Biologically inspired adaptive walking of a quadruped robot

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We describe here the efforts to induce a quadruped robot to walk with medium-walking speed on irregular terrain based on biological concepts. We propose the necessary conditions for stable dynamic walking on irregular terrain in general, and we design the mechanical and the neural systems by comparing biological concepts with those necessary conditions described in physical terms. PD-controller at joints constructs the virtual spring-damper system as the viscoelasticity model of a muscle. The neural system model consists of a central pattern generator (CPG), reflexes and responses. We validate the effectiveness of the proposed neural system model control using the quadruped robots called ‘Tekken1&2’. MPEG footage of experiments can be seen at http://www.kimura.is.uec.ac.jp.

Keywords: adaptive walking; quadruped robot; neural system model; central pattern generator; reflexes and responses; irregular terrain

1. Introduction

Many previous studies of legged robots have been performed, including studies on running and dynamic walking on irregular terrain. However, most of those studies assumed that the structure of the terrain was known, even though the height of the step or the inclination of the slope was unknown. The purpose of this study is to realize high-speed mobility on irregular terrain with less knowledge using a mammal-like quadruped robot, the dynamic walking of which is less stable than that of hexapod robots, by referring to the well-known abilities of animals to autonomously adapt to their environment.

As many biological studies of motion control progressed, it has become generally accepted that animals’ walking is mainly generated at the spinal cord by a combination of a central pattern generator (CPG) and reflexes receiving adjustment signals from a cerebrum, cerebellum and brain stem (Orlovsky et al. 1999). A great deal of the previous research on this attempted to generate

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walking using a neural system model, including studies on dynamic walking in simulation (Taga et al. 1991; Ijspeert 2001; Tomita & Yano 2003) and real robots (Ilg et al. 1999; Kimura 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 our studies using quadruped robots called ‘Patrush’ (Kimura et al. 1999, 2001) and ‘Tekken1’ (Fukuoka et al. 2003). This paper reports on our progress using a self-contained (power autonomous) quadruped robot called ‘Tekken2’, which was newly developed for adaptive walking on irregular terrain in outdoor environment.

2. Design concepts for adaptive walking

(a) Legged locomotion control schemes

The schemes for legged locomotion control are classified into ZMP-based control and limit-cycle-based control (table 1). Zero moment point (ZMP) is the extension of the centre of gravity considering inertia force and so on. It was shown that ZMP-based control is effective for controlling posture and low-speed walking of a biped and a quadruped. However, ZMP-based control is not good for medium- or high-speed walking from the standpoint of energy consumption, since a body with a large mass needs to be accelerated and decelerated by actuators in every step cycle.

In contrast, motion generated by the limit-cycle-based control has superior energy efficiency; but there exists the upper bound of the period of the walking cycle, in which stable dynamic walking can be realized (Kimura et al. 1990). It should be noted that control by a neural system consisting of CPGs and reflexes is dominant for various kinds of adjustments in medium-speed walking of animals (Orlovsky et al. 1999). Full & Koditschek (1999) also pointed out that, in high-speed running, kinetic energy is dominant, and self-stabilization by a mechanism with a spring and a damper is more important than adjustments by the neural system. Our study is aimed at medium-speed walking controlled by neural system consisting of CPGs and reflexes (table 1).

Table 1. Legged locomotion control schemes and methods.

<table>
<thead>
<tr>
<th>limit cycle based</th>
<th>ZMP based</th>
<th>by neural system (CPG and reflexes)</th>
<th>by mechanism (spring and damper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>good for control of posture and low speed walking</td>
<td>medium speed walking</td>
<td>high speed running</td>
<td></td>
</tr>
<tr>
<td>main controller upper neural system acquired by learning</td>
<td>lower neural system (at spinal cord, brain stem, etc.)</td>
<td>musculoskeletal system through self-stabilization</td>
<td></td>
</tr>
<tr>
<td>methods (i), (ii)</td>
<td>(i), (ii), (iii)</td>
<td>(ii), (iii)</td>
<td></td>
</tr>
</tbody>
</table>
Legged locomotion control methods

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

(i) adjustment of joint torques within a single step cycle and
(ii) adjustment of initial conditions of the legs at the transition from swing to stance.

We would like to add a third method:

(iii) adjustment of phases (stance or swing) of the legs.

The method (ii) involves the adjustment of touchdown angle (stepping reflex) of a swinging leg (Miura & Shimoyama 1984; Townsend 1985; Raibert 1986; Bauby & Kuo 2000) and the switching of leg stiffness between stance and swing phases (Raibert 1986; Kimura et al. 1990; Taga et al. 1991; Fukuoka et al. 2003). Since the running speed can be stabilized using the constant touchdown angle, self-stabilization (Blickhan 1989; Full & Koditschek 1999; Cham et al. 2004; Poulakakis et al. 2005) at musculoskeleton is also involved in (ii). As the examples of the method (iii), we employed a ‘response’ as modulation of the CPG phase as described in §2e. Cham et al. (2004) also used the method (iii) for stabilizing the running speed of a hexapod on irregular terrain.

Of course, those three methods are not completely independent. For example, the method (iii) becomes much effective when the switching of leg stiffness between stance and swing phases is employed. The control methods mostly used in each scheme described in §2a are shown in table 1.

(b) Legged locomotion control methods

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(c) Mutual entrainment between neural system and mechanical system

Motion generation based on the neural system model is shown in figure 1, where a neural system and a mechanical system have their own nonlinear dynamics. The characteristic of this method is that there is no adaptation through motion planning. These two dynamic systems are coupled to each other, generating motion by interacting with the environment emergingly and adaptively (Taga et al. 1991). We call this method ‘coupled dynamics-based motion generation’.

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The coupled dynamic system can induce autonomous adaptation according to its own dynamics, under changes in the environment (e.g. adaptive walking on irregular terrain) and adjustment of the neural system parameters by an upper level controller (e.g. gait transition in change of walking speed). Therefore, we can avoid such serious problems in robotics as modelling of mechanical system and environment, autonomous planning, conflict between planned motion and actual motion and so on.

\((d)\) Necessary conditions for stable dynamic walking on irregular terrain

We propose the necessary conditions to keep the limit cycle for stable dynamic walking on irregular terrain\(^1\), which can be itemized in physical terms:

(i) the period of the walking cycle should be shorter enough than the upper bound of it, in which stable dynamic walking can be realized,
(ii) the swinging legs should be free to move forward during the first period of the swing phase,
(iii) the swinging legs should land reliably on the ground during the second period of the swing phase,
(iv) the angular momentum of the robot during its pitching motion or rolling motion around the contact points should be kept constant at the moment of landing or leaving of legs,
(v) the phase difference between rolling motion of the body and pitching motion of legs should be maintained regardless of a disturbance from irregular terrain, and
(vi) 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.

We design the neural system for these necessary conditions to be satisfied in order to realize adaptive walking.

\((e)\) Design of neural system

We construct the neural system centring a neural oscillator as a model of a CPG, since the exchange between the swing and stance phases in the short-term and the quick adjustment of these phases on irregular terrain are essential in the dynamic walking of a quadruped, where the unstable two-legged stance phase appears. On the other hand, the gait pattern generator proposed by Cruse (1990) referring to a stick insect is more sensor-dependent and more decentralized by using a non-oscillator type CPG. The characteristics of our neural system in comparison with the one proposed by Cruse (1990) are as follows.

(i) The cyclic period is mainly determined by the time constant of CPGs. This makes it easy for the necessary condition (i) described in §2d to be satisfied.
(ii) The gait is mainly determined by the connecting weights of the CPGs network.

\(^1\) When one of those conditions is not satisfied, walking motion is much away from the limit cycle and the robot may fall down at its worst.
As sensor feedback for adaptation on irregular terrain, a ‘response’ directly and quickly modulating the CPG phase is employed in parallel with a ‘reflex’ directly generating joint torque (figure 1).

About the characteristic (iii), it is well known in physiology that ‘some sensory stimuli modify CPG activity and reflexive responses to sensory stimuli are phase dependent under CPG activity’ (Cohen & Boothe 1999). Such interaction between CPG activity and a sensory stimulus is very important for adaptation, and corresponds to the necessary conditions described in physical terms in §2d.

(f) Design of mechanical system

In order to obtain appropriate mutual entrainment between neural and mechanical systems, mechanical systems should be well designed to have good dynamic properties. In addition, the performance of dynamic walking such as adaptability on irregular terrain, energy efficiency, maximum speed and so on, greatly depends on the mechanical design. The design concepts of Tekken1&2 (figure 2) are:

— high-power actuators and small inertia moment 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; and
— small contacting area at toes to increase adaptability on irregular terrain.

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3. Implementation of neural system for adaptive walking

(a) Rhythmic motion by CPG

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 and to be mutually entrained with a rhythmic joint motion (Taga et al. 1991; Cohen & Boothe 1999; Orlovsky et al. 1999). As a model of a CPG, we used a neural oscillator proposed by Matsuoka (1987), and applied to the biped simulation by Taga et al. (1991). A single neural oscillator consists of two mutually inhibiting neurons (figure 3a). Each neuron in this model is represented by the following nonlinear differential equations:

\[
\tau \dot{u}_{e,f} = -u_{e,f} + w_{ei} y_{e,f} - \beta v_{e,f} + u_0 + \text{Feed}_{e,f} + \sum_{j=1}^{n} w_{ij} y_{e,f,j},
\]

\[
y_{e,f} = \max(u_{e,f}, 0),
\]

\[
\tau' \dot{v}_{e,f} = -v_{e,f} + y_{e,f},
\]

where the suffixes e, f and i mean an extensor neuron, a flexor neuron and the i\textsuperscript{th} neural oscillator, respectively. \(u_{e,f}\) is \(u_{ei}\) or \(u_{fi}\) i.e. the inner state of an extensor neuron or a flexor neuron of the i\textsuperscript{th} neural oscillator; \(v_{e,f}\) is a variable representing the degree of the self-inhibition effect of the neuron; \(y_{ei}\) and \(y_{fi}\) are the output of

Figure 3. Neural oscillator (NO) as a model of a CPG. The suffix i, j = 1, 2, 3, 4 corresponds to LF, LH, RF, RH. L, R, F or H means the left, right, fore or hind leg, respectively.
extensor and flexor neurons; \( u_0 \) is an external input with a constant rate; \( \text{Feed}_{(e,f)} \) is a feedback signal from the robot, i.e. a joint angle, angular velocity and so on; and \( \beta \) is a constant representing the degree of the self-inhibition influence on the inner state. The quantities \( \tau \) and \( \tau' \) are the time constants of \( u_{(e,f)} \) and \( v_{(e,f)} \); \( w_{ef} \) is a connecting weight between flexor and extensor neurons; \( w_{ij} \) is a connecting weight between neurons of the \( i \)th and \( j \)th neural oscillator.

In figure 3a, the output of a CPG is a phase signal, \( y_i \):

\[
y_i = -y_{e_i} + y_{f_i}. \tag{3.2}
\]

The positive or negative value of \( y_i \) corresponds to the activity of a flexor or extensor neuron, respectively. The output of a CPG: \( y_i \) while walking on flat floor is shown in figure 12.

We use the following hip-joint angle feedback as a basic sensory input to a CPG called a ‘tonic stretch response’ in all the experiments of this study. This negative feedback makes a CPG be entrained with a rhythmic hip joint motion.

\[
\text{Feed}_{e,\text{tsr}} = k_{\text{tsr}}(\theta - \theta_0), \quad \text{Feed}_{f,\text{tsr}} = -\text{Feed}_{e,\text{tsr}}, \tag{3.3}
\]

\[
\text{Feed}_{(e,f)} = \text{Feed}_{(e,f),\text{tsr}}, \tag{3.4}
\]

where \( \theta \) is the measured hip joint angle, \( \theta_0 \) the origin of the hip joint angle in standing and \( k_{\text{tsr}} \) the feedback gain. We eliminate the suffix \( i \) when we consider a single neural oscillator.

By connecting the CPG of each leg (figure 3b), 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. The gait is a walking pattern, and can be defined by phase differences between the legs during their pitching motion. The typical symmetric gaits are a trot and a pace. The diagonal and lateral legs are paired and move together in a trot and a pace gaits, respectively. A walk gait is the transversal gait between the trot and pace gaits. We used a trot gait for most of the experiments. But the autonomous gait transition in changing walking speed was discussed in our former study (Fukuoka et al. 2003).

(b) Virtual spring–damper system

We employ the model of the muscle stiffness, which 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 for supporting a body against the gravity and low in a swing phase for compliance against the disturbance (Akazawa et al. 1982). All the joints of Tekken are proportional and derivative (PD) controlled to move to their desired angles in each of the three states (A, B, C) 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 timing for all joints of a leg to switch to the next state are:

\[
A \rightarrow B: \text{ when the hip joint of the leg reaches the desired angle of the state (A)}; \quad B \rightarrow C: \text{ when the CPG extensor neuron of the leg becomes active (} y_i < 0); \quad C \rightarrow A: \text{ when the CPG flexor neuron of the leg becomes active (} y_i > 0).
\]

The desired angles and P-gain of each joint in each state are shown in table 2, where constant values of the desired joint angles and constant P-gains were determined through experiments. Since Tekken has high backdrivability with small
gear ratio in each joint, PD-controller can construct the virtual spring–damper system with relatively low stiffness coupled with the mechanical system. Such compliant joints of legs can improve the passive adaptability on irregular terrain.

Table 2. 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 shown in figure 4. \( \theta, \phi \) and \( \psi \) are the hip pitch joint angle, the knee pitch joint angle and the hip yaw joint angle, respectively. \( \theta_{C \rightarrow A} \): the hip joint angle measured at the instance when the state changes from (C) to (A). \( \theta_{\text{stance}} \): variable to change the walking speed. Body pitch angle: the measured pitching angle of the body used for the vestibulospinal reflex. * means that the desired angle is calculated on-line for the height from the toe to the hip joint to be constant. \( v \) (m s\(^{-1}\)): the measured walking speed of Tekken.

<table>
<thead>
<tr>
<th>angle in state</th>
<th>desired value (rad)</th>
<th>P-gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta ) in A</td>
<td>1.2( \theta_{C \rightarrow A} )</td>
<td>( G_1 )</td>
</tr>
<tr>
<td>( \theta ) in B</td>
<td>(-0.17)</td>
<td>( G_2 v + G_3 )</td>
</tr>
<tr>
<td>( \theta ) in C</td>
<td>( \theta_{\text{stance}} + \text{body pitch angle} )</td>
<td>(- G_4 v + G_5 )</td>
</tr>
<tr>
<td>( \phi ) in A and B</td>
<td>*</td>
<td>( G_6 )</td>
</tr>
<tr>
<td>( \phi ) in C</td>
<td>0.61</td>
<td>( G_7 )</td>
</tr>
<tr>
<td>( \psi ) in all states</td>
<td>0</td>
<td>( G_8 )</td>
</tr>
</tbody>
</table>

(c) CPGs and pitching motion of legs

The diagram of the pitching motion control consisting of CPGs and the virtual spring–damper system is shown in the middle part of figure 10. Joint torque of all the joints is determined by the PD controller, corresponding to a stretch reflex at
the α motor neuron in animals. The desired angle and P-gain of each joint is switched based on the phase of the CPG output: \( y_i \) in equation (3.2) as described in §3b. As a result of the switching of the virtual spring–damper system and the joint angle feedback signal to the CPG in equation (3.4), the CPG and the pitching motion of the leg are mutually entrained.

(d) Reflexes and responses

As described in §2e, we use responses for direct and quick modulation of the CPG phase and reflexes for direct and quick adjustment of joint torque. Referring to biological knowledge, we employed the several reflexes and responses (table 4, figure 10) to satisfy the necessary conditions (ii)–(v) described in physical terms in §2d in addition to the stretch reflex and response described in §3a,b. The necessary condition (vi) can be satisfied by the mutual entrainment between CPGs and the pitching motion of legs, and the mutual entrainment among CPGs (Kimura et al. 2001).

(i) Flexor reflex

The flexor reflex contributes to satisfy the necessary conditions (ii). In our former studies (Kimura et al. 1999, 2001), the stumble of a swinging leg on an obstacle was detected by force sensor, and the flexor reflex was activated afterwards. In Tekken, we substitute the flexor reflex for the passive ankle joint mechanism (Fukuoka et al. 2003) utilizing the fact that the collision with a forward obstacle occurs in the first half of a swing phase.

(ii) Vestibulospinal reflex and response for pitching

About posture control, it is known in physiology (Ogawa et al. 1998) that when the vestibule in a head detects an inclination in pitch or roll plane, a downward-inclined leg is extended while an upward-inclined leg is flexed (figure 5). We call this a ‘vestibulospinal reflex.’

We call the reflex/response for an inclination in the pitch plane a ‘vestibulospinal reflex/response for pitching’, the role of which corresponds to the necessary conditions (iv) and (vi). In Tekken, hip joint torque in the stance phase is adjusted by the vestibulospinal reflex (figure 5a), since the body pitch angle is added to \( \theta_{\text{stance}} \) in table 2. For the vestibulospinal response, the following equations are used rather than equations (3.3) and (3.4):

\[
\theta_{\text{vsr}} = \theta - \text{(body pitch angle)} \quad \text{Feed}_{\text{(e,f)·tsr·vsr}} = \pm k_{\text{tsr}}(\theta_{\text{vsr}} - \theta_0), \tag{3.5}
\]

\[
\text{Feed}_{\text{(e,f)}} = \text{Feed}_{\text{(e,f)·tsr·vsr}}. \tag{3.6}
\]

(iii) Vestibulospinal response for rolling

We call the response for an inclination in the roll plane a ‘tonic labyrinthine response’\(^2\). The tonic labyrinthine response (TLRS) is employed as rolling motion feedback to CPGs (upper left part of figure 10). In Tekken, we made the body roll angle be given as input to the CPGs as a feedback signal expressed by

\(^2\) The ‘tonic labyrinthine reflex’ is defined in Ogawa et al. (1998). The same reflex is called ‘vestibular reflex’ in Ghez (1991).
The rolling motion feedback to CPGs, equations (3.7) and (3.8), contributes to an appropriate adjustment of the periods of the stance and swing phases while walking on irregular terrain (figure 6; Fukuoka et al. 2003). It helps the necessary conditions (iii) and (iv) be satisfied.

The rolling motion feedback to CPGs is important also in order to satisfy the necessary condition (v). CPGs, the pitching motions of the legs and the rolling motion of the body are mutually entrained through the rolling motion
feedback to CPGs (figure 7). This means that the rolling motion can be the standard oscillation for whole oscillations, in order to compensate for the weak connection between the fore and hind legs in the CPG network (figure 3b). As a result, the phase difference between the fore and hind legs is fixed and the gait becomes stable.

(iv) Sideway stepping reflex to stabilize rolling motion

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

For example, when Tekken walks on a right-inclined slope (figure 8) it can continue to walk while keeping the phase differences between left and right legs with the help of the tonic labyrinthine response. But Tekken cannot walk straight and shifts its walking direction to the right owing to the difference of the gravity load between left and right legs. In addition, Tekken typically falls down to the right for the perturbation from the left in the case of figure 8a, since the wide stability margin: $WSM^3$ is small. The sideway stepping reflex helps to stabilize the walking direction and prevent the robot from falling down while keeping $WSM$ large on such sideway inclined slope (figure 8b).

Since Tekken has no joint round the roll axis, the sideway stepping reflex is implemented as changing the desired angle of the hip yaw joint from 0 (table 2)

---

$WSM^3$ The shortest distance from the projected point of the centre of gravity to the edges of the polygon constructed by the projected points of legs independent of their stance or swing phases (Fukuoka et al. 2003).
to $\psi^*$ according to equation (3.9),

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

(3.9)

(v) **Re-stepping reflex and response for walking down a step**

When loss of ground contact is detected in a swing phase while walking over a ditch, a cat activates re-stepping to extend the swing phase and make the leg land on the more forward position (Hiebert et al. 1994). We call this ‘re-stepping reflex/response’, which is effective for the necessary conditions (iii) and (iv) to be satisfied also in walking down a large step (figure 9).

(e) **Active landing control on the soft ground**

While walking on the soft ground, the rolling motion is much disturbed since it takes longer to establish the reliable landing of the swinging legs. Tekken changes the state of the virtual spring–damper system from the swinging to the stance before the actual contact of a leg on the ground, when the output phase of a CPG changes from the flexor neuron active phase to the extensor neuron active phase ($y_l \leq 0$) as described in §3b. This control
contributes to obtain the reliable landing of the swinging legs as soon as possible, and helps the necessary condition (iii) be satisfied.

4. Experiments

The control diagram for Tekken1&2 is shown in figure 10. Values of all parameters in the neural system including the virtual spring–damper system except for \( \theta_{\text{stance}} \) were determined experimentally. But it should be noted that values of all parameters for Tekken1 (Fukuoka et al. 2003) or 2 (table 3) were constant in the following experiments independent of terrain. The sensitivity and robustness of those parameters were discussed in our former study (Fukuoka et al. 2003).

(a) Indoor experiments

We made Tekken1 walk on flat floor while changing the walking speed in relating to §3d(iii). In figure 12, when \( \theta_{\text{stance}} \) was changed at 3.5 s, Tekken1 increased its walking speed from 0.3 to 0.5 m s\(^{-1}\). We can see that the cyclic period of walking was decreased from 0.64 to 0.48 s while \( \tau \) is constant, and the
amplitude of the rolling motion became much smaller after 3.5 s. In addition, we can see especially in the first half that CPG output and rolling motion of the body were mutually entrained.

We made Tekken1 walk over several types of irregular terrain in indoor environment (Fukuoka et al. 2003). Tekken1 walked over an obstacle 4 cm in height while stumbling and landing on the obstacle (figure 11a). Tekken1 walked up and down a slope of 10° in the forward direction (figure 11b), walked over sideways inclined slopes of 3 and 5° (figure 11c), and walked over pebbles (figure 11d).

Tekken1 successfully walked down a large step with ca 0.5 m s\(^{-1}\) speed using the re-stepping reflex/response. In figure 13, a re-stepping response was activated when the contact of the right fore leg had not been detected for 0.14 s after the activity of the flexor neuron became 0. Without the re-stepping reflex/response, Tekken1 typically fell down forward because fore legs landed on the more backward position excessively and could not depress the increased forward speed.

(b) Outdoor experiments

Even on a paved road in outdoor environment, there exist a slope of 3° at most, bumps of 1 cm in height and small pebbles everywhere. With all responses and reflexes (table 4) described in §3d, Tekken2 successfully maintained a stable gait on the paved road for 4 min with ca 0.5 m s\(^{-1}\) speed while changing its walking speed and direction by receiving the operation commands from the radio controller (figure 14a). In addition, the effectiveness

Table 3. Values of the parameters used in experiments using Tekken2.

<table>
<thead>
<tr>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_0)</td>
<td>1.0</td>
</tr>
<tr>
<td>(\tau)</td>
<td>0.04</td>
</tr>
<tr>
<td>(\tau')</td>
<td>0.6</td>
</tr>
<tr>
<td>(\beta)</td>
<td>3.0</td>
</tr>
<tr>
<td>(w_{fr})</td>
<td>-2.0</td>
</tr>
<tr>
<td>(W_{[13,31,24,42]})</td>
<td>-2.0</td>
</tr>
<tr>
<td>(W_{[12,34]})</td>
<td>0</td>
</tr>
<tr>
<td>(W_{[21,43]})</td>
<td>-0.57</td>
</tr>
<tr>
<td>(k_{tst}(\text{rad}^{-1}))</td>
<td>3.0</td>
</tr>
<tr>
<td>(k_{thr}(\text{rad}^{-1}))</td>
<td>2.25</td>
</tr>
<tr>
<td>(k_{spr})</td>
<td>0.5</td>
</tr>
<tr>
<td>(\theta_0(\text{rad}))</td>
<td>-1.06</td>
</tr>
<tr>
<td>(G_1(\text{Nm rad}^{-1}))</td>
<td>7.0</td>
</tr>
<tr>
<td>(G_2(\text{Nm rad}^{-1}))</td>
<td>0.6</td>
</tr>
<tr>
<td>(G_3(\text{Nm rad}^{-1}))</td>
<td>0.6</td>
</tr>
<tr>
<td>(G_4(\text{Nm rad}^{-1}))</td>
<td>1.0</td>
</tr>
<tr>
<td>(G_5(\text{Nm rad}^{-1}))</td>
<td>2.0</td>
</tr>
<tr>
<td>(G_6(\text{Nm rad}^{-1}))</td>
<td>7.0</td>
</tr>
<tr>
<td>(G_7(\text{Nm rad}^{-1}))</td>
<td>2.6</td>
</tr>
<tr>
<td>(G_8(\text{Nm rad}^{-1}))</td>
<td>2.0</td>
</tr>
</tbody>
</table>
of the active landing control on the soft ground was confirmed by the successful experiment of walking on the natural ground with scattered pebbles and grasses (figure 14b).

Figure 11. Tekken1 is walking over irregular terrain.
5. Conclusion

In this study, we designed the neural system consisting of CPGs, responses and reflexes referring to biological concepts while taking the necessary conditions for adaptive walking into account. In this neural system model, the relationships among CPGs, sensory input, reflexes and the mechanical system were simply defined, and motion generation and adaptation were emergingly induced by the coupled dynamics of a neural system and a mechanical system by interacting with the environment.

In order to make the self-contained quadruped robot walk in outdoor natural environment, we newly employed a sideway stepping reflex, a re-stepping reflex/response and the active landing control of the swinging legs. We should...
employ additional reflexes and responses to increase the degrees of terrain irregularity which Tekken can cope with, and also navigation ability using vision.

Table 4. Reflexes and responses employed on Tekken. All responses are categorized into the control method (iii) described in §2b. Flexor and vestibulospinal reflexes are categorized into the control method (i). Stepping, sideway stepping and re-stepping reflexes are categorized into the control method (ii). The sp and sw mean the supporting leg and swinging leg, respectively. The corresponding necessary conditions are described in §2d.

<table>
<thead>
<tr>
<th>Reflexes and responses</th>
<th>sensed value or event</th>
<th>activated on</th>
<th>necessary conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>flexor reflex</td>
<td>collision with obstacle</td>
<td>sw</td>
<td>(ii)</td>
</tr>
<tr>
<td>stepping reflex</td>
<td>forward speed</td>
<td>sw</td>
<td>(iv)</td>
</tr>
<tr>
<td>vestibulospinal reflex/response</td>
<td>body pitch angle</td>
<td>sp</td>
<td>(iv)</td>
</tr>
<tr>
<td>tonic labyrinthine response</td>
<td>body roll angle</td>
<td>sp&amp;sw</td>
<td>(iii), (iv), (v)</td>
</tr>
<tr>
<td>sideway stepping reflex</td>
<td>body roll angle</td>
<td>sw</td>
<td>(iv)</td>
</tr>
<tr>
<td>re-stepping reflex/response</td>
<td>loss of ground contact</td>
<td>sw</td>
<td>(iv)</td>
</tr>
</tbody>
</table>

Figure 14. Photos of walking of Tekken2 on (a) paved road and (b) natural ground. The cable is just to prevent Tekken2 from damage in case of emergency and is usually slack.

References


