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Dynamic locomotion of a biomorphic quadruped 'Tekken' robot using various gaits: walk, trot, free-gait and bound

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Numerous quadruped walking and running robots have been developed to date. Each robot walks by means of a crawl, walk, trot or pace gait, or runs by means of a bound and/or gallop gait. However, it is very difficult to design a single robot that can both walk and run because of problems related to mechanisms and control. In response to this, we adapted a biological control method for legged locomotion in order to develop a dog-like quadruped robot we have named 'Tekken'. Tekken has a control system that incorporates central pattern generators, reflexes and responses as well as a mechanism that makes the most of the control system. Tekken, which is equipped with a single mechanism, an unchangeable control method, and modifiable parameters, is capable of achieving walking and trotting on flat terrain, can walk using a free gait on irregular terrain, and is capable of running on flat terrain using a bounding gait. In this paper, we describe the mechanism, the control method and the experimental results of our new development.

Keywords: quadruped robot; dynamic walking; running; legged locomotion gait; central pattern generator

1. Introduction

A large number of quadruped walking robots (Hirose 1984; Kimura et al. 1990; Sano and Furusho 1990; Berns et al. 1999; Kimura et al. 1999; Tsujita et al. 2005) and running robots (Kimura et al. 1999; Raibert 1986; Poulakakis et al. 2005; Zhang et al. 2006) have been developed, but it is difficult to design a single quadruped robot that is capable of both walking and running. This is because, for the most part, walking and running require different control methods and mechanisms.

In human beings, the part of the brain that coordinates posture is very active when we walk at low speeds. Thus, to mimic this behaviour, many robots employ Zero Moment Point (ZMP) based control, which emphasises walking stability. Such robots are equipped with reduction gears that have high gear reduction ratios in order to reduce the control errors and to consider energy efficiency. However, such reduction gears often generate a great deal of friction. This means that the joints of such robots do not have back-drivability. Without that ability, it is difficult for robots with such joints to handle the high-speed impacts incurred when walking and running. However, there are some benefits of such designs. Of them is the fact that these robots can support their own weight without output to their actuators simply by locking their joints in place. Thus, we can state that legged robots equipped with these control methods and mechanisms are suitable for walking at low speed.

On the other hand, Full and Koditschek (1999) also pointed out that kinetic energy is dominant during running and self-stabilisation by means of a mechanical compliance quadruped robot: Raibert's robot (Raibert 1986), Scout II (Poulakakis et al. 2005), and Patrush (Kimura et al. 1999) among others are capable of running using mechanically compliant legs and a simple control method. Such robots also have flexible joints capable of absorbing shock.

As can be understood from the above, since walking and running robots utilise very different control methods and mechanisms, it would appear to be difficult to design a single robot capable of both walking and running.

In response to that challenge, we have been engaged in the development of a dog-like quadruped robot known as 'Tekken', which is capable of walking at low and medium speeds and running. Tekken utilises a simple walking control method, which refers to a biological neural system for locomotion, and succeeds in dynamic walking flexibly with stability on unmeasured irregular terrains such as steps, slopes and so on. Thus, we emphasise that Tekken is capable of dynamic walking, by means of the simple control method as based on a neural system. In this paper, moreover, based on the same concept, we construct a simple control

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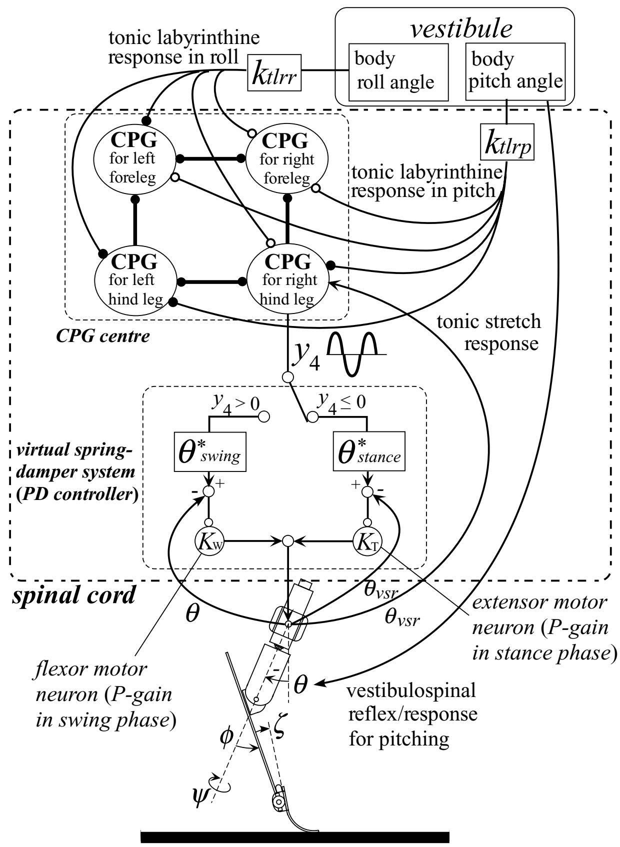

Figure 1. Control diagram for Tekken. This figure shows the local control system of the right hind leg below its CPG.

method to achieve Tekken's running with exactly the same mechanism as Tekken's mechanism for walking.

A control diagram based on a neural system model for the Tekken series is shown in Figure 1. After referring to Full's view (Full and Koditschek 1999) and Kimura's experimental results (Kimura et al. 1999), it was decided that each of Tekken's legs would be equipped with a generator capable of mimicking biological rhythms, known as a central pattern generator (CPG), which is an effective motion generation and control system for middle- and high-speed legged locomotion. During operation, each of the CPGs in each leg switches between the swing and stance phases in order to generate locomotion rhythm (Section 3.1.). We also constructed local PD controllers, which are installed below the CPG in each leg yet operate independently of the other legs, in order to mimic spinal reflexes and muscles viscoelasticity. We call this control method 'biologically inspired control'. Using biologically inspired control, we can switch easily between walking and running by changing the control method parameters. This demonstrates that it is a control method that can be utilised for both walking and running. The PD controller is referred as a virtual spring-damper system (Section 3.4.). When the P-gain is small, the robot absorbs shock from the ground during walking and achieves dynamic walking on the irregular terrain. On the other hand, when the P-gain becomes very large, the robot obtains the high-compliance level required for running and succeeds in bounding along flat terrain. In order to make the virtual spring of the virtual spring-damper system worked as an actual spring, all of Tekken's leg joints consist of spar gears with low reduction ratios and have large back-drivability. This means that it is a suitable mechanism for reducing the disturbance caused by walking on irregular terrain as well as to self-stabilise when running.

In this research, we achieved dynamic walking and running with Tekken, which utilises a single mechanism and a control method that can self adjust its parameters by means of a biologically inspired control and the flexible mechanism that provides back-drivability. Specifically, Tekken accomplishes various locomotion gaits such as 'walk' and 'trot' at less than 1.0 m/s on flat terrain. It can accomplish 'free gait' on irregular terrain at less than 1.0 m/s, and 'bound' gait at 0.9 to 1.1 m/s. MPEG footage of these experiments can be seen at: *http://fukuoka.ise.ibaraki.ac.jp/index-english.html*.

We heuristically fix the parameters of equations in this paper, but Tekken does not have many parameters. The purpose of our research is to propose a simple control method with a small number of parameters, capable of adjusting to various situations of locomotion, and demonstrate the effectiveness by a quadrupedal robot. Especially in terms of dynamic walking of a small walking robot like Tekken, which mimics small animals, it is very difficult for such a robot to precisely adjust the leg trajectories online within every short walking cyclic period. However, the construction of the control system, which properly utilises CPGs, reflexes and responses, makes the walking gaits autonomously adjusted by the CPGs in various walking situations. Further to this, Tekken is capable of adapting autonomously to changeable walking speeds and terrains without noticeable trajectory adjustment. Moreover, in this paper, we demonstrate that it is capable of utilising the control method also in high-speed bounding.

2. Mechanism

A photograph and a leg structure of Tekken are shown in Figure 2. The length of the body and each leg when standing are 28 cm and 22 cm, respectively. The entire weight of the leg (except for peripheral devices such as PC, motor drivers, power source, etc.) is 3.1 kg. Each leg is equipped with the same mechanism. The hip pitch joint, knee pitch joint and hip yaw joint are activated by DC motors with power consumptions of 20, 20 and 5 W, respectively. The ankle joint is not motorised. Instead, it is equipped with spring lock mechanism (Fukuoka et al. 2003). The robot's walking direction can be changed by means of the hip yaw joints. Every joint angle is measured by a photo encoder or potentiometer and walking velocity is calculated using

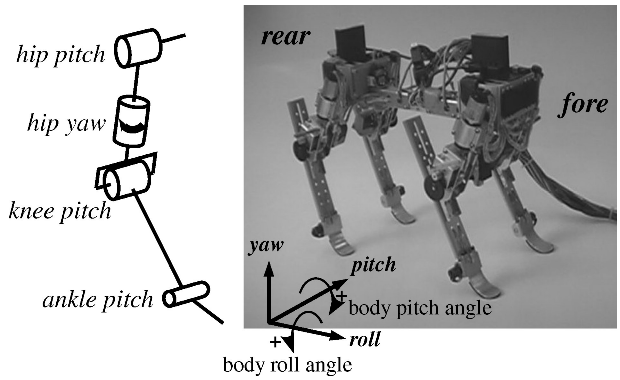

Figure 2. Tekken.

hip joint angular velocity of the supporting legs. Two rate gyros and two inclinometers are mounted on the body in order to measure body pitch and roll angles. The gear reduction ratios of the hip pitch joint and hip knee pitch joint are 15.6 and 18.8, respectively. Since these ratios are very small, each joint has back-drivability. As a result, the virtual spring-damper system is especially useful during sagittal plane motion. Simple drawings and the specifications of the Tekken devices are shown in our previous paper (Fukuoka et al. 2003).

3. Biologically inspired control

An unchangeable control method, except for the parameters between walking and running is utilised. We employ neural oscillators to serve as CPGs as shown in Figure 1. Each leg was equipped with a neural oscillator that is designed to issue a switching command between swing and stance phase to the lower system, which consists of the virtual spring-damper system (local PD controller). Furthermore, by connecting the neural oscillator of each leg, it is possible to autonomously modify the rhythm of each leg in order to make four-legged locomotion gaits suitable for a walking situation, including autonomous gait transitions (Section 4.) and autonomous adaptations to walking on irregular terrain (Section 5.).

The value of the parameters of equations used in experiments in this paper is shown in Appendix (Tables 2, and 3), because those parameters are different between walking and running.

3.1. Rhythmic motion by a neural oscillator

Although the actual neurons that act as a CPG in higher animals have not yet become well understood, the features of a CPG have been actively studied in biology, physiology and in other areas (Pearson 1976). Furthermore, several mathematical models have been proposed, and it has been pointed out that a CPG is capable of generating and modulating walking patterns while being mutually entrained with a rhythmic joint motion (Grillner 1981). As a CPG model, we used a neural oscillator proposed by Matsuoka (1987) and applied it to the biped simulation proposed by Taga et al. (1991). A single neural oscillator consists of two mutually inhibiting neurons. Each neuron in this model is represented by the following non-linear differential equations:

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

where the suffix e, f, and i mean an extensor neuron, a flexor neuron, and the ith neural oscillator, 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 neural oscillator; $v_{\{e,f\}i}$ 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; 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_{fe} is a connecting weight between flexor and extensor neurons; w_{ij} is a connecting weight between neurons of the ith and jth neural oscillator.

The output of a neural oscillator is a phase signal y_i.

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

The positive or negative value of y_i corresponds to activity of a flexor or extensor neuron, respectively (Figure 1).

3.2. Legged locomotion gait produced by neural oscillator network

By connecting the neural oscillator of each leg as shown in Figure 1, neural oscillators are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the neural oscillators of the legs results in a legged locomotion gait. A gait refers to a walking or running pattern, the walking gaits (walk, trot and free-gait) and running gait (bound) are produced by the neural oscillator network in Figure 3(a), (b), respectively. The gait can be defined by the phase differences between the legs during their pitching motion. Tekken employs four basic gaits as follows:

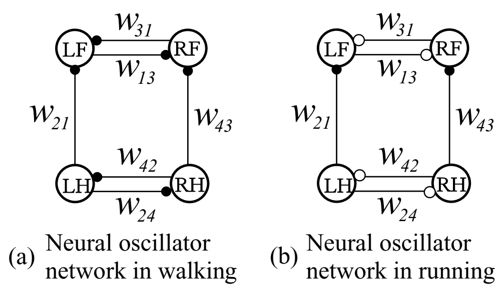

Figure 3. Neural oscillator networks in walking (the walk, trot and free-gait) (a) and running (the bound) (b) for Tekken. The parameters w_{ij} is in Equation (1). The suffix i, j = 1,2,3,4 corresponds to LF, LH, RF, RH. L, R, F and H means the left, right, fore and hind leg, respectively.

- The primary walking gait of Tekken produced shown in Figure 3 (a) is the middle-speed trot gait. When trotting, an animal moves its legs in unison in diagonal pairs.
- The trot gait autonomously shifts to the walk gait with body oscillation around the roll axis when the pace slows. When walking, a four-legged animal will always have one foot raised and the other three feet on the ground (Section 4).
- When walking on irregular terrain, the gait shifts to free-gait autonomously in order to adapt to disturbances to the oscillation of the body and legs (Section 5).
- Tekken runs at high speed using the bound gait by changing the neural oscillator network as shown in Figure 3 (b). Using the bound gait, a four-legged animal moves its legs in unison in lateral pairs (Section 6).

3.3. Feedbacks to neural oscillators

We use the following hip joint angle feedback, called 'tonic stretch response' (Figure 1), (see Equations (4) and (5)) as a basic sensory input to a CPG (neural oscillator). k_{tsr} is a feedback gain. θ_{vsr} is adjusted in Equation (3) by (body pitch angle), which is the body inclination around pitch axis and the orientation as shown in Figure 2. We call the reflex of see Equation (3) 'vestibulospinal reflex for pitching' (Figure 1). θ is the measured hip joint angle, θ_0 is the origin point of the hip joint angle when standing. This negative feedback entrains a neural oscillator with a rhythmic hip joint motion. We eliminate the suffix i when we refer to a single neural oscillator.

$$\theta_{vsr} = \theta - (\text{body pitch angle})\,, \tag{3}$$

$$Feed_{e \cdot tsr \cdot vsr} = k_{tsr}(\theta_{vsr} - \theta_0)\,, \tag{4}$$

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

A rolling motion is naturally generated in walking gaits. The change of the phase difference between the rolling motion of the body and pitching leg motions will disturb stable walking. We input the body inclination around the roll axis (body roll angle) to the neural oscillators as a feedback signal expressed by Equation (6) in order to synchronise rolling motion and pitching motion. The orientation of (body angle) is shown in Figure 2. We call this response 'tonic labyrinthine response in roll' (Figure 1); see

$$\begin{aligned} Feed_{e \cdot tlrr} &= \delta(leg)\, k_{tlrr} \times (\text{body roll angle}) \\ Feed_{f \cdot tlrr} &= -Feed_{e \cdot tlrr} \end{aligned} \tag{6}$$

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

Thus, we use the following feedback equations in Equation (1).

$$\begin{aligned} Feed_e &= Feed_{e \cdot tsr \cdot vsr} + Feed_{e \cdot tlrr} \\ Feed_f &= Feed_{f \cdot tsr \cdot vsr} + Feed_{f \cdot tlrr}\,. \end{aligned} \tag{7}$$

The rolling motion is naturally generated while walking at low speed (Section 4.) and walking on irregular terrain (Section 5), and Tekken could be expected to lose its balance on the lateral plane. However, while The tonic labyrinthine response in roll contributes to an appropriate adjustment of the periods of the stance and swing phases, Tekken keeps its body stabilisation. For example, when its body inclines toward the right on the lateral plane, 'The tonic labyrinthine response in roll' extends the stance phase of the right legs and shortens the stance phase of the left legs for an appropriate period. As a result, Tekken does not fall to the right side and is capable of being ready for the next reliable landing of the left-side legs.

3.4. Virtual spring-damper system

We employ the muscle stiffness model that is generated by the stretch reflex and variable according to the stance/swing phases, adjusted by the neural system. The muscle stiffness is high in a stance phase to support a body against gravity and low in a swing phase for compliance against perturbation. All the joints of a Tekken robot, except ankle pitch joint, are PD controlled to allow movement to their desired angles in each of the three states (A, B, C) shown in Figure 4 in order to generate each motion, such as swinging up (A), swinging forward (B) and pulling down/back of a supporting leg (C). The timings used to switch to the next state are

$A \rightarrow B$**:** when the hip joint angle of the leg reaches the desired angle of the state A;
$B \rightarrow C$**:** when the neural oscillator extensor neuron of the leg becomes active ($y_i \leq 0$);
$C \rightarrow A$**:** when the neural oscillator flexor neuron of the leg becomes active ($y_i > 0$).

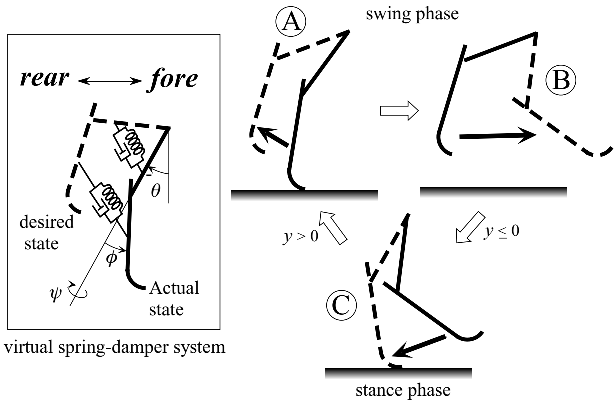

Figure 4. State transition in the virtual spring-damper system. The desired joint angles in each state are shown by broken lines.

The desired angles and P-gain of each joint in each state are shown in Table 1, where the constant values of the desired joint angles and constant P-gain were determined through experiments. θ, ϕ and ψ are the hip pitch joint angle, the knee pitch joint angle and the hip yaw joint angle shown in Figure 1.

Since Tekken has high back-drivability with a small gear ratio in each joint, the PD controller can construct a virtual spring-damper system with relatively low stiffness when coupled with the mechanical system. Such compliant leg joints can improve passive adaptability when in unstable state.

Referring to the viewpoint of Akazawa et al. (1982), the P-gains of θ in B and C in both Table 1(a) and (b) are adjusted by the desired Tekken velocity v. While bounding, the P-gain of θ in C of the hind legs is much larger than that of the forelegs. This is because running requires much stronger propulsive force from the hind legs.

Table 1. Desired values and P-gains utilised for the PD control by the virtual spring-damper system in Figure 4 [(a) for the walk, trot and free-gait, (b) for the bound]. All D-gains in every gait are 0.03 Nm·s/rad. Each value inside the parentheses shown in (b) are for the hind leg. In other fields, the forelegs and hind legs have the same value.

	P control	
Angle in state	Desired value[rad]	P-gain[Nm/rad]
	(a)	
θ in A	$1.2\theta_{C\rightarrow A}$	7.0
θ in B	-0.17	$0.5v + 0.4$
θ in C	$\theta_{stance} + BPA$	$0.38v + 0.83$
ϕ in A & B	*	1.0
ϕ in C	0.61	2.6
ψ in all states	0	1.0
	(b)	
θ in A	$1.2\theta_{C\rightarrow A}$	7.0
θ in B	-0.17	$v + 0.5$
θ in C	$-0.66 + BPA$	1.0
	$(-0.94 + BPA)$	$(2.3v + 18.0)$
ϕ in A & B	$*$	10.0
ϕ in C	0.7 (0.65)	1.8 (3.0)
ψ in all states	0	5.0

θ_{stance}: the parameter used to change walking speed.
$\theta_{C\rightarrow A}$: the hip joint angle measured at the instance.
when the state changes from (C) to (A).
v m/s: walking speed.
BPA: body pitch angle.
$*$: the desired angle calculated on-line for the height from the toe to the hip joint to be constant.

4. Autonomous gait transition between walk and trot

Figure 5 shows the experimental result of walking on flat terrain, in which Tekken increased its walking speed from approximately 0.3 to 0.5 m/s by changing θ_{stance} from -0.7 rad to -0.8 rad at $t = 3.5$ sec. The ankle joint angle ζ is measured by a potentiometer on each leg. When the ζ is around 10 degrees, the leg phase is swing. When the ζ is around 2 degrees, the leg phase is stance. We can see the walking gait at low-speed (approximately 0∼4) in Figure 5: when walking at the slowest speed, the cyclic walking period and the stance phase are long, resulting in a large body oscillation around roll axis. At that point, Tekken is strongly affected by the tonic labyrinthine response in roll shown in Equation (6), the phase difference between right legs and left legs become large, and the walking gait appears. For example, in Figure 5, when the body inclined to the right side (A), the extensor neurons of the neural oscillators of the two right legs strengthened while the flexor neurons weakened, and the two right legs moved close to the stance phase (B). On the opposite side, the flexor neurons of the neural oscillators of the two left legs strengthened while the extensor neurons weakened, and the two left legs moved close to the swing phase (C). In situations where the inclination was towards the left side (D), the opposite motion occurred (E).

As shown in Figure 5, the amplitude of the rolling motion became smaller as walking speed increased (F). Because the propulsion force in the stance phase increased by changing θ_{stance} from -0.7 rad to -0.8 rad at $t = 3.5$, the period for supporting the leg shortened, and rolling motion decreased. As a result, the influence of the tonic labyrinthine response in roll (Equation (6)) became smaller and the gait was slightly shifted from a walk to a trot, which is the basic Tekken gait.

5. Adaptive walking on irregular terrain by free-gait

Since the phase difference between the rolling motion of a body and the pitching motion of legs is largely disturbed when walking on irregular terrain, the tonic labyrinthine response in roll is essential. The result of an experiment

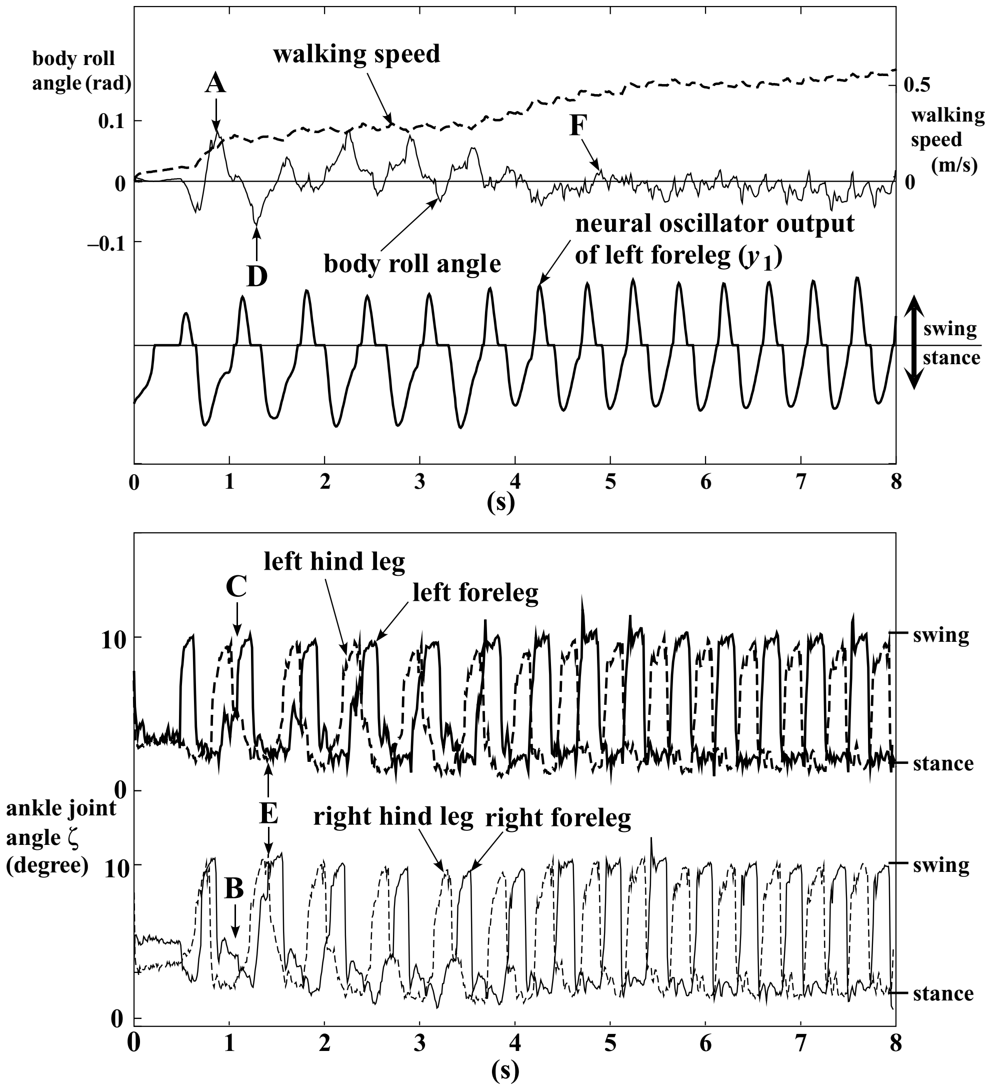

Figure 5. The result of the experiment in changing walking speed. θ_{stance} was changed from -0.7 rad to -0.8 rad at $t = 3.5$. We can clearly see in the first half that neural oscillator output and the rolling motion of the body were mutually entrained.

where Tekken walked over an obstacle 2 cm in height and 4 cm in depth by means of Equation (6) are shown in Figure 6. $\theta_{stance} = -0.8$ (see Table 1) is used in this experiment. The parts in the figure that show intense convex upward movement (A) indicate that Tekken's foot has encountered the obstacle.

In Figure 6, The foot of the left hind leg encountered the obstacle (A). Since the left hind leg landed on the obstacle and then dropped from the obstacle afterwards, the body inclined to the left (B) for about 5. In response to this body inclination, the stance phase of the left hind leg was extended (C), the swing phase of the left foreleg was shortened (D) and the swing phase of the right hind leg was extended (E) by the effect of Equation (6). The natural gait for the time when this appropriate adjustment to the disturbed phase is carried out is called the free-gait (F). The body inclination became smaller at around 5.4 and was cancelled at around 6. Finally, the free-gait transitioned to the trot gait again at around 7. This showed that the tonic labyrinthine response in roll was very effective for stabilising the body on irregular terrain. Furthermore, the low-speed walk gait appeared just after Tekken started to walk (G) as discussed in Section 4.

6. Bounding with a tonic labyrinthine response in pitch

When walking, Tekken utilised the body inclination around the roll axis as feedback to the neural oscillator. We called this the tonic labyrinthine response in roll. When

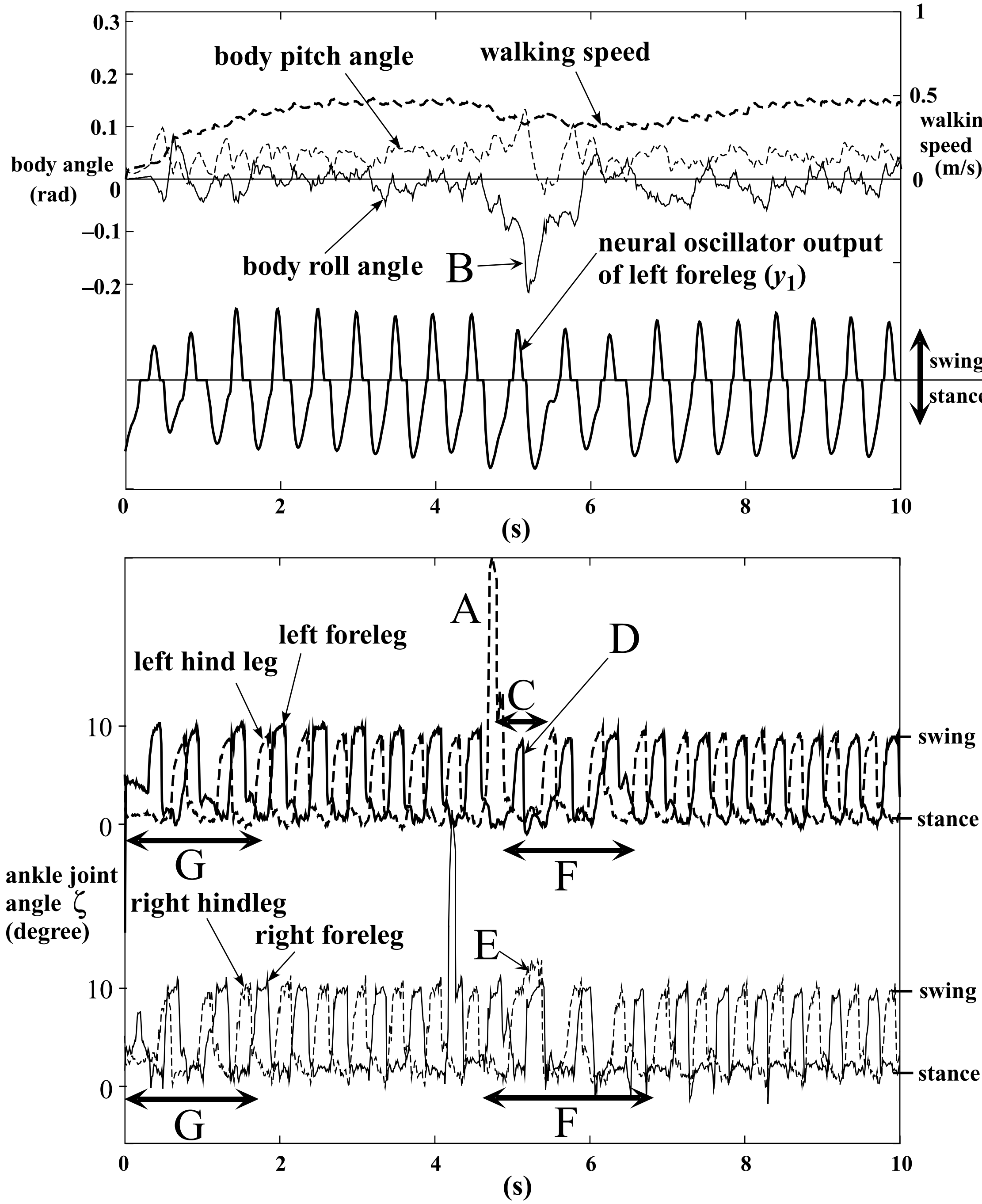

Figure 6. An experiment involving walking over a step 2 cm in height with the tonic labyrinthine response in roll ($\theta_{stance} = -0.8$).

running using the bound gait, at that time the legs are moved in unison in lateral pairs, body oscillation around the pitch axis becomes large. Thus, we recalculate the following equation (8) to the former feedbacks Equation (7) as a tonic labyrinthine response in pitch (see), and newly employed Equation 9. This creates an entrainment between the body oscillation around the pitch axis and the neural oscillators, thereby allowing Tekken to run stably using the bound gait.

$$\begin{aligned} Feed_{e\cdot tlrp} &= \sigma(leg)\, k_{tlrp} \times (\text{body pitch angle}) \\ Feed_{f\cdot tlrp} &= -Feed_{e\cdot tlrp}\,, \end{aligned} \tag{8}$$

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

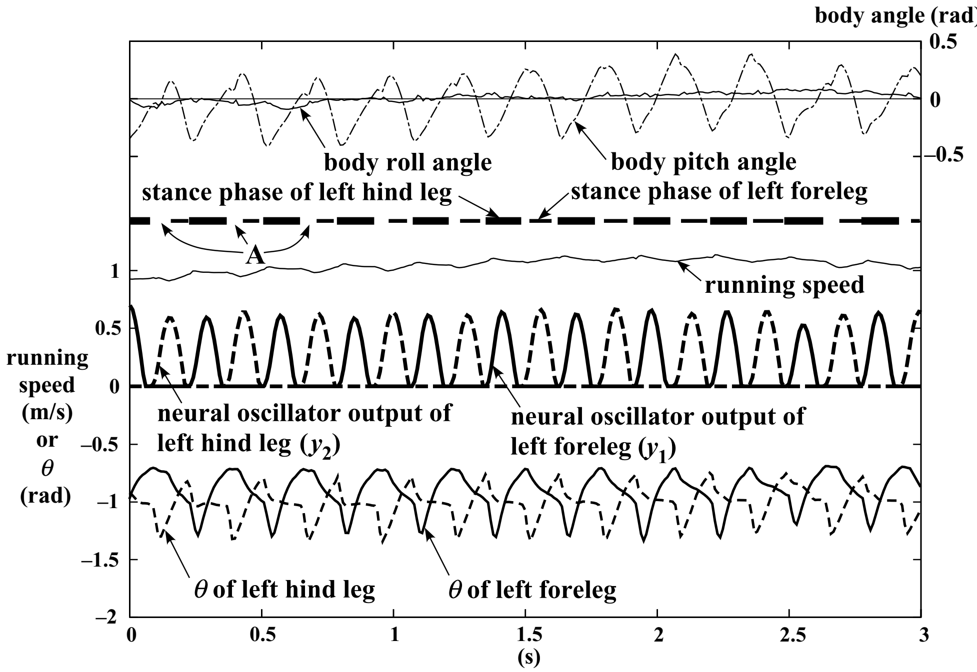

Figure 7. An experiment involving bounding on flat terrain.

$$\begin{aligned} Feed_e &= Feed_{e\cdot tsr\cdot vsr} + Feed_{e\cdot tlrr} + Feed_{e\cdot tlrp} \\ Feed_f &= Feed_{f\cdot tsr\cdot vsr} + Feed_{f\cdot tlrr} + Feed_{f\cdot tlrp}\,. \end{aligned} \tag{9}$$

In Figure 7 we will show an experimental result made by Tekken with the tonic labyrinthine response in pitch bounding on flat terrain. Since lateral legs record the same data while bounding, we presented data from the left legs only. The stance phases of left foreleg and left hind leg are shown as horizontal thin lines and horizontal thick lines, respectively, and the portions (A) where neither of them are visible indicate flight phases. Flight phases are recorded mainly after the hind legs leave the ground. We can see that Tekken ran rhythmically at 0.9∼1.1 m/s.

In Figure 7, the phase of neural oscillator output for fore leg and hind leg are opposite. Although, when walking, the outputs of the neural oscillators have negative as well as positive values, only positive values are recorded during the bound experiment. This is because the origin point of the hip joint θ_0 in Equation. (4) is set to -0.26 (see Table 3), which is larger than $\theta_0 = -0.87$ when walking. Thus, only the flexor neuron in the neural oscillator was enhanced and the leg was strongly led to swing phase.

Even though the oscillation of 'body pitch angle' was very large, as shown in Figure 7, the θ of two legs and body

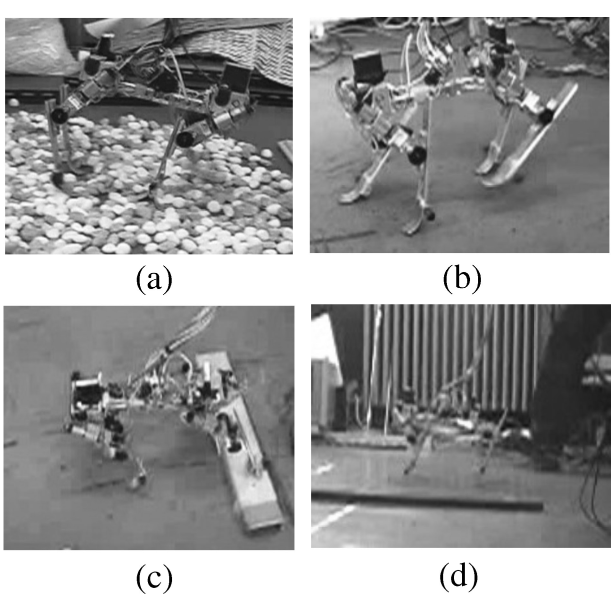

Figure 8. Photographs of Tekken when walking on pebbles at 0.6 m/s (a), walking via the walk gait at 0.3 m/s (b), stepping over an obstacle at 0.7 m/s (c) and bounding at 1.0 m/s (d).

Table 2. Walking experiments.

Parameters	Value	Parameters	Value
u_0	1.0	$w_{\{12,34\}}$	0
τ	0.04	$w_{\{21,43\}}$	−0.57
τ'	0.6	θ_0 rad	−0.87
β	3.0	k_{tsr} [1/rad]	3.0
w_{fe}	−2.0	k_{tlrr} [1/rad]	3.3
$w_{\{13,31,24,42\}}$	−2.0	k_{tlrp}[1/rad]	0

Table 3. Bounding experiments.

Parameters	Value	Parameters	Value
u_0	1.0	$w_{\{12,34\}}$	0
τ	0.02	$w_{\{21,43\}}$	-1.0
τ'	0.6	θ_0 rad	-0.26
β	3.0	k_{tsr}[1/rad]	3.0
w_{fe}	-2.0	k_{tlrr}[1/rad]	3.3
$w_{\{13,31,24,42\}}$	1.0	k_{tlrp}[1/rad]	3.0

pitch angle were entrained and achieved bounding due to the effects of the tonic labyrinthine response in pitch.

Since the roll body angle during bounding was very small, as shown in Figure 7, the tonic labyrinthine response in roll was not very effective. However, our experiment confirmed that the tonic labyrinthine response in pitch sometimes worked as a disturbance, in walking, where an oscillation occurs around pitch axis as well as roll axis. As a result, we set k_{tlrp} in Equation (8) to 0 in walking as shown in Table 2.

7. Conclusion

In this study, we designed a neural system consisting of CPGs (neural oscillators), responses, reflexes and a virtual spring-damper system based on a muscle mechanism by referring to biological concepts. We also constructed a flexible mechanism with back-drivability to make the best use of our biologically inspired control. Locomotion experiments based on the system resulted in success. Photographs of Tekken's legged locomotion are presented in Figure 8. Tekken achieved walking by low-speed walking gait (approximately 0.2∼0.4 m/s) trotting gait at middle-speed (approximately 0.4∼1.0 m/s), running by bound gait at high speed (approximately 0.9∼1.1 m/s) and walked on irregular terrain by free-gait.

The tonic labyrinthine response in roll was beneficial in providing autonomous adaptation to disturbance when walking on irregular terrain as well as stable gait walking. We also achieved autonomous gait transitions between walking and trotting. The tonic labyrinthine response in pitch also proved beneficial when bounding, where body oscillation around the pitch axis is large.

We did not need to change the framework of the control system, and simply adjusted the parameters of the neural oscillators, reflexes, responses and virtual spring-damper systems instead. This allowed us to demonstrate that Tekken could accomplish various forms of locomotion.

Although, the walking gait transferred autonomously between walking and trotting, autonomous gait transitions between trotting and bounding have yet to be achieved. This achievement, as well as bounding on irregular terrain, will be the basis of our future work.

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