

Biologically Inspired Adaptive Dynamic Walking of the Quadruped on Irregular Terrain *

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Abstract

We are trying to induce a quadruped robot to walk dynamically on irregular terrain by using a nervous system model. In our previous studies, we employed a control system involving a CPG (Central Pattern Generator) and reflex mechanism for terrain with a low degree of irregularity. In this paper, for terrain with both medium and high degrees of irregularity, we propose the biologically inspired control method consisting of four levels. The results of basic experiments for each level show that a robot can walk on a single bump, walk up and down a slope, and walk up a step. We discuss about meanings and advantages of the biologically inspired control method. It is shown that principles of dynamic walking as a physical phenomenon are identical in animals and robots in spite of difference of actuators and sensors. 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. About dynamic walking on irregular terrain, both biped[1, 2] and quadruped[3, 4] 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 nervous 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[5, 6, 7]. Much previous research attempted to generate autonomously and emergently adaptable walking using such a biologically inspired control mechanism. With regard to two-legged walking, it was shown by simulation that stable and flexible biped walking[8, 9] could be realized by a global entrainment between a CPG and a musculoskeletal system. As for four-legged walking, it was shown that neural controllers optimized by using an evolutionary method like GA[10] or a reinforcement learning method[11] could generate quadrupedal walking. But dynamic walking of a real robot using CPG or neural controllers was rarely realized in these earlier studies.

In our previous studies using a quadruped robot, we realized dynamic walking on flat terrain in trot and pace gaits using a CPG alone[12], and dynamic walking on irregular terrain using a CPG and reflex mechanisms[13]. However, the irregularity of terrain in that study was very low, and walking over terrain undulations and up and down steps has not yet been realized. In the case of animals, it is known that adjustments of activities of both a CPG and reflexes based on vestibular sensation, somatic sensation, and vision are important in order to adapt walking to irregular terrain[6, 7]. Therefore, in this study we employ four control mechanisms referring to such biological knowledge for adaptive dynamic walking on terrain with both medium and high degrees of irregularity. The effectiveness of such control mechanisms is validated through experiments using a quadruped robot. We

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discuss about meanings and advantages of the biologically inspired control method in comparison with the control method based on dynamics.

2. Control of Dynamic Walking

2.1. Control mechanism in animals

Nervous system for legged locomotion control in animals[7] is shown in Figure 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.

Shik[5] investigated the motion generation mechanism of a decerebrate cat and found that CPG is located in the spinal cord, and that walking motions are autonomously generated by the nervous systems below the brain stem. Although actual neurons as a CPG in higher animals have not yet become well known, features of a CPG have been actively studied in biology, physiology, and so on. Several mathematical models were also proposed, and it was pointed out that a CPG has the capability to generate and modulate walking patterns[14], to be mutually entrained with rhythmic joint motion[8], and to adapt walking motion to the terrain[9]. In Figure 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. Drew[15] proposed a model about the adjustment of the directive signal to a CPG via motor cortex based on vision by analyzing data from physiological experiments.

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. Since sensitivity of the muscle spindle is controlled by the γ motor neuron and the γ motor neuron has a descending signal from the cerebellum via the vestibular nucleus, the activity of stretch reflex is adjusted based on somatic sensation. 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 ac-

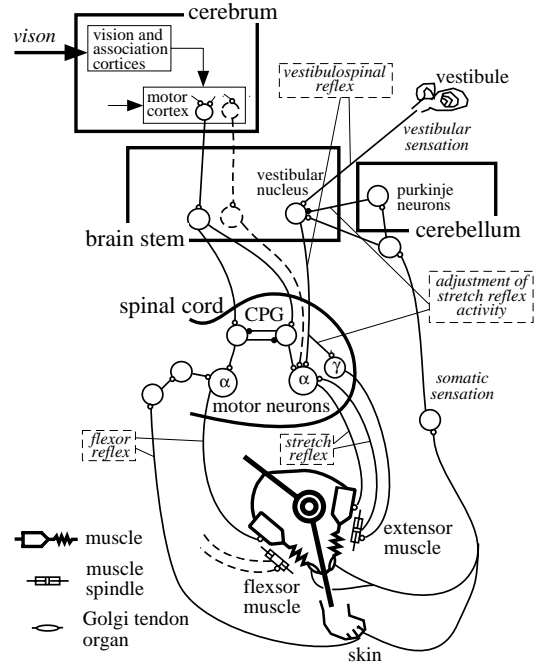


Figure 1: Simplified nervous system for adaptive control of legged locomotion in animals.

tivating muscles of legs based on vestibular sensation via the vestibular nucleus and α motor neurons. This stabilization is called “vestibulospinal reflex.”

2.2. The 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 4.8 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, micro-switches are attached to the undersides of the feet and the toes to detect contact with the floor and with fore obstacles, respectively. A rate-gyro as an angular velocity sensor is mounted on a body as vestibule. In addition, binocular stereo cameras are mounted on the body to find a step. All control programs below are written in C language and executed on RT-Linux.

2.3. Conventional robotics method

Conventional control methods of dynamic walking of a biped and a quadruped can be classified into a “ZMP-based method” and an “inverted pendulum model-based method.” In a ZMP- (Zero Moment Point) based method, such disadvantages are pointed out that relatively large feet are necessary and that a body of which inertia is very large must be swung by actuators to keep stability. In an inverted pendulum model-based method, such disadvantages are pointed out that delay of control leads a robot to fall down, and there exists an upper limit of the period for stable walking[16] since a robot is always falling by gravity. Between these two methods, the disadvantages of one method are negated and become the advantages of the other.

When we consider ZMP-based control in mammals, a human might use ZMP-based control in dynamic walking since a human has relatively large feet and a lot of pressure sensors beneath them. Yet cats, which have small paws, and horses, which have hooves with no pressure sensors, seem not to use ZMP-based control.

In inverted pendulum model-based control, constructing a stable limit cycle on the phase plane utilizing exchange of supporting legs means stabilization of walking[17, 18] and hopping[19]. In such a sense that the stable limit cycle means a stable oscillation, inverted pendulum model-based control has much similarity with the generation and control of walking by CPG in animals.

3. Walking Using CPG and Reflexes

As a model of CPG, we used a neural oscillator proposed by Matsuoka[20] and applied to the biped by Taga[8]. A neural oscillator (NO) consists of two mutually inhibiting neurons (Figure 2-(a)). Each neuron in this model is represented by the nonlinear differential equations[13].

By connecting NO of each leg, the NOs are mutually entrained and oscillate in the same period and with a fixed phase difference. This mutual entrainment between the NOs 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. The NO network for a trot gait is shown in Figure 2-(b).

Although we realized dynamic walking on flat terrain in trot and pace gaits using a CPG alone[12], sometimes walking became unstable

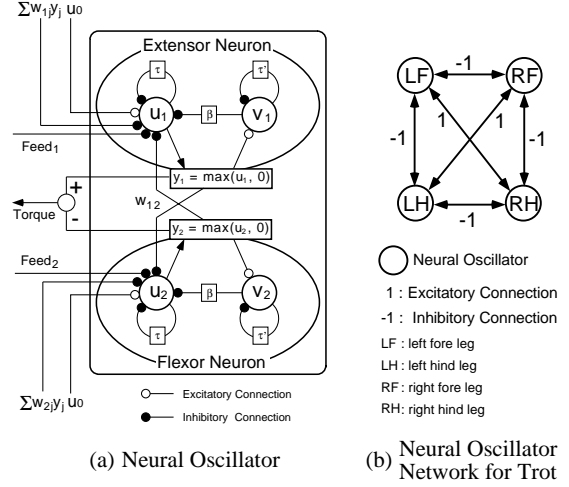


Figure 2: (a) Neural oscillator. (b) Neural oscillator network as a model of a CPG.

even on flat terrain because the supporting legs slipped. This meant that it was difficult to realize stable walking using a CPG alone since CPG could not directly deal with the interaction of legs with a floor. Therefore, for dynamic walking on irregular terrain with a low degree of irregularity, we employed a control system involving a CPG and stretch and flexor reflexes, and obtained the following results from our experiments[13].

- (1) Dynamic walking became much more stable, compared with the use of a CPG alone, because stretch reflex torque assisted in the phase transition from swinging to supporting and in preventing the supporting leg from slipping.
- (2) Walking on terrain furnished with obstructions to swinging legs was made possible by the flexor reflex.

4. Walking on Irregular Terrain

4.1. Adaptive control mechanism

When we consider walking as an exchange of supporting legs, the stability of walking is nothing but the reliability of the exchange of supporting legs. Therefore, in the case of walking on irregular terrain, it is essential that:

- (A) a leg not be prevented from moving forward in the former period of the swinging phase,

- (B) a leg be landed reliably on the ground in the latter period of the swinging leg phase, and
- (C) the angular velocity of the supporting legs around the contact points at landing moments be kept constant in spite of changes in the height of the ground surface.

For (A) and (B) to be satisfied, we have already employed the flexor reflex and the stretch reflex, respectively. In order to avoid collision of a leg with an obstacle as far as possible, recognition of the environment by vision and prior adjustment of swinging leg motion is needed. Condition (C) was commonly used in the control of dynamic walking[16, 17] and running[19] in inverted pendulum model-based control. In order to satisfy condition (C), a larger torque at the hip joints of the supporting legs is required when going up and a smaller torque is required when going down. The adjustment of torque by reflexes based on vestibular and somatic sensation as feedback control is effective to some extent. But, when a change of height in a step is large, prior adjustment of supporting leg torque by vision is needed as feedforward control.

Therefore, we employ the following four adaptive control mechanisms referring to the nervous system of animals (Figure 1) in order to realize dynamic walking on terrain shown in Figure 3.

- (1) Adaptive control using a muscle stiffness model for (C) in walking on terrain with a low degree of irregularity.
- (2) Adaptive control based on vestibular sensation for (C) in walking on terrain with a medium degree of irregularity.
- (3) Adjustment of activity of a stretch reflex by cerebellum based on somatic sensation for (C).
- (4) Adaptive control based on vision for (A) and (C) in walking on terrain with a high degree of irregularity.

In Figure 4, such adaptive control mechanisms are added into our previous control system consisting of a CPG and reflexes described in Section 3..

4.2. Adaptive control using muscle stiffness model

It is pointed out by physiological experiments that when the length of an extensor muscle becomes large, the stiffness of a stretch reflex of the muscle becomes small[21]. We call this property of a

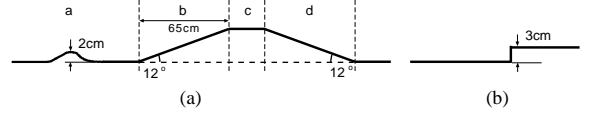


Figure 3: Irregular terrains used in experiments.

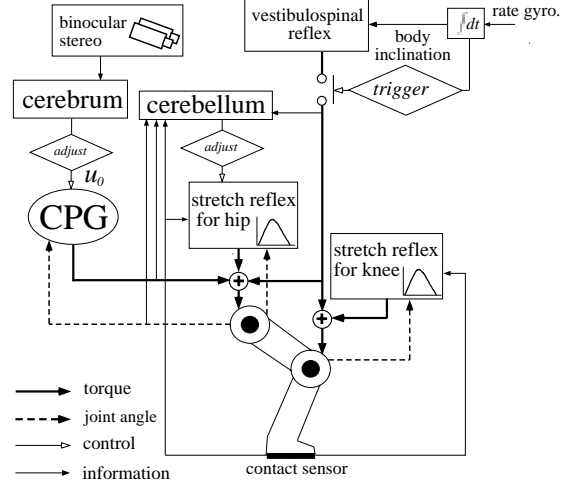


Figure 4: Diagram of actual control of a leg in this study. The flexor reflex in a swinging leg is not included in this figure.

stretch reflex a “muscle stiffness model.” In this study, we assume that the stiffness of a stretch reflex has a relation to the length of a muscle, as shown in Figure 5-(a).

When a leg lands on a bump (Figure 5-(b)), the knee joint is bent and the extensor muscles are more stretched (x_1 in Figure 5-(a)) than they are in landing on a flat floor (x^* in Figure 5-(a)). Since the stiffness of a stretch reflex (S_1 in Figure 5-(a)) becomes small according to the muscle stiffness model, the bending of the knee joint is kept and a body is prevented from rising by excess reaction force from the ground. In addition, when walking up a slope, adjustment of the stretch reflexes of the extensor muscles of a supporting leg based on the muscle stiffness model assists in keeping body posture flat.

The results of the experiment using the muscle stiffness model: a robot succeeded in walking on a bump 2cm in height and walking up a slope of 7 degrees smoothly with a low degree of up-and-down motion of a body[22], but it failed in walking up a slope of 12 degrees.

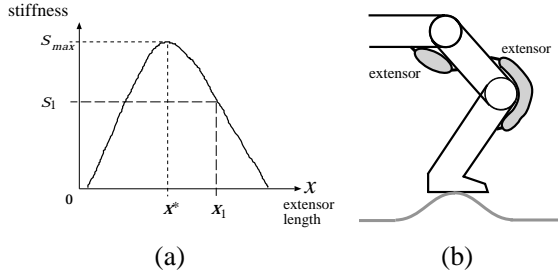


Figure 5: (a) Muscle stiffness model. (b) Landing of a leg on a bump.

4.3. Adaptive control based on vestibular and somatic sensation

4.3.1. Vestibulospinal reflex

When a vestibule sensor of a quadruped robot detects an inclination of the body in walking up a slope, a vestibulospinal reflex bends the knee joints of the forelegs and extends the knee joints of the hindlegs (Figure 6-(a)), and tries to keep the posture of the body flat and prevent the center of gravity from being pulled backward. When walking down a slope, a vestibulospinal reflex causes the extending of the forelegs and the bending of the hindlegs oppositely. The results of the experiment using both the muscle stiffness model and the vestibulospinal reflex: a robot succeeded in walking up a slope of 12 degrees and 40 cm length. In Figure 7, we can see that the hip joint of the right hindleg is more extended in walking up a slope and more flexed in walking down a slope according to the body inclination.

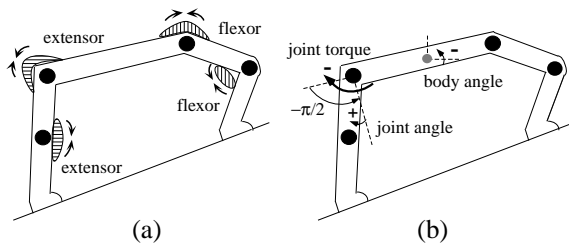


Figure 6: (a) Vestibulospinal reflex. (b) Origin and direction of angles and direction of torque in Figure 7.

4.3.2. Adjustment of stretch reflex activity

The results of the experiment using both the muscle stiffness model and the vestibulospinal reflex:

a robot failed in walking up a slope of 12 degrees and 65 cm length (Figure 3-(a)), and often fell down backward, since the robot could not obtain enough thrusting force for walking up a long slope. Therefore, we employ adjustment of the stretch reflex activity of the hip joints of the supporting legs in order to complement thrusting force for walking up a long slope. When a vestibulospinal reflex is activated, the cerebellum model detects a lack of thrusting force based on somatic sensation and increases the stretch reflex torque of supporting legs through the adjustment of the activity of the γ motor neuron controlling sensitivity of the muscle spindle (Section 2.1.). A lack of thrusting force is detected by using information from two sensors. One is the delay of the actual supporting phase measured by a contact sensor from the CPG supporting phase. Another is a decrease of the angular velocity of a hip joint of a supporting leg.

The results of the experiment using the above-described all adaptive control mechanisms: a robot succeeded in walking up and down a long slope (Figure 7, Figure 9-(a)). In Figure 7, we can see that large stretch reflex torque of a hip joint was added to CPG output torque when the activity of the γ motor neuron became large in the supporting phase.

4.4. Adaptive control based on vision

Drew[15] proposed a model about the adjustment of the directive signal to a CPG based on vision (Figure 1). When we use neural oscillators as a model of a CPG, the directive signal to a CPG corresponds with external input to neural oscillators: u_0 (Figure 2-(a)). We realized walking up a step 2 cm in height by increasing u_0 in the previous study[13]. These results showed that, once a step has been recognized by the upper controller, knowing when and how much u_0 should be changed is sufficient to generate the directive signal to the lower controller. This is because the lower controller: CPG has the ability for automatic interpolation and self-stabilization. This fact suggests the validity of Drew's model.

Although we have not yet succeeded in autonomous adjustment of u_0 based on Drew's model, a robot succeeded in walking up a step 3 cm in height (Figure 8, Figure 9-(b)) by increasing u_0 based on the height of the step and distance to the step measured by using stereo vision. In Figure 8, we can see that u_0 of each CPG was 5 times increased in swinging phase and 2 times increased in

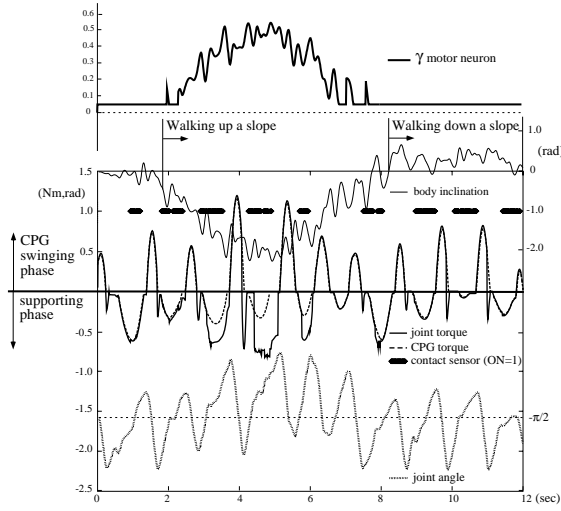


Figure 7: Result of the experiment involving walking up and down a long slope of 12 degrees by using the adjustment of stretch reflex activity in addition to the muscle stiffness model and a vestibulospinal reflex. CPG output torque, joint torque, the joint angle and activity of the γ motor neuron of a hip joint of a right hindleg are shown. The joint torque is the sum of output torque of CPG and reflexes. Contact sensor value of the leg and the body inclination are also shown. Origins and directions of angles and torque are shown in Figure 6-(b). Positive value and negative value of CPG output torque mean swinging phase and supporting phase of the leg in CPG level, respectively.

supporting phase in the order of LF, RF, RH and LH, and that CPG torque of a hip joint of each leg became large in the same order if we ignore the side effect by the neural oscillator coupling between diagonal paired legs. As a result, necessary torque for a swinging leg to be prevented from collision with a step and partial torque for a supporting leg to lift a body against gravity were obtained.

5. Discussion

5.1. Meaning of CPG and reflexes

As a result of physiological experiments using decerebrate cats, it is known that walking motion can be initiated both by electric stimulus to the brain stem and by peripheral stimulus from a treadmill. This fact prompts a simple question. That is, what kind of role does each stimulus play in the initia-

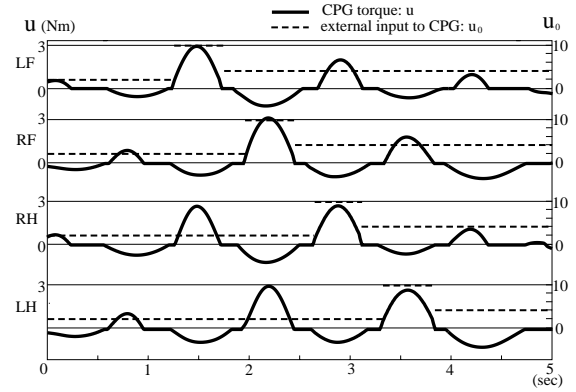


Figure 8: Result of the experiment involving walking up a step 3 cm in height by using adjustment of external input to CPG based on vision.

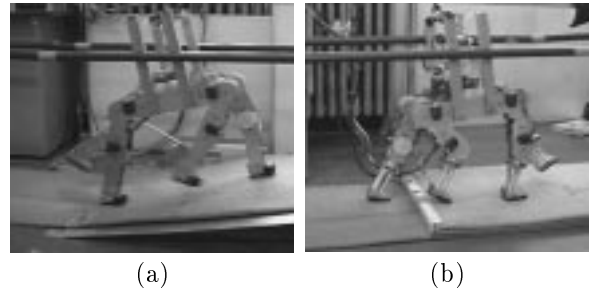


Figure 9: Photos of the quadruped walking up a long slope (a) and walking up a step by using vision (b).

tion and continuation of walking?

In the case of static walking, transitions between static states could be initiated and continued by peripheral stimulus alone, such as contact sensor input. But in the case of dynamic walking, a mechanism in a central system which directly outputs joint driving torque is essential in order to compensate inertia torque needed in quick motion. Feedforward torque calculation using dynamic equation in robotics and CPG in biology correspond with this mechanism.

This correspondence is made be clear when we consider “passive dynamic walking”[23] where a walking machine with no actuator can walk down a slope dynamically. In passive dynamic walking, it is clear that the passive mechanism itself has the ability for walking, 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.

On the other hand, contact sensor input is con-

sidered as a trigger to change a phase of dynamic equation in robotics and to activate a stretch reflex of supporting legs in biology.

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 trajectory planning¹, can be used in order to generate and control walking motion. Taga[9] pointed out that a single system can autonomously generate adaptation as a result of interaction between an internal nervous system, a musculoskeletal system, and environment without explicit models of a robot and environment.

5.3. Advantages of biologically inspired method

In order to make the advantages of the biologically inspired control method clear, let us compare results of the experiments in this study to results from experiments employing the conventional control method based on dynamics[16]. After this comparison, we can note the following advantages:

- (a) Abilities of CPG for mutual entrainment, pattern generation, automatic interpolation, and self-stabilization make CPG much more useful as a lower controller.
- (b) All elements of dynamics and algorithm in trajectory generation and control in the conventional method have been condensed into the parameters of a CPG and reflexes.

¹There exist neutral angles of hip and knee joints for stretch reflexes in a supporting phase. But neutral angles are constant. In addition, knee joints are PD-controlled so that the angles of knee joints become 60 degrees in a swinging phase.

- (c) A single system, where outputs of CPG and reflexes mean torque and there is no trajectory planning, is used in order to generate and control walking motion.

Parameterization and singularity as a system in generation and control of motion can make optimization, adaptation, and learning of motion be simple (Section 5.2.), since we can consider the adjustment of output torque directly for changes of terrain and external force.

5.4. What is legged locomotion?

Since the ZMP is very similar to the center of gravity, let us call walking controlled by the ZMP-based method “static walking.” We call walking controlled by the inverted pendulum model-based method or the biologically inspired method “dynamic walking.”

The studies on legged locomotion of a robot have various aspects in their intentions. One important goal is to realize a practical walking machine. For this purpose, significant endeavors have been made in mechanical design, static gait control on irregular terrain, and so on. On the other hand, studies aiming to clarify principles of legged locomotion have been actively continued. Passive dynamic walking[23] and a simply controlled hopping robot[24] were analyzed and realized as a nonlinear dynamic system. The realization of dynamic walking and running of robots by simplified control[17, 19] showed another principle of legged locomotion. This study aims to clarify principles of legged locomotion, especially dynamic walking, in view of dynamic adaptation to irregular terrain, which is another important aspect clearly.

Not all principles of dynamic walking have been clarified at this moment. But we can point out following principles obtained in biology[25] and robotics in spite of difference of actuators and sensors.

- (1) Since “passive dynamic walking” is possible but “passive static walking” is definitely impossible, we can consider dynamic walking is more primitive than static walking.
- (2) Dynamic walking is induced on a walking mechanism by external or internal force (Section 5.1.). If the ability of the mechanism for walking is high, such simple control by internal force as biologically inspired control proposed in this study is sufficient.

- (3) As similar to juggling and hopping, the realization of dynamic walking can be considered as the stabilization of non-linear oscillation repeating contact and non-contact with a floor.
- (4) The adjustment of parameters of reflexes and CPG based on sensor information enables the adaptation to irregular terrain.

6. Conclusion

We proposed the biologically inspired control method consisting of four levels. It is worthy of note that adaptive dynamic walking on irregular terrain was realized by using simple adjustments of reflexes and a CPG based on sensor information. We discussed about meanings and advantages of the biologically inspired control method and also discussed about principles of dynamic walking in animals and robots. Finding principles of adaptive dynamic walking should contribute to future engineering development of walking machines having both efficiency and adaptability.

Walking over terrain undulations and walking up and down steps are 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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