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Adaptive Dynamic Walking of the Quadruped on Irregular Terrain - autonomous adaptation using neural system model -

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Abstract

We are trying to induce a quadruped robot to walk dynamically on irregular terrain by using a neural system model. In this paper, we integrate several reflexes such as stretch reflex, vestibulospinal reflex, and extensor and flexor reflex into CPG (Central Pattern Generator). The success in walking on terrain of medium degree of irregularity with fixed parameters of CPG and reflexes shows that the biologically inspired control proposed in this study has an ability for autonomous adaptation to unknown irregular terrain. MPEG footage of these experiments can be seen at: http://www.kimura.is.uec.ac.jp.

1 Introduction

Many previous studies of legged robots have been performed[1]. About dynamic walking on irregular terrain, both biped and quadruped robots have been studied. Most of these earlier studies employed precise models of a robot and an environment, and involved planning joint trajectories as well as controlling joint motions on the basis of an analysis of the models. If we know all about one particular irregular terrain before an experiment, we can prepare control program for it. However, when a legged robot moves quickly across a variety of places, a method consisting of modeling, planning, and control such as those mentioned above is not effective and not adaptable. In order to cope with an infinite variety of terrain irregularity, robots need autonomous adaptation.

On the other hand, animals show marvelous abilities in autonomous adaptation. It is well known that the motions of animals are controlled by internal neural systems. 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 rhythm pattern generator (Central Pattern Generator: CPG) and reflexes in response to the peripheral stimulus[2, 3]. Much previous research attempted to generate autonomously and emergently adaptable walking using such a biologically inspired control mechanism. It was shown by simulation that stable and adaptive biped walking[4, 5] could be realized by a global entrainment between a CPG and a musculoskeletal system. But dynamic walking of a real robot using CPG or neural controllers was rarely realized in these earlier studies[6, 7, 8].

In our previous studies using a quadruped robot, we realized dynamic walking on flat terrain in trot and pace gaits using a CPG alone[6], and dynamic walking on irregular terrain using a CPG and reflex mechanisms[7]. However, the irregularity of terrain in that study was very low. Therefore, in this study we propose two types of models about combination of CPG and reflexes, and show that reflexes via CPG is much effective in adaptive dynamic walking on terrain of medium degree of irregularity through experiments using a quadruped robot. We also discuss about meanings and advantages of the biologically inspired control method in comparison with the control method based on dynamics. In the proposed method, there does not exist adaptation based on trajectory planning commonly used in the conventional robotics and adaptation to irregular terrain is autonomously generated as a result of interaction of the torque-based system consisting of a rhythm pattern generator and reflexes with environment.

2 Dynamic Walking Using CPG

2.1 Control mechanism in animals

Neural system for legged locomotion control in animals[3] is shown in Fig.1. A joint is actuated by the flexor and extensor muscles. Each muscle receives a control signal from an α motor neuron at the spinal cord. By investigation of the motion generation mechanism of a spinal cat, it was found that CPG is located in the spinal cord, and that walking motions are autonomously generated by the neural systems below the brain stem[2]. Several mathematical models

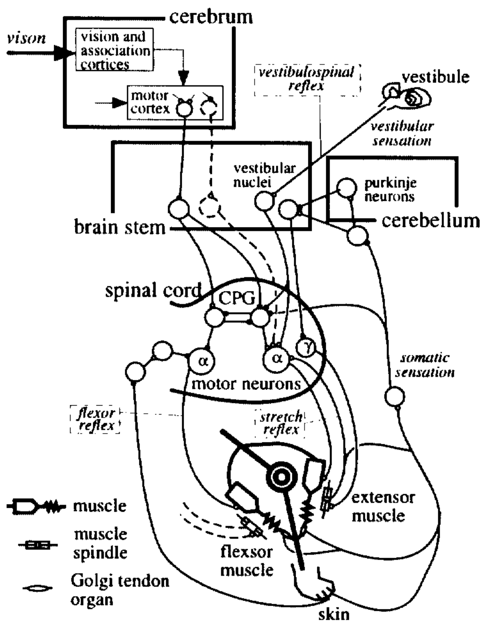


Fig.1 Simplified neural system for adaptive control of legged locomotion in animals.

of CPG were also proposed, and it was pointed out that a CPG has the capability to generate and modulate walking patterns[9], to be mutually entrained with rhythmic joint motion[4], and to adapt walking motion to the terrain[5]. In Fig.1, the outputs of the CPG are transmitted to α motor neurons and alternately induce torque in a joint in opposite directions of contraction of the flexor and extensor muscles. The CPG is activated by descending signals from the brain stem.

A muscle spindle and Golgi tendon organ detect stretched length and tension of the muscle, respectively. When an extensor muscle is stretched, the α motor neuron outputs a signal to contract the muscle based on the signal from the muscle spindle. This feedback loop is called "stretch reflex" and gives stiffness to a muscle. The "flexor reflex" contracts a flexor muscle based on signals from sensors in the skin. Both stretch reflex and flexor reflex occur at the spinal cord.

The vestibule detects acceleration and angular acceleration of head motion. Postural stability during standing and walking is maintained by activating muscles of legs based on vestibular sensation via the vestibular nucleus and α motor neurons. This stabilization is called "vestibulospinal reflex."

2.2 Quadruped robot

In order to apply the above-described biologically inspired control, we made a quadruped robot, Patrush. Each leg of the robot has three joints, namely the hip, knee, and ankle joint, that rotate around the pitch axis. A DC motor and a photo encoder are attached to each hip and knee joint, and an ankle joint is passive. The robot is 360 mm in length, 240 mm in width, 330 mm in height and 5.2 kg in weight. The body motion of the robot is constrained on the pitch plane by two poles since the robot has no joint around the roll axis. For a reflex mechanism, 6 axes force/torque sensor is attached to on a lower link beneath the knee joint. A rate-gyro as an angular velocity sensor is mounted on a body as vestibule. All control programs below are written in C language and executed on RT-Linux.

In this study, we define the virtual extensor and flexor muscles on a quadruped robot, and origin and direction of joint angle and torque as shown in Fig.2. In addition, we use such notation as L(left), R(right), F(fore), H(hind), S(hip), x(joint angle), f_x and f_z(force sensor value in x and z direction). For example, LFS means the hip joint of the left foreleg, and LFS.x and LF.fx mean the angle at this joint and force sensor value at this leg.

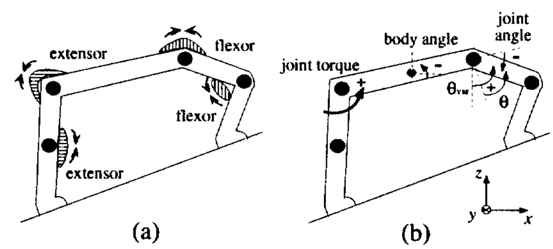


Fig. 2 (a) Virtual extensor and flexor muscle on a quadruped robot. (b) Origin and direction of angles and direction of torque.

2.3 Walking on flat terrain using CPG

As a model of CPG, we used a neural oscillator (N.O.) proposed by Matsuoka[10] and applied to the biped by Taga[4, 5]. The stability and parameters tuning of a N.O. was analyzed using describing function method[11]. Single N.O. consists of two mutually inhibiting neurons (Fig.3-(a)). Each neuron in this model is represented by the nonlinear differential equations:

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

where suffix e, f, and i mean extensor muscle, flexor muscle, and the ith neuron, respectively. u_i is the inner state of neuron; v_i is a variable representing the degree of the self-inhibition effect of the ith neuron; y_i is the output of the ith neuron; u_0 is an external input with a constant rate; $Feed_i$ 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_i and v_i; w_{ij} is a connecting weight between the ith and jth neurons. u_0 is constant in the following experiments. As a result, CPG outputs torque proportional to the inner state u_e, u_f to a DC motor of a joint:

$$N\_Tr = -p_e u_e + p_f u_f \qquad (2)$$

The periods when extensor muscle ($N\_Tr < 0$) or flexor muscle ($N\_Tr > 0$) is active correspond to a supporting phase or a swinging phase at CPG level.

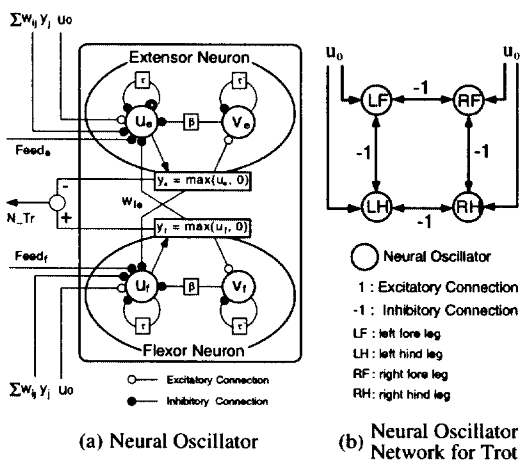


Fig.3 Neural oscillator as a model of a CPG.

When we consider $Feed_i$ in Eq.(1), stretch reflex acts as feedback loop as described in Section **2.1**. The neutral point of this feedback in upright position of a robot is $\theta = 0$, where $\theta =$ (joint angle) $+ \pi/2$ in Fig.2-(b). It is known in biology that there are two different types of stretch reflex. One is a short term reflex called "phasic stretch reflex" and another is a long term reflex called "tonic stretch reflex". When we assume that the tonic stretch reflex occurs on the loop between CPG and muscles, the joint angle feedback to CPG used in Taga's simulation[4, 5] based on biological knowledge[12] corresponds to tonic stretch reflex. We also use such joint angle feedback to CPG:Eq.(3) in all experiments of this study.

$$Feed_{e\cdot tsr} = k_{tsr}\theta, \quad Feed_{f\cdot tsr} = -k_{tsr}\theta \qquad (3)$$

We also assume that the phasic stretch reflex occurs on the loop between α motor neurons and muscles locally, and use this reflex in Section **3**.

By connecting N.O. of a hip joint of each leg, the N.O.'s are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the N.O.'s of legs results in a gait. We used a trot gait, where the diagonal legs are paired and move together, and two legs supporting phase are repeated[7].

In all experiments of this study, only hip joints are controlled by CPG and knee joints are PD-feedback controlled for simplicity. The desired angle of a knee joint in a supporting phase is 4 degrees and that in a swinging phase is calculated based on Eq.(4) using CPG output torque N_Tr at a hip joint of the same leg.

$$\text{desired angle} = 1.7 N\_Tr + 0.26 \qquad (4)$$

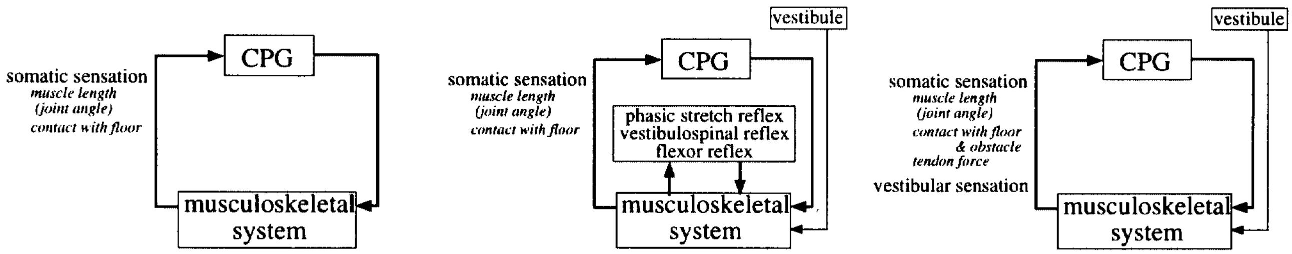
By the experiment using only joint angle feedback to CPG, where $Feed_e = Feed_{e\cdot tsr}$, $Feed_f = Feed_{f\cdot tsr}$, we confirmed that Patrush can walk stably on flat terrain by CPG and tonic stretch reflex. Patrush walked dynamically with approximately 25 [cm] stride, 0.8 [sec] period and 0.6 [m/sec] speed in this experiment.

2.4 Walking on irregular terrain using CPG

It is well known in biology that adjustment of CPG and reflexes based on somatic sensation such as contact with floor and tension of muscle of supporting legs, and vestibular sensation are very important in adaptive walking [2, 3, 13]. Although it is also well known that activity of CPG is modified by sensory feedback[13], the exact mechanism of such modification in animals is not clear since the neural system of animals is too complicated. Therefore, we consider the following three types of models for adaptation based on sensory information, discuss about which model is better through results of experiments, and propose physical mechanism of relation between CPG and reflexes in view of robotics.

(a) CPG involving tonic stretch reflex
(b) CPG and reflexes independent of CPG
(c) CPG and reflexes via CPG

The control model (a) was proposed by Taga[4, 5] and used in our experiment described in Section **2.3** (Fig.4-(a)). Sensory information used in this model is only simple somatic sensation such as joint angle/angular velocity for stretch reflex, and contact with floor for switching feedback in supporting and swinging phases of a leg. In model (b), we consider reflexes independent of CPG, and sum of CPG torque and reflexes



(a) involving tonic stretch reflex (b) reflexes independent of CPG (c) reflexes via CPG

Fig.4 Relation between CPG and reflexes in Taga's model:(a) and models proposed in this study:(b),(c)

torque is output to a motor (Fig.4-(b)). In model (c), reflexes torque is output as part of CPG torque by feedback of all sensory information to CPG (Fig.4-(c)).

3 Reflexes Independent of CPG

Patrush failed in walking over an obstacle 3 cm in height and walking up a slope of more than 7 degrees by using control model shown in Fig.4-(a) and fell down backward because of lack of thrusting force against gravity. Taga[5] pointed out the autonomous adaptability of CPG in Fig.4-(a). But this result of experiments showed the limitation of control model shown in Fig.4-(a). Therefore, we employed other reflexes independent of CPG in addition to tonic stretch reflex. In Fig.4-(b), CPG takes motion adjustment by reflexes torque as disturbance and makes itself and musculoskeletal system go back to stable state autonomously by self stabilization ability of CPG after disturbance disappears.

By using phasic stretch reflex, vestibulospinal reflex and flexor reflex with CPG (Fig.1) based on Fig.4-(b), we realized walking up and down a slope of 12 degrees, and walking over an obstacle of 3cm in height[7, 14, 15]. But following problems were pointed out:

(1) The delay of joint motion from the CPG phase was caused by a lack of thrusting force in walking up a slope, could not be canceled in spite of mutual entrainment ability of CPG, resulted in slipping and stamping with no progress, and made walking far from smooth[15].

(2) Flexor reflex on a swinging leg resulted in extension of the swinging phase of the leg. But since CPGs could not extend the supporting phase of other supporting leg, it happened for both legs to be in the swinging phase at the same time and Patrush often fell down forward.

We showed that it was possible to solve such problems to some extent by changing CPG internal parameters[15] and employing other reflex[7]. But such adjustments increased number of parameters and made control system complicated.

4 Reflexes via CPG

In this section, we consider reflexes via CPG in response to vestibular sensation, tendon force and contact with floor. Since these reflexes may be confused with such usual reflexes as vestibulospinal reflex and so on, we call reflexes via CPG as vestibulospinal "response" and so on.

Diagram of actual control of a leg employed in this section is shown in Fig.5.

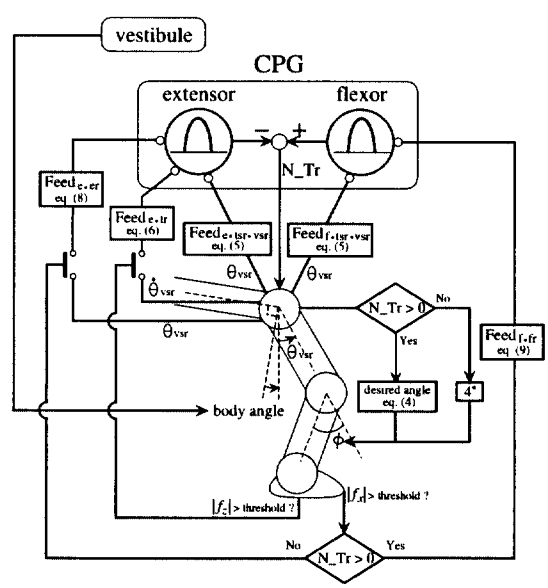


Fig.5 Diagram of actual control of a leg consisting of CPG and reflexes via CPG.

4.1 Walking up and down a slope using vestibulospinal response

Most of extensor muscles output force to keep posture as antigravity muscle. Since tonic stretch reflex continues while a muscle is extended, it is appropriate to adjust activity of antigravity muscles for posture control by tonic stretch reflex utilizing the body angle detected by vestibule. According to our assumption described in Section **2.3**, tonic stretch reflex is a feedback via CPG. Therefore, the reflex (vestibulospinal response) for posture control based on vestibular sensation is via CPG and expressed by:

$$\begin{aligned} \theta_{vsr} &= (\text{joint angle}) + \pi/2 - (\text{body angle}) \\ Feed_{\{e,f\}\cdot tsr\cdot vsr} &= \pm k_{tsr}\theta_{vsr}. \end{aligned} \tag{5}$$

Since excitatory feedback signal to extensor neuron of CPG in walking up a slope makes the period of a supporting phase at CPG level become longer, phase difference between CPG and joint motion becomes small. In Fig.6, we can see that the vestibulospinal response via CPG in walking up a slope made the period of a supporting phase at CPG level ($N\_Tr < 0$) be longer in comparison with that in walking on flat terrain. This means that autonomous adaptability of CPG solved the problem (1) mentioned in Section **3**.

As a result, Patrush succeeded in walking up and down a slope of 12 degrees by using vestibulospinal response much more stably and smoothly without increasing number of parameters. On the other hand, vestibulospinal reflex employed in Section **3** needed an additional gain parameter adjusted through experiments.

4.2 Walking up and down a slope using tendon response

Stable and smooth walking up a slope was realized in Section **4.1**. But since vestibulospinal reflex tends to keep static stability by adjusting the position of center of gravity or ZMP (zero moment point), it was slow walking with less thrusting force. Therefore, we employ the tendon response for faster walking up a slope.

Pearson[16] pointed out that extensor neuron of CPG gets excitatory signal when the tendon organ detects the load to the ankle joint muscle in a supporting phase. We call this as tendon response, which acts to complement thrusting force against reaction force from floor in a supporting phase.

Patrush uses the load at the hip joint muscle, since it has no ankle joint muscle. In addition, since it is difficult to detect the load at the hip joint muscle using the force sensor attached on a lower link beneath the knee joint, we use amount of decrease of $\dot{\theta}$ of a hip joint in a supporting phase for the tendon response. The tendon response via CPG on a supporting leg is generated by the excitatory feedback signal:$Feed_{e\cdot tr}$ to extensor neuron of CPG.

$$Feed_{e\cdot tr} = \begin{cases} k_{tr}(\dot{\theta}+1) & (\dot{\theta} \geq -1) \\ 0 & (\dot{\theta} < -1) \end{cases} \tag{6}$$

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

By using sensory feedback to CPG expressed by Eq.(7), Patrush succeeded in walking up and down a slope of 12 degrees (Fig.6). In Fig.6, output torque of the tendon response via CPG appears as bumps on N_Tr while extensor neuron of CPG is active ($N\_Tr < 0$) at 1.9 and 2.3[sec], for example. Although Patrush took 4[sec] to walk up a slope in the experiment without the tendon response in Section **4.1**, it took only 2.2[sec] in Fig.6. This means that faster walking up a slope was realized by using the tendon response.

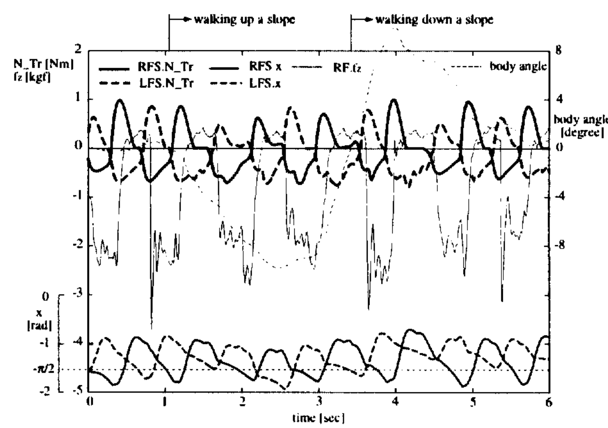


Fig. 6 Walking up a slope of 12 degrees using feedback:Eq.(7).

4.3 Avoiding falling down after stumbling using extensor and flexor responses

It is known in biology that the response to stimulus on the paw dorsum in walking of a cat depends on which of extensor or flexor muscle is active:

[a] When extensor muscle is active, a leg is strongly extended in order to avoid falling down.

[b] When flexor muscle is active, a leg is flexed in order to escape from the stimulus.

We call [a] and [b] as extensor response and flexor response respectively, and assume that phase signal from CPG switches such responses[13].

For the extensor response, we employ the following excitatory feedback signal:$Feed_{e \cdot er}$ to extensor neuron of CPG, when reaction force larger than threshold (f_x > 1.5[Kgf]) is detected by force sensor while extensor muscle is active ($N\_Tr < 0$).

$$Feed_{e \cdot er} = \begin{cases} k_{er}\theta_{vsr} & (\theta_{vsr} \geq 0) \\ 0 & (\theta_{vsr} < 0) \end{cases} \quad (8)$$

Eq.(8) means that the tonic stretch reflex:Eq.(3) is strengthened by using feedback signal to CPG: $Feed_e = (k_{tsr} + k_{er})\theta_{vsr}$, when a leg stumbles while the leg is in the forward position with respect to the perpendicular line.

For the flexor response, we employ the following instant excitatory feedback signal:$Feed_{f \cdot fr}$ to flexor neuron of CPG, when reaction force larger than threshold (f_x > 1.5[Kgf]) is detected by force sensor while flexor muscle is active ($N\_Tr > 0$).

$$Feed_{f \cdot fr} \;=\; (k_{fr}/0.12)(0.12 - t) \quad (9)$$

where t = 0[sec] means the instance when a leg stumbles, and $Feed_{f \cdot fr}$ is active for t=0~0.2[sec]. Constant:k_{fr} was experimentally determined so that the peak of flexor response torque through CPG became same (3[Nm]) with the flexor reflex torque used in Section **3**.

Finally, feedback signal to CPG to avoid falling down after stumbling is expressed by:

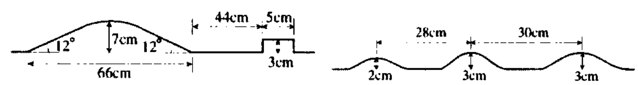
$$\begin{aligned} Feed_e &= Feed_{e \cdot tsr \cdot vsr} + Feed_{e \cdot tr} + Feed_{e \cdot er} \\ Feed_f &= Feed_{f \cdot tsr \cdot vsr} + Feed_{f \cdot fr} \end{aligned} \quad (10)$$

The reason why $Feed_{e \cdot tr}$ is included in Eq.(10) is that the tendon response is necessary to avoid falling down backward when a leg lands on a step or an obstacle after its stumbling.

In Fig.9, the right hindleg stumbled on the slope at 3[sec], and the neuron torque of the right hindleg (RHS.N_Tr) was instantly increased by the flexor response. This flexor response made the period of the swinging phase of the right hindleg much longer (2.4~3.1[sec]). Autonomous adaptability of CPG made the period of the supporting phase of the left hindleg be longer correspondingly in order to prevent Patrush from falling down by solving the problem (2) mentioned in Section **3**.

4.4 Adaptation to terrain of medium degree of irregularity

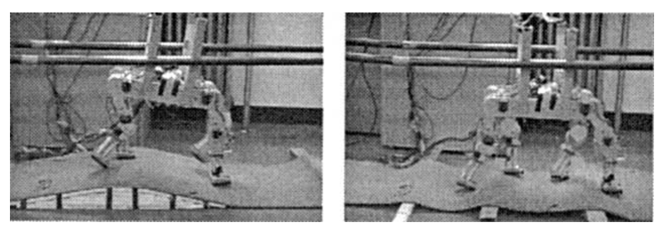
We tried to realize dynamic walking on terrain of medium degree of irregularity, where a slope, an obstacle and undulations continue in series (Fig.7). By realization of such adaptive walking using control method expressed by Eq.(1), (10) with fixed value of all parameters, we can show that the control method proposed in this section (Fig.5) has ability for adaptation to unknown irregular terrain. In Fig.7, the distance between irregular parts on terrain is shorter than the distance with which Patrush proceeds in one period, so that irregular parts on terrain always disturbs walking before CPG network gets back to stable states from the transitional states by the former disturbance.



(a) (b)

Fig.7 Terrain of medium degree of irregularity

The photos of walking on such irregular terrain are shown in Fig.8. The experimental results of walking on irregular terrain (Fig.7-(a)) is shown in Fig.9. In Fig.9, Patrush walked up a slope for 1~3.7[sec] with the tendon response, and stumbling on the slope of the right hindleg at 3[sec] caused the flexor response. In addition, Patrush walked down a slope (3.7~4.9) and walked over an obstacle by another flexor response at 5.5[sec]. We can see that RHS.N_Tr in the next supporting phase after those flexor responses was also increased autonomously by CPG and reflexes in order to complement necessary torque after the flexor response.



(a) (b)

Fig.8 Photos of walking up and down a slope:(a) and walking on terrain undulations:(b).

5 Discussion

5.1 CPG and Reflexes

Reflexes independent of CPG had several problems as described in Section **3**. In the case of reflexes via CPG, it was shown by experiments in Section **4** that the period of phases of CPGs can be appropriately adjusted autonomously by ability of CPG for entrainment while reflexes via CPG output necessary torque for instant adaptation based on sensory information.

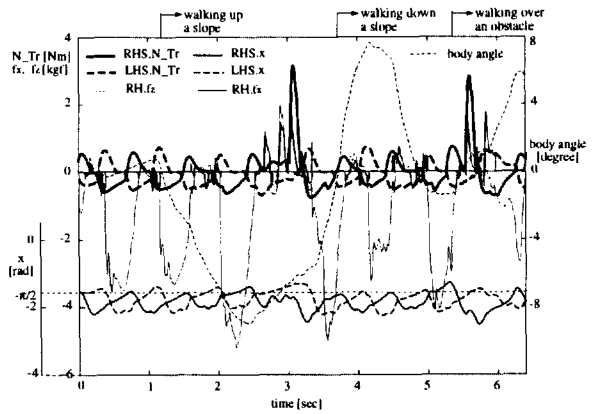


Fig.9 Walking up and down a slope of 12 degrees and over an obstacle 3 cm in height using feedback:Eq.(10).

In addition, the following results obtained in experiments using control system expressed by Eq.(1), (10):

- several reflexes via CPG coincide with each other without improper conflicts,
- adaptive walking on terrain of medium degree of irregularity was realized with fixed value of all parameters,
- strengthening sensory feedback to CPG promotes the autonomous adaptability of walking,

showed that the simple control method using neural system model (Fig.4-(c), Fig.5) has ability for adaptation to unknown irregular terrain.

5.2 Single system vs. Dual system

Conventional robotics methods generate and control walking as a dual system, where a joint trajectory is planned and a joint is controlled to move along the trajectory. Such a dual system is a very effective method for control of a manipulator in both human and robot, since a final position of an end-effector can be obtained in a vision coordinate prior to motion in most cases. However, such a dual system makes optimization, adaptation, and learning of motion difficult since we must always consider two different matters, planning and control, at the same time.

On the other hand, the exact position of a foot landing on the ground is usually not given in dynamic walking even though the step distance is often adjusted. Therefore, a single system, where outputs of CPG and reflexes mean torque and there is no adaptation based on trajectory planning can be used in order to generate and control walking motion. Such singularity as a system can make optimization, adaptation, and learning of motion simple, since we can consider adjustment of output torque directly for changes of terrain and external force. For example, Taga[5] pointed out that a single system can autonomously generate adaptation as a result of interaction between an internal neural system, a musculoskeletal system, and environment without explicit models of a robot and environment.

5.3 What is walking using CPG?

Conventional control methods of dynamic walking of a biped and a quadruped can be classified into a "ZMP-based method" and an "IPM- (inverted pendulum model) based method." In IPM-based control, constructing a stable limit cycle on the phase plane utilizing exchange of supporting legs means stabilization of walking[17] and hopping[18, 19]. In such a sense that the stable limit cycle means a stable oscillation, IPM-based control has much similarity with the generation and control of walking by CPG. Such similarity becomes more clear when we consider "passive dynamic walking"[20] where a walking machine with no actuator can walk down a slope dynamically.

When we compare torque induced by gravity in passively walking down a slope and CPG output torque in walking on flat terrain, there exists the similarity in torque patterns in both supporting phase and swinging phase[21]. If we notice that dynamic walking is autonomously generated on a link mechanism by external or internal force in both walking as a result of interaction of the single system with environment, this similarity is clearly understandable. That is, the passive mechanism itself has the ability for walking[22], and that dynamic walking is induced on the passive mechanism by external force: gravity. In the case of a flat floor or a up-slope, since external force does not exist, internal force is necessary for walking. Feedforward torque and CPG torque correspond with this internal force. This study showed that ability of CPG for mutual entrainment, autonomous adjustment of the period of phases of CPGs, and self-stabilization make CPG much more useful as a lower controller than combination of feedforward torque calculation and feedback control in the conventional robotics method[23].

We also realized adaptive walking up a step and over an obstacle by using adjustment of external input to CPG:u_0 based on vision (Fig.1) in another study[14]. This means that we can construct well-coordinated control system from motion generation and adaptation at the lower spinal cord level to motion adjustment based on vision at the upper cerebrum level by centering CPG in neural system model for adaptive dynamic walking on irregular terrain.

6 Conclusion

By referring to the neural system of animals, we integrated several reflexes such as stretch reflex, vestibulospinal reflex, and extensor and flexor reflex into CPG. The success in walking on terrain of medium degree of irregularity with fixed parameters of CPG and reflexes showed that the biologically inspired control method proposed in this study has an ability for autonomous adaptation to unknown irregular terrain. It is also shown that principles of dynamic walking as a physical phenomenon are identical in animals and robots in spite of difference of actuators and sensors.

3D dynamic walking on 3D irregular terrain is one of the next challenges this study aims for. Walking realized in this study is as primitive as the first steps of a horse, several hours after its birth, perhaps by a genetically programmed mechanism. Learning at the cerebellum for adaptation and learning at the basal ganglia for adjustment based on vision are left unsolved.

Acknowledgments

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Appendix

Table 1 Value of parameters used in this study.

τ	0.05	p_f, p_e [Nm]	0.075, 0.12
τ'	0.6	k_{tsr} [1/rad]	8
β	1.5	k_{er} [1/rad]	5
w_{fe}, w_{ij}	-2, ± 1	k_{tr} [sec/rad]	5.8
u_0	20	k_{fr}	50

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