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

Abstract

The paper reports on a project to make a quadruped robot walk with medium forward speed on irregular terrain in an outdoor environment using a neural system model. The necessary conditions for stable dynamic walking on irregular terrain in general are proposed, and the neural system is designed by comparing biological concepts with those necessary conditions described in physical terms. A PD-controller is used at joints to construct a 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, several new reflexes and responses are developed in addition to those developed in previous studies. A flexor reflex prevents a leg from stumbling on small bumps and pebbles. A sideways stepping reflex stabilizes rolling motion on a sideways inclined slope. A corrective stepping reflex/response prevents the robot from falling down in the case of loss of ground contact. A crossed flexor reflex helps a swinging leg keep enough clearance between the toe and the ground. The effectiveness of the proposed neural system model control and especially the newly developed reflexes and responses are validated 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 the other legs is maintained autonomously. 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.

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

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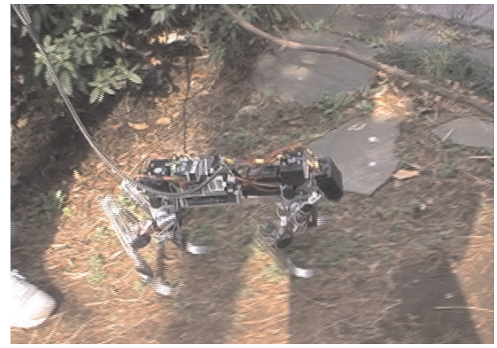
1. Introduction

Most studies on legged robots have been biologically inspired to some extent in mechanical design, control, navigation and so on. In particular, dynamic walking and running of animals and humans, rather than static walking, was investigated by several robotics researchers in the 1980s (Miura and Shimoyama 1984; Raibert 1986; Kimura et al. 1990; Sano and Furusho 1990). In the 1990s, several studies on running (Hodgins and Raibert 1991), and dynamic walking of biped robots (Yamaguchi et al. 1994; Kajita and Tani 1996; Hirai et al. 1998; Chew et al. 1999; Yokoi et al. 2004) and quadruped robots (Yoneda et al. 1994; Buehler et al. 1998) on irregular terrain were carried out. However, most of these studies assumed that the structure of the terrain was known, even though the height

(a)



(b)

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

of the step or the inclination of the slope was unknown. Since 2000, several hexapod robots (Saranli et al. 2001; Quinn et al. 2001; Cham et al. 2004) have 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 an outdoor environment with little knowledge about the 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 the biological studies of motion control have progressed, it has become generally accepted that animal 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 in this area attempted to generate walking using a neural system model, including simulation studies of dynamic walking (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 et al. 2001; Lewis et al. 2003). But autonomously adaptive dynamic walking on irregular terrain was rarely realized in those earlier studies except for studies using quadruped robots called "Patrush" (Kimura et al. 1999, 2001) and "Tekken1" (Fukuoka et al. 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 the mechanical and neural systems of Tekken2 (Kimura and Fukuoka 2004). In that report, it was mentioned that there existed a slope of 3 degrees 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 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 for 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 is maintained autonomously. 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.

2. Considerations for Adaptive Walking

Before design and implementation of the neural system model, we 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) stated that two general methods are available to maintain stability during legged locomotion. These 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]

Method [a] is very popular in several legged locomotion studies (Kajita and Tani 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 running speed can be stabilized using the constant touchdown angle, self-stabilization of the musculo-skeletal system in running (Full and Koditschek 1999; Seyfarth et al. 2002; Cham et al. 2004; Hackert et al. 2006; Poulakakis et al. 2006) is also involved in [b].

As an example 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 method [c] to stabilize the running of a hexapod and a quadruped, respectively, on irregular terrain.

Of course, these three methods are not completely independent. For example, 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 a 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 phase (Figure 2).

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

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

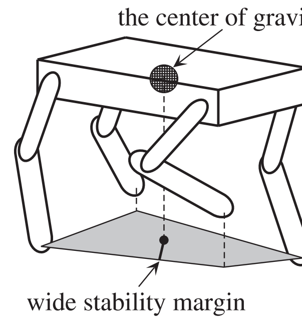


Fig. 2. Definition of the wide stability margin.

2.3 Necessary Conditions for Stable Dynamic Walking on Irregular Terrain

We proposed the necessary conditions to keep the limit cycle for stable dynamic walking on irregular terrain[2] in a 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]–[6] again for completeness:

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

[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,

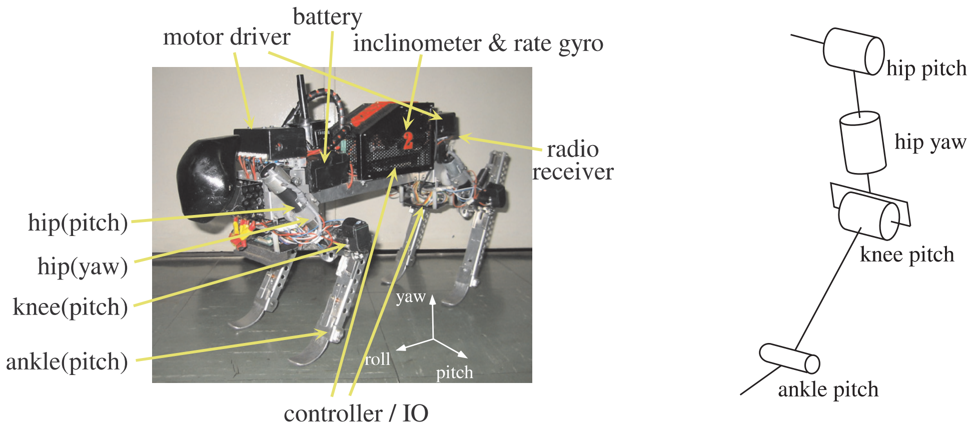
[4] the angular momentum of the robot during its pitching motion or rolling motion around the contact points should be kept constant at the moment legs land or leave,

[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.

Regarding 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 less stable mainly for the following reasons:

2. It should be noted that these conditions are not sufficient, but necessary conditions. Therefore, stable walking cannot be ensured with these conditions. When one of these 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.



(a) (b)

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

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

In order to make Tekken2 walk with longer cyclic periods (slower step rates), we need to use a walk gait[5] and larger duty factors to decrease the period in which an inverted pendulum appears. However, we consider walking with a 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 a neural system consisting of CPGs, responses and reflexes to satisfy these necessary conditions in order to realize adaptive walking with 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 must be well designed to have good dynamic properties (i.e. small moment of inertia, low friction, high backdrivability and so on). In addition, the performance of dynamic walking, such as adaptability on irregular terrain, energy efficiency, maximum speed and so on, strongly depend 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 contact area at toes to increase adaptability on irregular terrain.

Tekken2 has the same configuration as Tekken1 except 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 ratios of 20, 28 and 18, respectively. The ankle joint is passive with a spring-lock mechanism (Figure 4). The walking direction can be changed 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 as 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 the stance phase, we can detect the contact of a leg with the floor using 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

3. For example, in the Tekken2 trot gait, a rolling motion is naturally generated although Tekken2 has no joint around the roll axis. A long cyclic period makes the amplitude of this rolling motion larger and WSM smaller.
4. Exchanging of supporting legs and swinging legs (i.e. phase switching) reduces the influence of disturbances in a step cycle in the next step cycle (Miura and Shimoyama 1984).
5. Diagonal legs and lateral legs are paired and move together in a trot gait and a pace gait, respectively. A walk gait is a transversal gait between the trot and pace gaits.

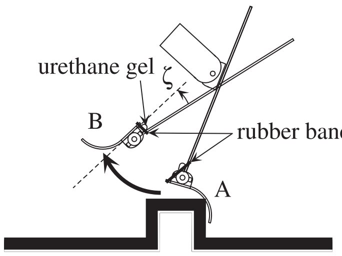


Fig. 4. Passive ankle joint mechanism. A leg stumbling on an obstacle at A, and the leg passively prevented from stumbling at B.

($\zeta \leq -10$ degrees), swing in the air ($-10 < \zeta \leq 5$ degrees) and stumble on an obstacle ($\zeta > 5$ degrees). 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 Tekken2 neural system (the middle part of Figure 5) is the same as that of Tekken1. Since we had already described a neural system consisting of CPGs and virtual spring–damper system in a 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 the earlier article.

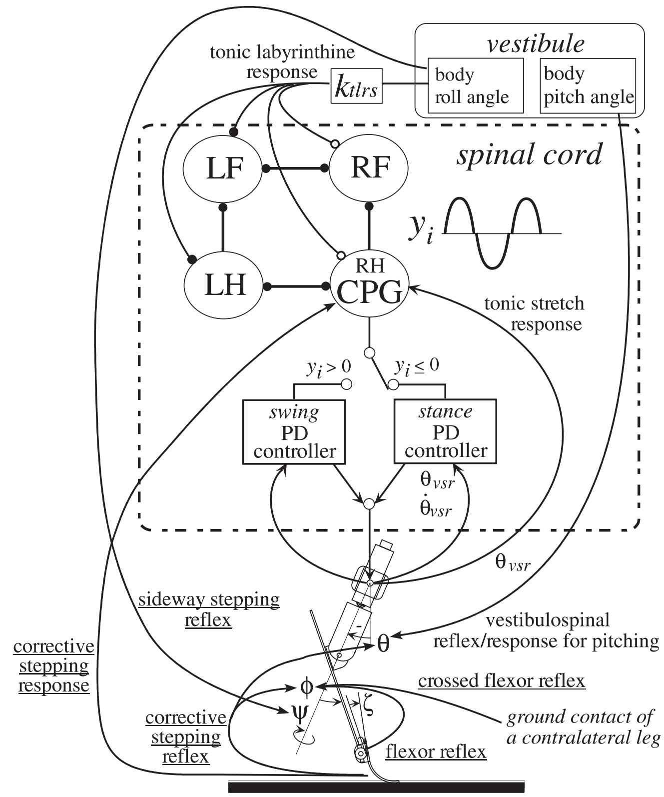


Fig. 5. Control diagram for Tekken2. PD-controls at the hip yaw and knee pitch joints are eliminated in this figure. The names of newly developed reflexes and responses are underlined.

3.1 Rhythmic Motion by CPG

We construct the neural system based on 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:

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

where the suffix e, f, and i denote an extensor neuron, a flexor neuron, and the ith 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 ith 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 ith and jth 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.

$$y_i = -y_{ei} + y_{fi} \qquad (2)$$

A 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 stability and 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 when 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 experiments, we used a trot gait.[7]

3.2 Virtual Spring–Damper System

We employ a 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 the stance phase to support a body against gravity, and low in the 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)
- $B \rightarrow C$: when the CPG extensor neuron of the leg becomes active ($y \leq 0$)
- $C \rightarrow A$: when the CPG flexor neuron of the leg becomes active ($y > 0$)

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

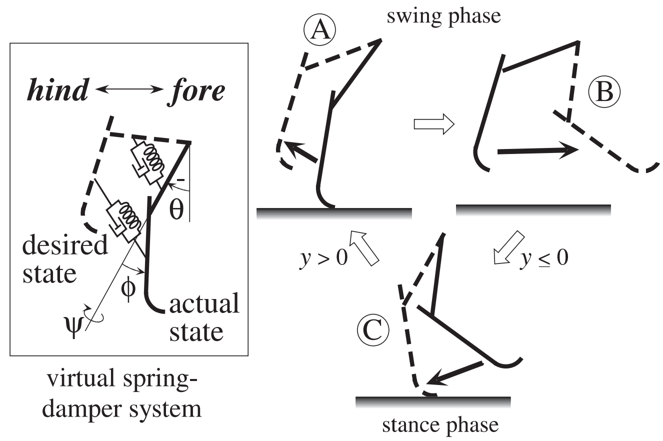


Fig. 6. State transition in the virtual spring–damper system. The desired joint angles in each state are shown by the broken lines.

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. ($\theta_{C \rightarrow A}$: 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 to make the height from the hip joint to the toe 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	$1.2\theta_{C \rightarrow A}$	G_1
θ in B	θ^*_{sw}	G_2v+G_3
θ in C	θ^*_{st}+ body pitch angle	$-G_4$v+G_5
ϕ in A & B	ϕ^*_{sw}	G_6
ϕ in C	ϕ^*_{st}	G_7
ψ in all states	ψ^*	G_8

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

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

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 walking speed by changing the P-gain of the hip pitch joint in the stance phase (G_5 in Table 1).

Table 2. Values of the parameters used in experiments on Tekken2. The value of τ is typical, and actual values are 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

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 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 the neural oscillator in Eq. (1) and Eq. (4) for Tekken2 were exactly the same as those for Tekken1 except for θ_0 in spite of the differences (approx. 25%) in size and weight. Thus, the parameters of the neural oscillator are not highly sensitive in terms of the generation of rhythmic leg motions. The sensitivity and robustness of parameters in reflexes and responses were discussed in our previous article (Fukuoka and Kimura 2003).

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 the legs (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, sideways 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 were developed in Tekken1, and described in a previous article (Fukuoka et al. 2003a). A tonic labyrinthine response[9] (rolling motion feedback to CPGs) is particularly important for mutual entrainment among CPGs, pitching motions of legs and rolling motion of the body. Such entrainment stabilized the walking gait and increased adaptability on irregular terrain (Fukuoka et al. 2003a).

Regarding the names of reflexes, Espenschied et al. (1996) employed the swaying, elevator, stepping and searching reflexes observed by Pearson and Franklin (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 satisfying the necessary condition [2].

In Tekken1, we substituted the flexor reflex for the passive ankle joint mechanism with spring and lock (Figure 4) utilizing the fact that 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 suitable in an outdoor environment because of stumbling on small bumps and pebbles, and stumbling due to high friction on rough surfaces. We therefore activate a flexor reflex at the knee joint by

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

Table 3. Reflexes and responses developed on Tekken2. (sp and sw denote 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]
sideways 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]

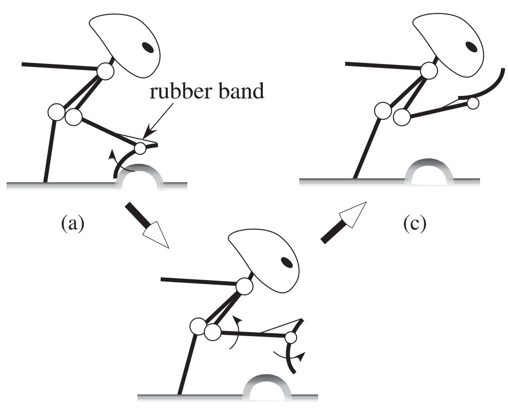


Fig. 7. Flexor reflex activated on stumbling.

using the following ϕ^*_{fr} instead of ϕ^*_{sw} in Table 1 in order to flex the knee joint (Figure 7(b)) when stumbling is detected ($\zeta > 5$ degrees, 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 the stumbling condition (Figure 7(c)), the passive ankle joint moves to the initial angle ($\zeta \simeq 0$ degrees) due to the elasticity (32 N/m) of the included rubber, and ϕ^*_{sw} in Table 1 is used for the desired angle in the PD controller.

The result of an indoor experiment is shown in Figure 8. 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 ($0.4w$–$0.5w$) while walking over a step.

3.4.2 Sideways stepping reflex to stabilize rolling motion

It is known that the adjustment of the sideways 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 "sideways stepping reflex," which helps to satisfy the necessary condition [4] during rolling motion. The sideways stepping reflex is effective also in walking on a sideways inclined slope.

For example, when Tekken2 walks on a right-inclined slope (Figure 9), Tekken2 continues to walk while maintaining 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 in the gravity load between left and right legs. In addition, Tekken2 typically falls down to the right for a perturbation from the left in the case of Figure 9(a), since WSM is small. The sideways stepping reflex helps to stabilize the walking direction and to prevent the robot from falling down while keeping WSM large on a sideways inclined slope (Figure 9(b)).

Since Tekken2 has no joint round the roll axis, the sideways stepping reflex is implemented as a change in 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 a 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 sideways stepping reflex in the swing phase on the slope. On the other hand, the hip yaw joint of the

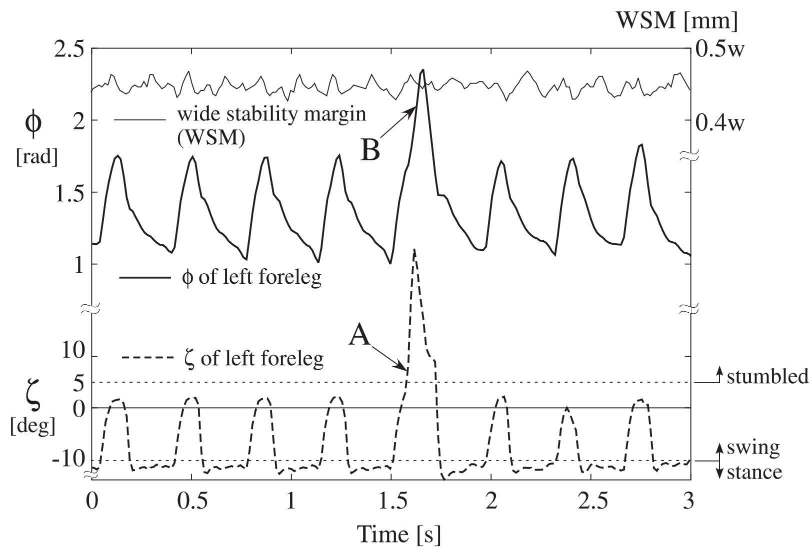


Fig. 8. An experiment in walking over a step 2 cm in height with a flexor reflex. We use degrees only for ζ in this article.

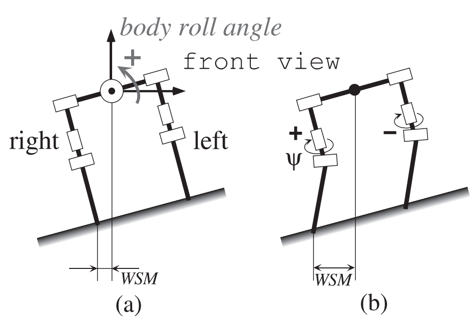


Fig. 9. Walking on a sideways inclined slope without a sideways stepping reflex (a) and with the reflex (b).

left foreleg moved to the inside of the body (right) by -0.06 to -0.02 rad (E) due to the sideways stepping reflex in the swing phase on the slope. Consequently, Tekken2 succeeded in straight walking on a sideways 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 a more forward position and to extend the swing phase (Hiebert et al. 1994). We call this a "corrective stepping reflex/response," which is effective for the necessary conditions [3] and [4] to be satisfied when 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 the normal case.

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

If leg contact with the ground is not detected ($\zeta > -10$ degrees) 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 $\phi \leq \phi^*_{csr}$), then corrective stepping reflex and response against loss of ground contact are activated on the leg. For the corrective stepping reflex, the hip and knee joints are PD controlled to the desired angles, θ^*_{csr} and ϕ^*_{csr}, respectively.[10] For the corrective stepping 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.

$$u^*_{csr} = u_0 \times 2. \quad (9)$$

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 a forward position of

10. The desired angles can be adjusted according to increased walking speed and step height if these values are measured in future.

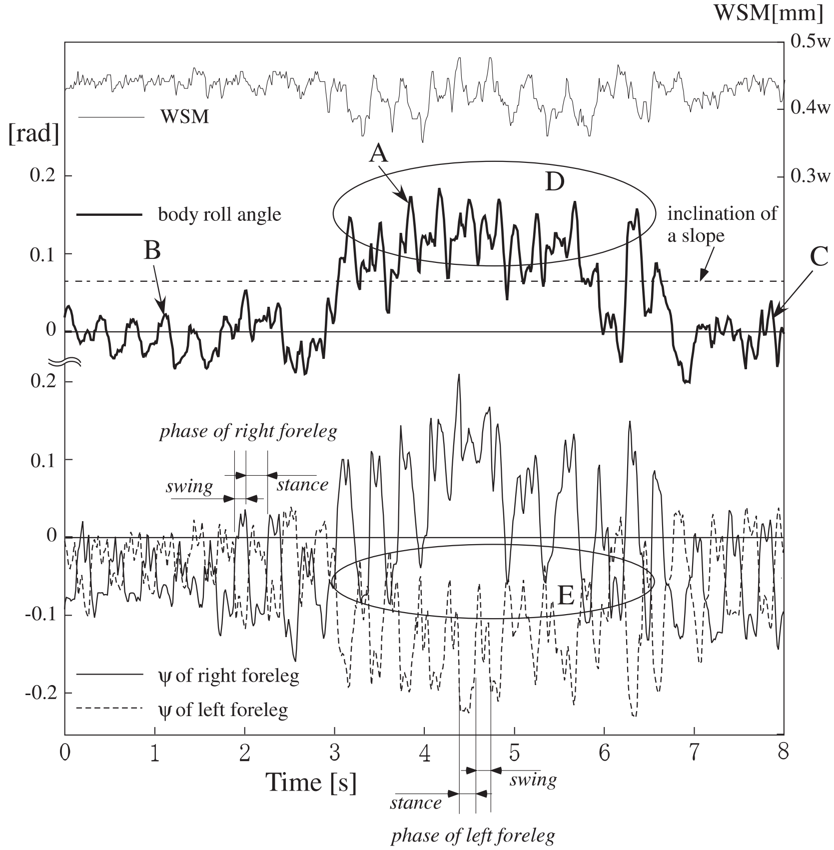


Fig. 10. An experiment in walking on a right-inclined slope of 0.07 rad (4 degrees) with a sideways stepping reflex.

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 increase due to 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 on the leg (Figure 14(a)). In such cases, in order to prevent the contralateral leg from stumbling when 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.

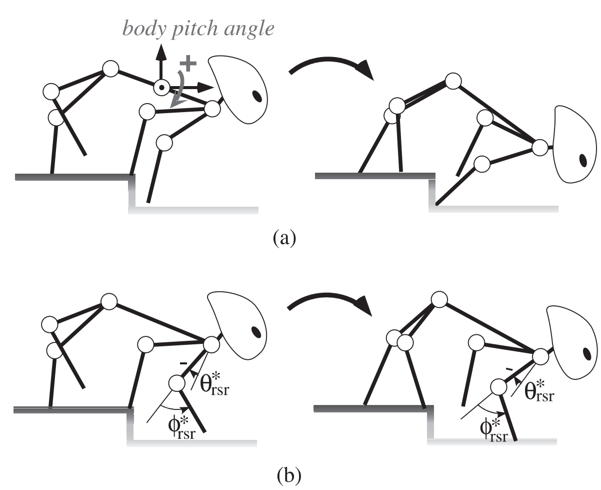


Fig. 11. Walking down a step (a) without corrective stepping and (b) with corrective stepping.

In Figure 14, the height of a supporting leg from the hip joint to the toe is measured at the landing moment ($h_{sw\rightarrow st}$).

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

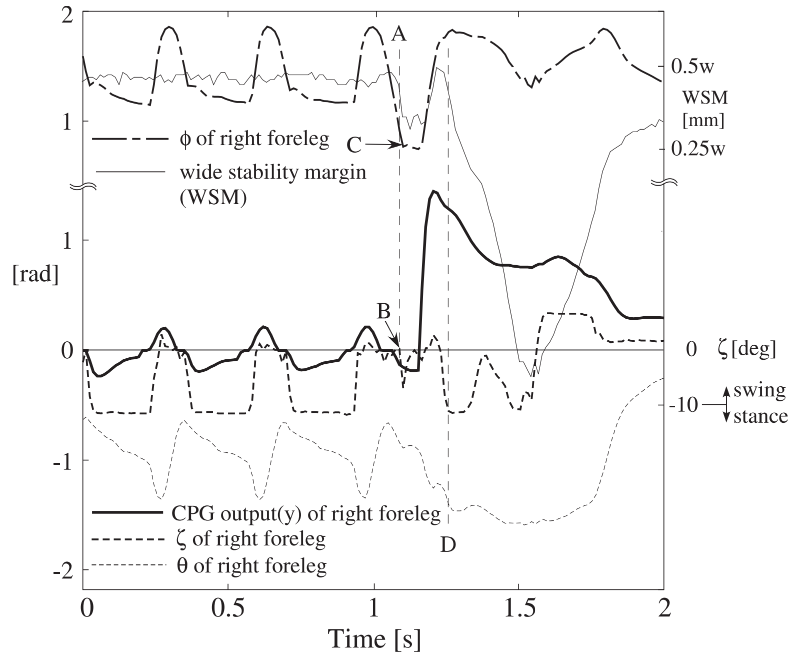


Fig. 12. An experiment of walking down a step 7 cm in height without a corrective stepping reflex/response.

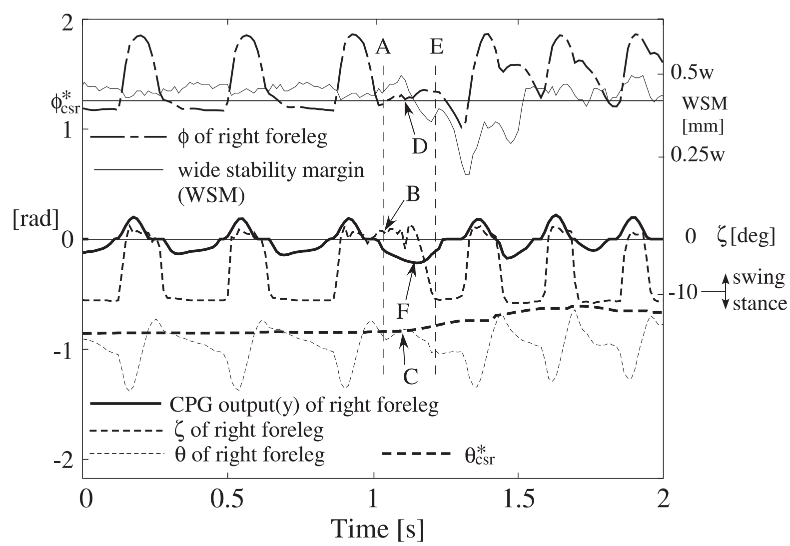


Fig. 13. An experiment of walking down a step 7 cm in height with a corrective stepping reflex/response.

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}.

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

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 as in the situation shown 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 $h_{sw\rightarrow st}$ of the right foreleg. The right foreleg landed on the lower ground from the upper step at (A), and $h_{sw\rightarrow st}$ was already larger than the usual desired height of the toe (-155 mm). In

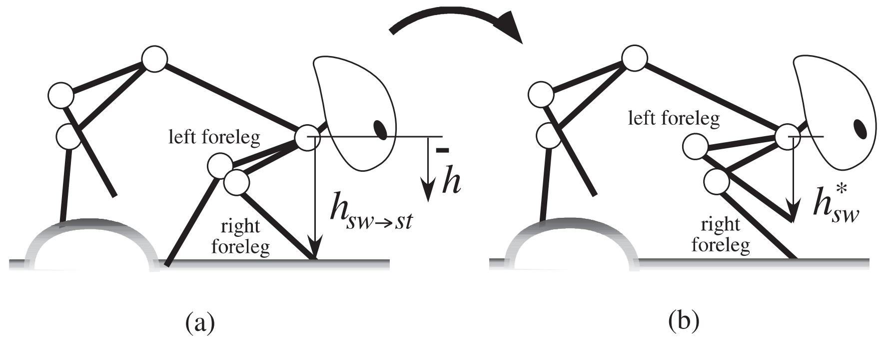


Fig. 14. Crossed flexor reflex.

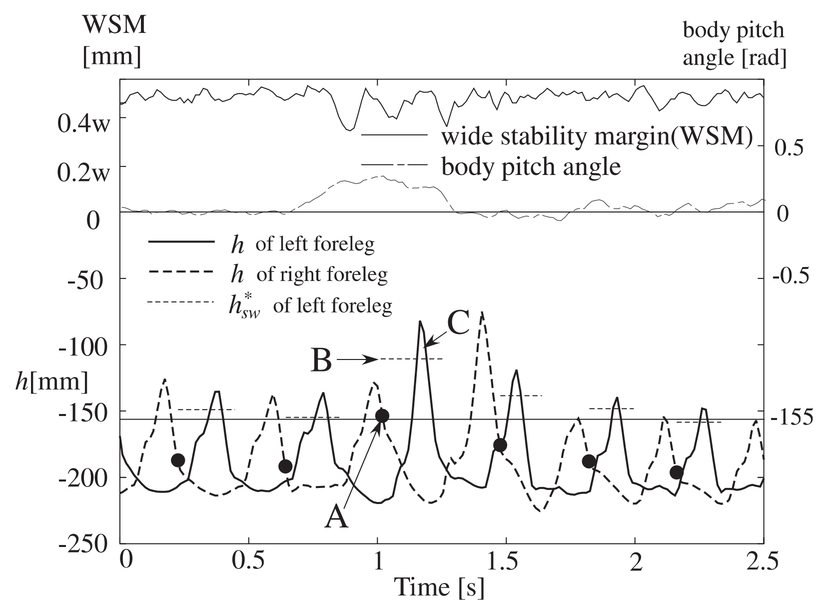


Fig. 15. An experiment in walking down a step 7 cm in height with a crossed flexor reflex in addition to a corrective stepping reflex/response.

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 between the toe and the ground (C). The crossed flexor reflex helps to satisfy the necessary condition [2].

4. Outdoor Experiments

Natural ground was selected containing scattered pebbles and grasses, hollows and slippery surfaces. With all reflexes and responses described in Section 3.4, Tekken2 successfully maintained stable walking on several types of natural ground with slopes up to 14 degrees pitch inclination and up to 6 degrees roll inclination, on pebbles with diameters up to 30 mm and on scattered fallen leaves. Snapshots of the experiments are shown in Figure 1.

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

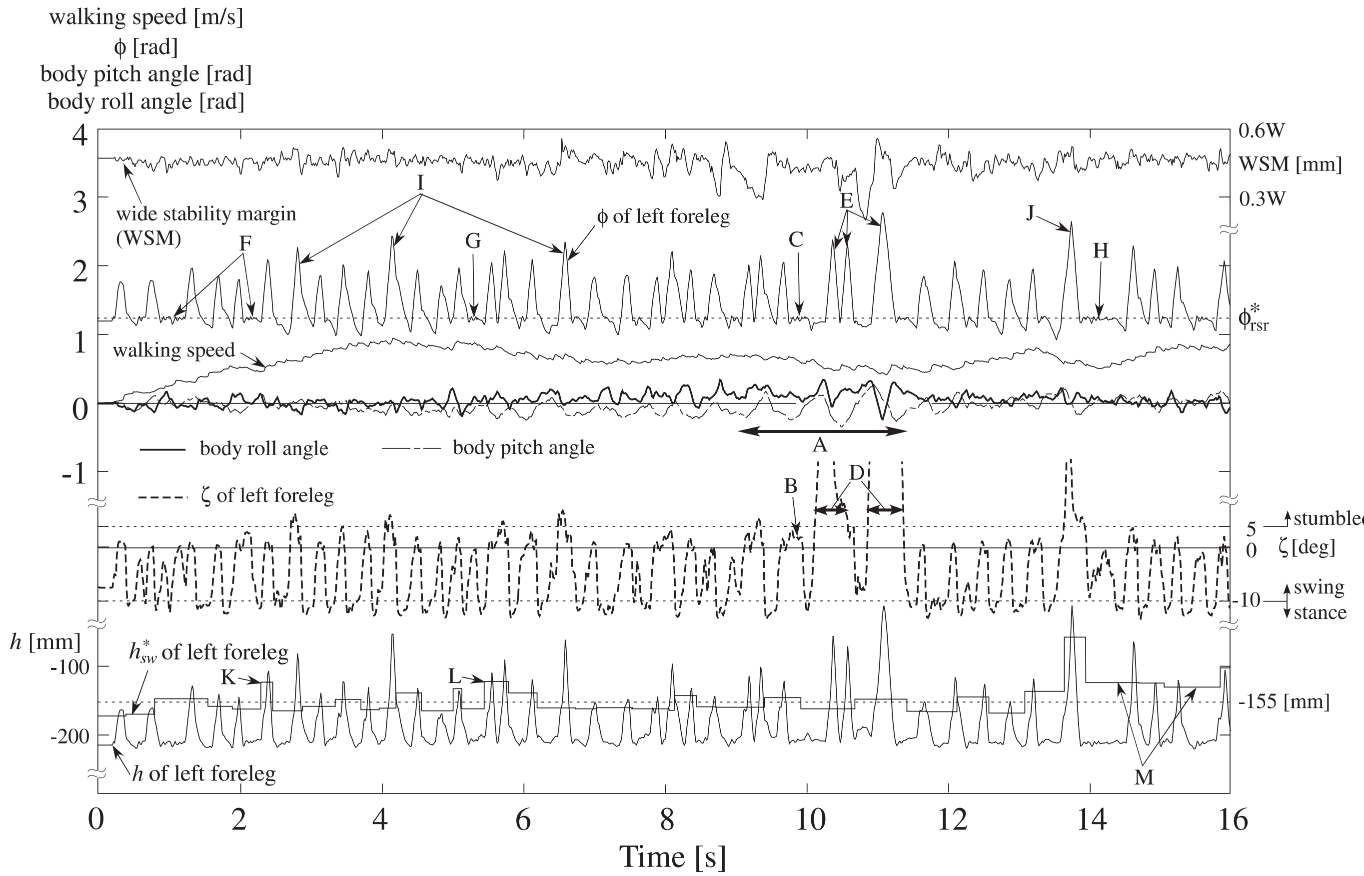


Fig. 16. An experiment of walking on natural ground: first 16 seconds of 60 seconds successful walking is shown. Tekken2 changed its walking speed and direction by receiving operational commands from the radio controller.

tact (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 sufficient ground–toe clearance. 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 proposed reflexes and responses were effective in preventing Tekken2 from falling down, and allowed Tekken2 to maintain stable walking on natural ground.

5. Discussion

5.1 Not Sufficient But Necessary Conditions

Employing reflexes and responses based on biological concepts means that the necessary conditions for stable walking have to be satisfied. But since these are not sufficient conditions, stable walking cannot be ensured even when these conditions are generally satisfied by reflexes and responses. What we have shown 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. Additional necessary conditions will be be required on more complicated terrain. This means that we might have to develop new reflexes and/or responses. This is a limitation of the method proposed in this study, but such difficulties are an essential feature of legged locomotion study dealing with an infinite variety of terrain irregularities.

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 can switch between stance and swing phases in a short time. Therefore, if the cyclic period is short enough, Tekken2 usually never falls down on an indoor flat floor with PD-control of the joints and without responses[12] and reflexes. This means that Tekken2 can walk stably on a flat floor mainly as a result 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, the 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, the relationships among CPGs, sensory input, reflexes and the mechanical system were simply defined, and motion generation and adaptation were induced by the coupled dynamics of the neural system and mechanical system by interacting with the environment. We 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 a previous article (Fukuoka et al. 2003a).

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

6. Conclusions

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 environments, we developed a flexor reflex, a sideways stepping reflex, a corrective stepping reflex/response, and a crossed flexor reflex in addition to reflexes and responses developed for Tekken1. The effectiveness of the 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 a 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 in an outdoor environment of a self-contained quadruped robot "BigDog" equipped with a gasoline engine and hydraulic actuators. Technical details have not yet been published as far as is known. The studies of the Tekken series and BigDog show that the engineering technologies for quadrupedal locomotion is getting closer to the practical level.

12. In this case, CPG acts simply as a clock.

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