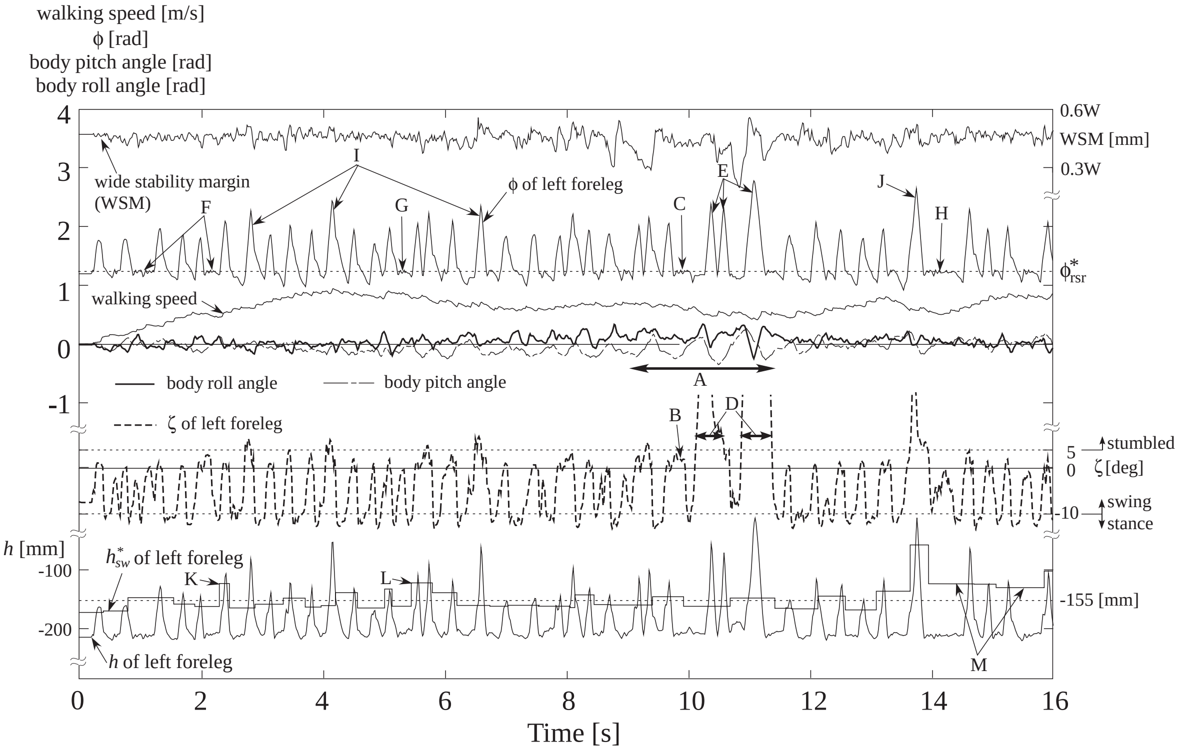

Figure 16: An experiment of walking on natural ground. First 16 seconds of 60 seconds successful walking is shown. Tekken2 changed its walking speed and direction by receiving the operational commands from the radio controller.

5 Discussion

5.1 Not Sufficient But Necessary Conditions

Employing reflexes and responses based on biological concepts means the contribution for the necessary conditions for stable walking to be satisfied. But since those are not sufficient conditions, stable walking cannot be ensured even when those conditions are mostly satisfied by reflexes and responses. What we showed in this study is that the simple combination of CPGs and a set of responses and reflexes is effective on several irregular terrains in spite of adaptation at the spinal cord level. Apparently, additional necessary conditions should be required on more complicated terrain. This means that we might have to develop new reflexes and/or responses. This is the limitation of the method proposed in this study. But such difficulty is an essential feature of the legged locomotion study dealing with infinite variety of terrain irregularity.

5.2 Mechanical System vs Neural System

Since the mechanical system of Tekken2 is well designed as described in Section *2.4*, Tekken2 can move a swinging leg quickly and switch the stance and swing phases in a short time. Therefore, if the cyclic period is short enough, Tekken2 usually never falls down on indoor flat floor with PD-control at joints and without responses[12] and reflexes. This means that Tekken2 can walk stably on flat floor mainly by the grace of the well designed mechanical system and the role of the neural system is not important. However, when the cyclic period becomes long, Tekken2 needs the tonic stretch and labyrinthine responses to walk stably for the reasons described in Section *2.3*. In dynamic walking on irregular terrain, responses and reflexes described in Section *3.4* are essential, and become effective on the well designed mechanics as shown in this study.

In the neural system model proposed in this article, the relationships among CPGs, sensory input, reflexes and the mechanical system were simply defined, and motion generation and adaptation were emergingly induced by the coupled dynamics of a neural system and a mechanical system by interacting with the environment. We had already discussed the meanings of coupled-dynamics-based motion generation and how to design a neural system taking into account the dynamics of a mechanical system in our previous article (Fukuoka *et al* 2003a).

Actually, the mechanical design concepts described in Section *2.4* were also based on biological concepts, even though we don't show references to corresponding biomechanics studies. Let the integration of biological concepts on both mechanics and control be our challenge in future.

6 Conclusion

In this study, we designed a neural system consisting of CPGs, responses, and reflexes with reference to biological concepts while taking the necessary conditions for adaptive walking into account. In order to make the self-contained quadruped robot:Tekken2 walk in outdoor natural environment, we newly developed a flexor reflex, a sideway stepping reflex, a corrective stepping reflex/response, and a crossed flexor reflex in addition to reflexes and responses developed in Tekken1. The effectiveness of those newly developed reflexes and responses was validated by indoor and outdoor experiments using Tekken2. In order to increase the degrees of terrain irregularity which Tekken2 can cope with, we will have to develop additional reflexes and responses, and also adaptation at the higher level using vision (Fukuoka *et al* 2003b).

As the next study for the platform of future service robots, we are developing "Tekken3 & 4" with navigation ability using vision (Kimura *et al* 2005). Recently, Boston Dynamics (2005) also realized dynamic walking of a self-contained quadruped robot "BigDog" equipped with a gasoline engine and hydraulic actuators in outdoor environment, even though technical details have not yet been published as far as authors know. The studies of Tekken series and BigDog show that the engineering technologies for quadrupedal locomotion is getting closer to the practical level.

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