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Gait Transition from Quadrupedal to Bipedal Locomotion of an Oscillator-driven Biped Robot

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1. Introduction

Studies on biped robots have attracted interest due to such problems as inherent poor stability and the cooperation of a large degree of freedom. Furthermore, recent advanced technology, including hardware and software, allows these problems to be tackled, accelerating the interest. Actually, many sophisticated biped robots have already been developed that have successfully achieved such various motions as straight walking, turning, climbing slopes, rising motion, and running (Aoi & Tsuchiya, 2005; Aoi et al., 2004; Hirai et al., 1998; Kuniyoshi et al., 2004; Kuroki et al. 2003; Löffler et al., 2003; Nagasaki et al., 2004).

Steady gait for a biped robot implies a stable limit cycle in its state space. Therefore, different steady gait patterns have different limit cycles, and gait transition indicates that the state of the robot moves from one limit cycle to another. Even if the robot obtains steady gait patterns, their transition is not necessarily confirmed as completed. Thus, smooth transition between gait patterns remains difficult. To overcome such difficulty, many studies have concentrated on model-based approaches using inverse kinematics and kinetics. These approaches basically generate robot motions based on such criteria as zero moment point (Vukobratović et al., 1990) and manipulate robot joints using motors. However, they require accurate modeling of both the robot and the environment as well as complicated computations. The difficulty of achieving adaptability to various environments in the real world is often pointed out, which means that in these approaches the robot is too *rigid* to react appropriately to environmental changes. Therefore, the key issue in the control is to establish a *soft* robot by adequately changing the structure and response based on environmental changes.

In contrast to robots, millions of animal species adapt themselves to various environments by cooperatively manipulating their complicated and redundant musculoskeletal systems. Many studies have elucidated the mechanisms in their motion generation and control. In particular, neurophysiological studies have revealed that muscle tone control plays important roles in generating adaptive motions (Mori, 1987; Rossignol, 1996; Takakusaki et al., 2003), suggesting the importance of compliance in walking. Actually, many studies on robotics have demonstrated the essential roles of compliance. Specifically, by appropriately employing the mechanical compliance of robots, simple control systems have attained highly adaptive and robust motions, especially in hexapod (Altendorfer et al., 2001; Cham et al., 2004; Quinn et al., 2003; Saranli et al., 2001), quadruped (Fukuoka et al., 2003; Poulakakis

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et al., 2005), and biped robots (Takuma & Hosoda, 2006; Wisse et al., 2005). However, note that control systems using motors continue to have difficulty adequately manipulating compliance in robot joints.

On the other hand, neurophysiological studies have also clarified that animal walking is generated by central pattern generators (CPGs) that generate rhythmic signals to activate their limbs (Grillner, 1981, 1985; Orlovsky et al., 1999). CPGs modulate signal generation in response to sensory signals, resulting in adaptive motions. CPGs are widely modeled using nonlinear oscillators (Taga et al., 1991; Taga, 1995a,b), and based on such CPG models many walking robots and their control systems have been developed, in particular, for quadruped robots (Fukuoka et al., 2003; Lewis & Bekey, 2002; Tsujita et al., 2001), multi-legged robots (Akimoto et al., 1999; Inagaki et al., 2003), snake-like robots (Ijspeert et al., 2005; Inoue et al., 2004), and biped robots (Aoi & Tsuchiya, 2005; Aoi et al., 2004; Lewis et al., 2003; Nakanishi et al., 2004).

This paper deals with the transition from quadrupedal to bipedal locomotion of a biped robot while walking. These gait patterns originally have poor stability, and the transition requires drastic changes in robot posture, which aggravates the difficulty of establishing the transition without falling over. Our previous work developed a simple control system using nonlinear oscillators by focusing on CPG characteristics that are used for both quadruped and biped robots, revealing that they achieved steady and robust walking verified by numerical simulations and hardware experiments (Aoi & Tsuchiya, 2005; Aoi et al., 2004; Tsujita et al., 2001). In this paper, we use the same developed control system for both quadrupedal and bipedal locomotion of a biped robot and attempt to establish smooth gait transition. Specifically, we achieve stable limit cycles of these gait patterns and their transitions by moving the robot state from one limit cycle to another by cooperatively manipulating their physical kinematics through numerical simulations. This paper is organized as follows. Section 2 introduces the biped robot model considered in this paper. Section 3 explains the developed locomotion control system, and Section 4 addresses the approach of gait transition and numerical results. Section 5 describes the discussion and conclusion.

2. Biped robot model

Figure 1(a) shows the biped robot model considered in this paper. It consists of a trunk, a pair of arms composed of four links, and a pair of legs composed of six links. Each link is connected to the others through a single degree of freedom rotational joint. A motor is installed at each joint. Four touch sensors are attached to the sole of each foot, and one touch sensor is attached to the tip of the hand of each arm. The left and right legs are numbered Legs 1 and 2, respectively. The joints of the legs are also numbered Joints 1…6 from the side of the trunk, where Joints 1, 2, and 3 are yaw, roll, and pitch hip joints, respectively. Joint 4 is a pitch knee joint, and Joints 5 and 6 are pitch and roll ankle joints. The arms are also numbered in a similar manner. Joints 1 and 4 are pitch joints, Joint 2 is a roll joint, and Joint 3 is a yaw joint. To describe the configuration of the robot, we introduce angles $\theta^i_{\mathrm{A}j}$ and $\theta^i_{\mathrm{L}k}$ (i=1,2, j=1,…,4, k=1,…,6), which are rotation angles of Joint j of Arm i and Joint k of Leg i, respectively. The robot walks quadrupedally and bipedally, as shown in Figs. 1(b) and (c). Its physical parameters are shown in Table 1. The ground is modeled as a spring with a damper in numerical simulations.

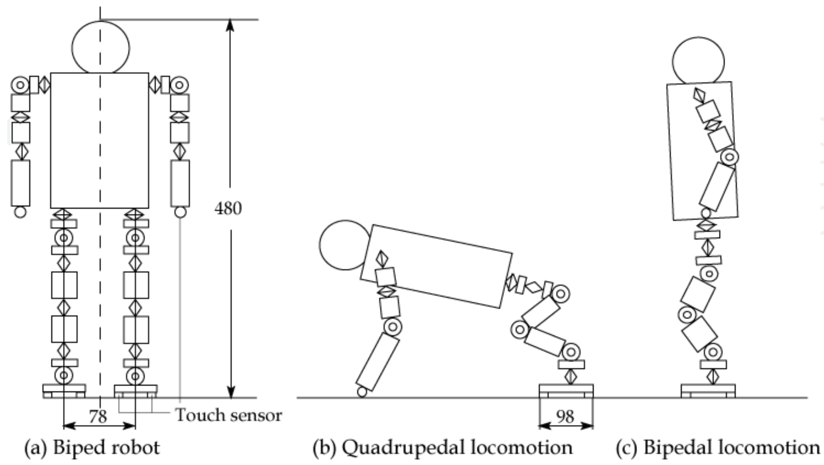


Fig. 1. Schematic model of a biped robot [mm].

Link	Mass [kg]	Length [m]
Trunk	2.34	0.20
Leg	1.32	0.28
Arm	0.43	0.25
Total	5.84	0.48

Table 1. Physical parameters of robot.

3. Locomotion control system

3.1 Concept of the control system

As described above, the crucial issue in controlling a biped robot is establishing a mechanism in which the robot adapts itself by changing its internal structure based on interactions between the robot's mechanical system and the environment. Neurophysiological studies have revealed that animal walking is generated by CPGs comprised of a set of neural oscillators present in the spinal cord. CPGs characteristically have the following properties:

1. CPGs generate inherent rhythmic signals that activate their limbs to generate rhythmic motions;
2. CPGs are sensitive to sensory signals from peripheral nerves and modulate signal generation in response to them.

Animals can immediately adapt to environmental changes and disturbances by virtue of these features and achieve robust walking.

We have designed a locomotion control system that has an internal structure that adapts to environmental changes, referring to CPG characteristics. In particular, we employed nonlinear oscillators as internal states that generate inherent rhythmic signals and adequately respond to sensory signals. Since the motor control of a biped robot generally uses local high-gain feedback control to manipulate the robot joints, we generated nominal joint motions using rhythmic signals from the oscillators. One of the most important factors in the dynamics of walking is the interaction between the robot and the external world, that is, dynamical interaction between the robot feet and the ground. The leg motion consists of swing and stance phases, and a harmonious balance must be achieved between these kinematical motions and dynamical interaction, which means that it is essential to adequately switch from one phase to another. Therefore, our developed control system focused on this point. Specifically, it modulated the signal generation of the oscillators and appropriately changed the leg motions from the swing to the stance phase based on touch sensors. Although we concisely describe the developed control system below, see our previous work (Aoi & Tsuchiya, 2005) for further details.

3.2 Developed locomotion control system

The locomotion control system consists of a motion generator and controller (see Fig. 2(a)). The former is composed of rhythm and trajectory generators. The rhythm generator has two types of oscillators: Motion and Inter (see Fig. 2(b)). As Motion oscillators, there are Leg 1, Leg 2, Arm 1, Arm 2, and Trunk oscillators. The oscillators follow phase dynamics in which they have interactions between themselves and receive sensory signals from touch sensors. The trajectory generator creates nominal trajectories of robot joints by phases of Motion oscillators, which means that it generates physical kinematics of the robot based on rhythmic signals from the oscillators. It receives outer commands and changes the physical kinematics to reflect the outer commands. The nominal trajectories are sent to the motion controller in which motor controllers manipulate the joint motions using the nominal trajectories as command signals. Note that physical kinematics is different between quadrupedal and bipedal locomotion, and except for the kinematics, throughout this paper we use the same control system regardless of gait patterns.

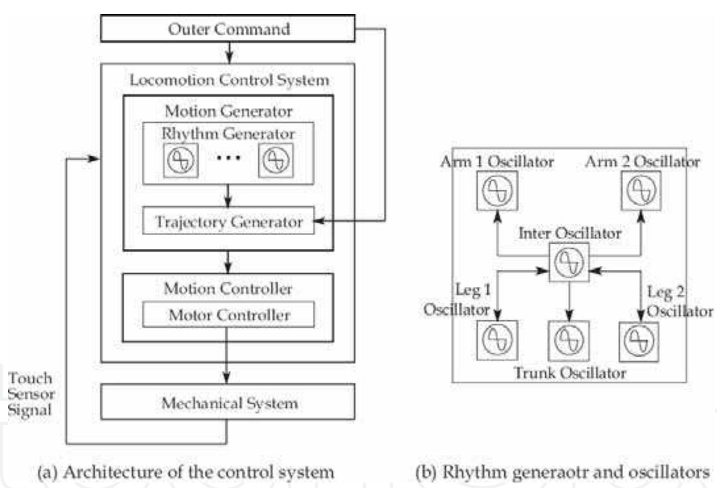


Fig. 2. Locomotion control system.

3.2.1 Trajectory generator

As mentioned above, the trajectory generator creates nominal trajectories of all joints based on the phases of the Motion oscillators. First, let φ_L^i, φ_A^i, φ_T, and φ_I (i=1,2) be the phases of Leg i, Arm i, Trunk, and Inter oscillators, respectively.

The nominal trajectories of the leg joints are determined by designing the nominal trajectory of the foot, specifically Joint 5, relative to the trunk in the pitch plane. The nominal foot trajectory consists of swing and stance phases (see Fig. 3). The former is composed of a simple closed curve that includes anterior extreme position (AEP) and posterior extreme position (PEP). This trajectory starts from point PEP and continues until the leg touches the ground. On the other hand, the latter consists of a straight line from the foot landing position (LP) to point PEP. Therefore, this trajectory depends on the timing of foot contact with the ground in each step cycle. Both in the swing and stance phases, nominal foot movement is designed to be parallel to the line that involves points AEP and PEP. The height and forward bias from the center of points AEP and PEP to Joint 3 of the leg are defined as parameters Δ_{L} and H_{L}, respectively. These two nominal foot trajectories provide nominal trajectories $\hat{\theta}^i_{\mathrm{L}j}$ (i=1,2, j=3,4,5) of Joint j (hip, knee, and ankle pitch joints) of Leg i by the functions of phase φ^i_{L} of Leg i oscillator written by $\hat{\theta}^i_{\mathrm{L}j}(\varphi^i_{\mathrm{L}})$, where we use $\varphi^i_{\mathrm{L}}=0$ at point PEP and $\varphi^i_{\mathrm{L}}=\hat{\varphi}_{\mathrm{AEP}}$ at point AEP. Note that nominal stride $\hat{S}$ is given by the distance between points AEP and PEP, and duty factor $\hat{\beta}$ is given by the ratio between the nominal stance phase and step cycle durations.

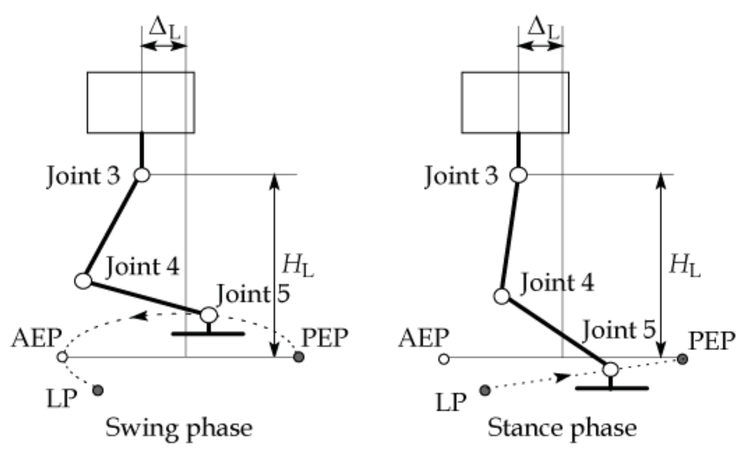


Fig. 3. Nominal foot trajectory.

The nominal trajectories of the arm joints are generated in a similar way to the leg joints described above except for the bend direction between Joint 4 of the arm and Joint 4 of the leg (see Fig. 4 below). Similar to the foot trajectory, the nominal trajectory of the hand, specifically the touch sensor at the tip of the arm, is designed relative to the trunk in the pitch plane, which consists of the swing and stance phases. Then, also from inverse kinematics, nominal trajectories $\hat{\theta}^i_{\mathrm{A}j}$ (i=1,2, j=1,…,4) of Joint j of Arm i are given by the functions of phase φ^i_{A} of Arm i oscillator. The nominal trajectories of the arm joints also have parameters Δ_{A} and H_{A}, similar to those of the leg joints, that use the same nominal stride $\hat{S}$ and duty ratio $\hat{\beta}$ as leg motions.

3.2.2 Rhythm generator and sensory signals

In the rhythm generator, Motion and Inter oscillators generate rhythmic behavior based on the following phase dynamics:

$$\begin{aligned} \dot{\varphi}_{\mathrm{I}} &= \hat{\omega} + g_{1\mathrm{I}} \\ \dot{\varphi}_{\mathrm{T}} &= \hat{\omega} + g_{1\mathrm{T}} \\ \dot{\varphi}_{\mathrm{A}}^{i} &= \hat{\omega} + g_{1\mathrm{A}}^{i} + g_{2\mathrm{A}}^{i} \quad i=1,2 \\ \dot{\varphi}_{\mathrm{L}}^{i} &= \hat{\omega} + g_{1\mathrm{L}}^{i} + g_{2\mathrm{L}}^{i} \quad i=1,2 \end{aligned} \tag{1}$$

where $g_{1\mathrm{I}}$, $g_{1\mathrm{T}}$, $g_{1\mathrm{A}}^{i}$, and $g_{1\mathrm{L}}^{i}$ (i=1,2) are functions regarding the nominal phase relationship shown below, $g_{2\mathrm{A}}^{i}$ and $g_{2\mathrm{L}}^{i}$ (i=1,2) are functions arising from sensory signals given below, and $\hat{\omega}$ is the nominal angular velocity of each oscillator obtained by

$$\hat{\omega} = 2\pi \frac{1-\hat{\beta}}{\hat{T}_{\mathrm{sw}}} \tag{2}$$

where $\hat{T}_{\mathrm{sw}}$ is the nominal swing phase duration.

To establish stable walking, the essential problem is the coordination of joint motions. Interlimb coordination is the key. For example, both legs must move out of phase to prevent the robot from falling over during bipedal locomotion. Since the nominal joint trajectories for the limbs are designed by oscillator phases, interlimb coordination is given by the phase relation, that is, the phase differences between oscillators. Functions $g_{1\mathrm{I}}$, $g_{1\mathrm{T}}$, $g_{1\mathrm{A}}^{i}$, and $g_{1\mathrm{L}}^{i}$ in Eq. (1), which deal with interlimb coordination, are given by the phase differences between oscillators based on Inter oscillator, written by

$$\begin{aligned} g_{1\mathrm{I}} &= -\sum_{i=1}^{2} K_{\mathrm{L}} \sin(\varphi_{\mathrm{I}} - \varphi_{\mathrm{L}}^{i} + (-1)^{i}\pi/2) \\ g_{1\mathrm{T}} &= -K_{\mathrm{T}} \sin(\varphi_{\mathrm{T}} - \varphi_{\mathrm{I}}) \\ g_{1\mathrm{A}}^{i} &= -K_{\mathrm{A}} \sin(\varphi_{\mathrm{A}}^{i} - \varphi_{\mathrm{I}} + (-1)^{i}\pi/2) \quad i=1,2 \\ g_{1\mathrm{L}}^{i} &= -K_{\mathrm{L}} \sin(\varphi_{\mathrm{L}}^{i} - \varphi_{\mathrm{I}} - (-1)^{i}\pi/2) \quad i=1,2 \end{aligned} \tag{3}$$

where nominal phase relations are given so that both the arms and legs move out of phase and one arm and the contralateral leg move in phase and K_{L}, K_{A}, and K_{T} are gain constants.

In addition to physical kinematics and interlimb coordination, the modulation of walking rhythm is another important factor to generate walking. Functions $g_{2\mathrm{A}}^{i}$ and $g_{2\mathrm{L}}^{i}$ modulate walking rhythm through the modulation of the phases of oscillators based on sensory signals. Specifically, when the hand of Arm i (the foot of Leg i) lands on the ground, Arm i oscillator (Leg i oscillator) receives a sensory signal from the touch sensor (i=1,2). Instantly, phase φ_{A}^{i} of Arm i oscillator (phase φ_{L}^{i} of Leg i oscillator) is reset to nominal value $\hat{\varphi}_{\mathrm{AEP}}$ from value $\varphi_{\mathrm{land}}^{i}$ at the landing. Therefore, functions $g_{2\mathrm{A}}^{i}$ and $g_{2\mathrm{L}}^{i}$ are written by

$$\begin{aligned} g_{2\mathrm{A}}^{i} &= (\hat{\varphi}_{\mathrm{AEP}} - \varphi_{\mathrm{land}}^{i})\delta(t - t_{\mathrm{land}}^{i}) \quad i=1,2 \\ g_{2\mathrm{L}}^{i} &= (\hat{\varphi}_{\mathrm{AEP}} - \varphi_{\mathrm{land}}^{i})\delta(t - t_{\mathrm{land}}^{i}) \quad i=1,2 \end{aligned} \tag{4}$$

where $\hat{\varphi}_{\mathrm{AEP}} = 2\pi(1-\hat{\beta})$, t_{land}^{i} is the time when the hand of Arm i (the foot of Leg i) lands on the ground (i=1,2) and $\delta(\cdot)$ denotes Dirac's delta function. Note that touch sensor signals not only modulate the walking rhythm but also switch the leg motions from the swing to stance phase, as described in Sec. 3.2.1.

4. Gait transition

This paper aims to achieve gait transition from quadrupedal to bipedal locomotion of a biped robot. As mentioned above, even if the robot establishes steady quadrupedal and bipedal locomotion, that is, each locomotion has a stable limit cycle in the state space of the robot, there is no guarantee that the robot can accomplish a transition from one limit cycle of quadrupedal locomotion to another of bipedal locomotion without falling over. Furthermore, these gait patterns originally have poor stability, and the transition requires drastic changes in robot posture, which aggravates the difficulty of preventing the robot from falling over during the transition.

4.1 Gait transition control

A biped robot generates quadrupedal and bipedal locomotion while manipulating many degrees of freedom in the joints. These gait patterns have different movements in many joints, which means that there are a million ways to achieve the transition. Therefore, the critical issue is designing gait transition.

In this paper, we generate both quadrupedal and bipedal locomotion of the robot based on physical kinematics. Figures 4(a) and (b) show schematics and parameters in quadrupedal and bipedal locomotion where COM indicates the center of mass of the trunk, l_{TA} and l_{TL} are the lengths from COM to Joint 1 of the arm and Joint 3 of the leg in the pitch plane, respectively, L_{A} and L_{L} are the forward biases from COM to the centers of the nominal foot and hand trajectories, respectively, ψ_{T} is the pitch angle of the trunk relative to the perpendicular line to the line that involves points AEP and PEP of the foot or the hand trajectory, and $*^{\mathrm{Q}}$ and $*^{\mathrm{B}}$ indicate the values of $*$ for quadrupedal and bipedal locomotion, respectively. Therefore, from a kinematical viewpoint, gait transition is achieved by changing parameters L_{A}, L_{L}, H_{A}, H_{L}, and ψ_{T} from values $L_{\mathrm{A}}^{\mathrm{Q}}$, $L_{\mathrm{L}}^{\mathrm{Q}}$, $H_{\mathrm{A}}^{\mathrm{Q}}$, $H_{\mathrm{L}}^{\mathrm{Q}}$, and $\psi_{\mathrm{T}}^{\mathrm{Q}}$ to values $L_{\mathrm{A}}^{\mathrm{B}}(=0)$, $L_{\mathrm{L}}^{\mathrm{B}}(=0)$, $H_{\mathrm{A}}^{\mathrm{B}}$, $H_{\mathrm{L}}^{\mathrm{B}}$, and $\psi_{\mathrm{T}}^{\mathrm{B}}$, while the robot walks. Note that from these figures, using parameters Δ_{A}, Δ_{L}, and ψ_{T}, parameters L_{A} and L_{L} are written as

$$\begin{aligned} L_{\mathrm{A}} &= l_{\mathrm{TA}} \sin\psi_{\mathrm{T}} + \Delta_{\mathrm{A}} \\ L_{\mathrm{L}} &= l_{\mathrm{TL}} \sin\psi_{\mathrm{T}} + \Delta_{\mathrm{L}} \end{aligned} \tag{5}$$

Animals generate various motions and smoothly change them by cooperatively manipulating their complicated and redundant musculoskeletal systems. To elucidate these mechanisms, many studies have investigated recorded electromyographic (EMG) activities, revealing that muscle activity patterns are expressed by the combination of several patterns, despite their complexity (d'Avella & Bizzi, 2005; Patla et al., 1985; Ivanenko et al., 2004, 2006). Furthermore, various motions have common muscle activity patterns, and different motions only have a few different specific patterns in combinations that express muscle activity patterns. This suggests that only a few patterns provide cooperation in different complex movements.

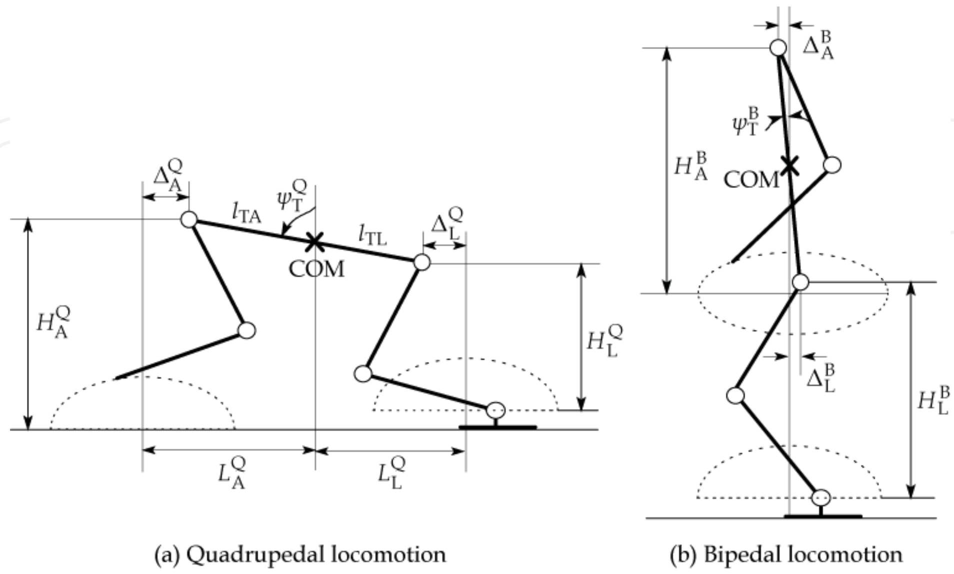


Fig. 4. Schematics and parameters in quadrupedal and bipedal locomotion.

Therefore, in this paper first we introduce a couple of parameters and then attempt to achieve gait transition by cooperatively changing the physical kinematics from quadrupedal to bipedal using the parameters. Specifically, two parameters, ξ_1 and ξ_2, are introduced, and parameters Δ_A, Δ_L, H_A, H_L, and ψ_T are designed as functions of parameters ξ_1 and ξ_2 by

$$\begin{aligned} \Delta_A(\xi_1, \xi_2) &= \Delta_A^Q - \{l_{TA} \sin \psi_T(\xi_1, \xi_2) + \Delta_A^Q\}\xi_1 \\ \Delta_L(\xi_1, \xi_2) &= \Delta_L^Q - \{l_{TL} \sin \psi_T(\xi_1, \xi_2) + \Delta_L^Q\}\xi_1 \\ H_A(\xi_1, \xi_2) &= H_A^Q + (H_A^B - H_A^Q)\xi_2 \\ H_L(\xi_1, \xi_2) &= H_L^Q + (H_L^B - H_L^Q)\xi_2 \\ \psi_T(\xi_1, \xi_2) &= \psi_T^Q + (\psi_T^B - \psi_T^Q)\xi_2 \end{aligned} \tag{6}$$

This aims to use parameters ξ_1 and ξ_2 to change the distance between the foot and hand trajectories and the posture of the trunk, respectively. Using this controller, gait transition is achieved by simply changing introduced parameters (ξ_1, ξ_2) from (0, 0) to (1, 1), as shown in Fig. 5.

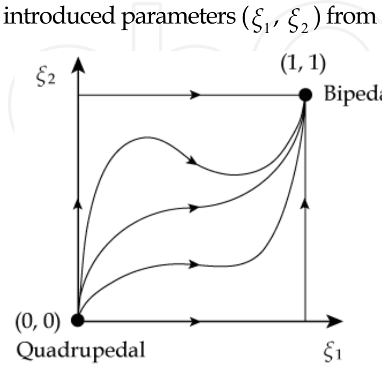


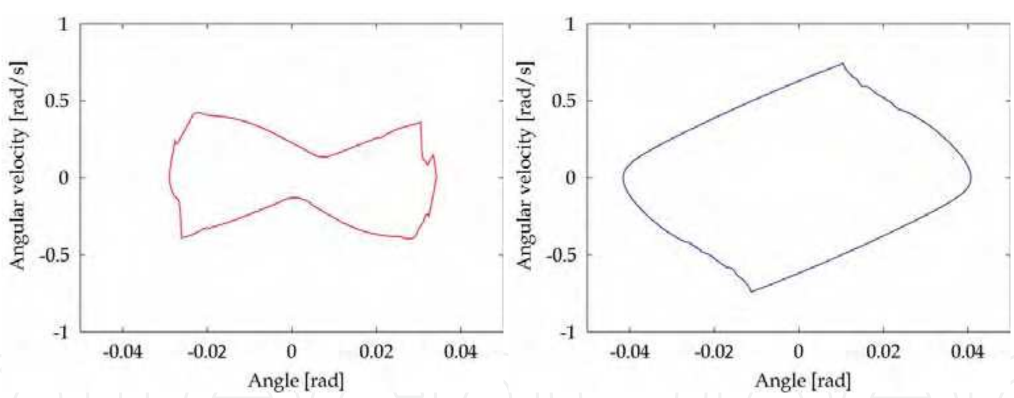
Fig. 5. Trajectories in $\xi_1 - \xi_2$ plane for gait transition from quadrupedal to bipedal locomotion.

4.2 Numerical results

In this section, we investigate whether the proposed control system establishes gait transition from quadrupedal to bipedal locomotion of the robot by numerical simulations. The following locomotion parameters were used: $\hat{S}$ =5 cm, $\hat{\beta}$ =0.5, $\hat{T}_{sw}$ =0.3 s, K_T =10.0, K_A =2.0, K_L =2.0, l_{TA} =6.9 cm, and l_{TL} =7.6 cm; the remaining parameters for quadrupedal and bipedal locomotion are shown in Table 2. These parameters were decided so that the robot achieves steady quadrupedal and bipedal locomotion. That is, each locomotion has a stable limit cycle in the state space of the robot. Figures 6(a) and (b) show the roll motions of the robot relative to the ground during quadrupedal and bipedal locomotion, respectively, illustrating the limit cycles in these gait patterns. Note that due to setting $\hat{\beta}$=0.5 and the nominal phase differences of the oscillators as described in Sec. 3.2.2, a trot appears in the quadrupedal locomotion in which the robot is usually supported by one arm and the contralateral leg.

Parameter	Quadrupedal ($*^Q$)	Bipedal ($*^B$)
Δ_A [cm]	-3.0	1.4
Δ_L [cm]	4.0	-1.6
H_A [cm]	22.2	22.2
H_L [cm]	14.0	16.5
ψ_T [deg]	72	12

Table 2. Parameters for quadrupedal and bipedal locomotion.



(a) Quadrupedal locomotion (b) Bipedal locomotion

Fig. 6. Roll motion relative to the ground.

To accomplish gait transition, parameters ξ_1 and ξ_2 are changed to reflect outer commands. Specifically, a trajectory in $\xi_1 - \xi_2$ plane is designed as the following two successive steps (see Fig. 7):

Step 1: while the robot walks quadrupedally, parameter ξ_1 increases from 0 to $\bar{\xi}_1$ during time interval T_1 s, where $0 \le \bar{\xi}_1 \le 1$.

Step 2: at the beginning of the swing phase of Arm 1, ξ_1 and ξ_2 increase from $\bar{\xi}_1$ to 1 and from 0 to 1, respectively, during time interval T_2 s.

Note that parameter ξ_2 >0 geometrically indicates that the robot becomes supported only by its legs: that is, the appearance of bipedal locomotion.

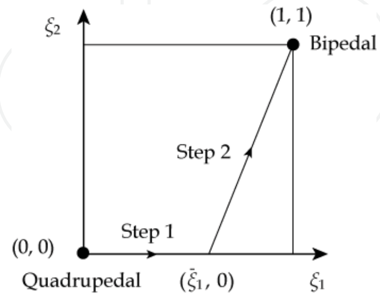
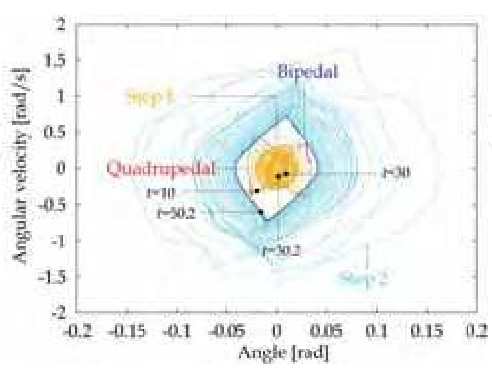
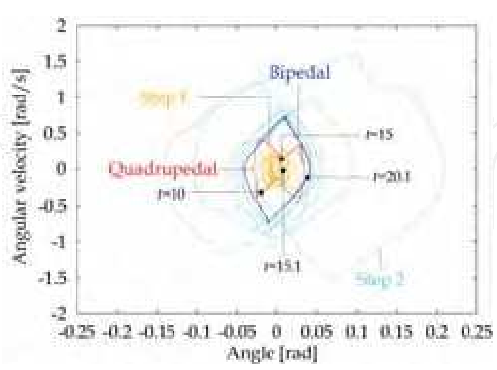


Fig. 7. Designed trajectory in $\xi_1 - \xi_2$ plane to change gait pattern from quadrupedal to bipedal locomotion.

Figures 8(a) and (b) show the roll motion of the robot relative to the ground during gait transition, by parameter $\bar{\xi}_1$=0.7. Specifically, in Fig. 8(a), time intervals T_1 and T_2 are both set at 20 s. Since the nominal step cycle is set at 0.6 s, the nominal kinematical trajectories of quadrupedal locomotion change slowly and gradually into bipedal locomotion, and it takes many steps to complete the change of gait patterns. Step 1 is from 10 to 30 s, and Step 2 is from 30.2 to 50.2 s. During Step 1, the foot and the hand positions come closer together, and the roll motion of the robot decreases. At the beginning of Step 2, since the robot becomes supported only by its legs, roll motion suddenly increases. However, during Step 2 roll motion gradually approaches a limit cycle of bipedal locomotion, and after Step 2 the motion converges to it. That is, the robot accomplishes gait transition from quadrupedal to bipedal locomotion. On the other hand, in Fig. 8(b), time intervals T_1 and T_2 are both set at 5 s. Step 1 is from 10 to 15 s, and Step 2 is from 15.1 to 20.1 s. In this case, although the nominal trajectories change relatively quickly, roll motion converges to a limit cycle of bipedal locomotion, and the robot achieves gait transition. Figure 9 displays the trajectory of the center of mass projected on the ground and the contact positions of the hands and the center of the feet on the ground during this gait transition. Figure 10 shows snapshots of this gait transition.



(a) Time intervals T_1, T_2 =20 s



(b) Time intervals T_1, T_2 =5 s

Fig. 8. Roll motion relative to the ground during gait transition from quadrupedal to bipedal locomotion.

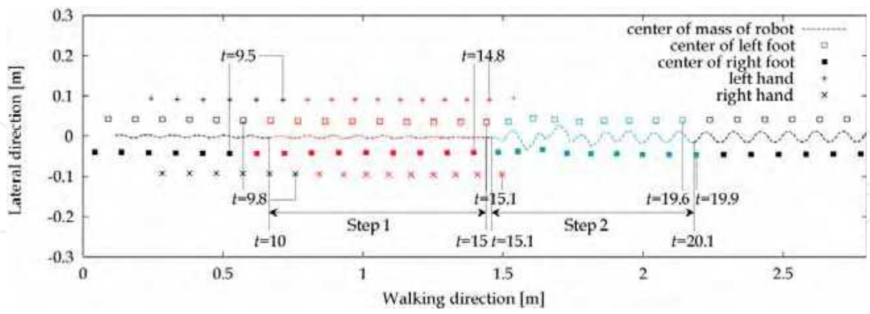


Fig. 9. Trajectory of center of mass of robot projected on the ground and contact positions of the hands and the center of feet on the ground. Time of feet and hands indicate when they land on the ground.

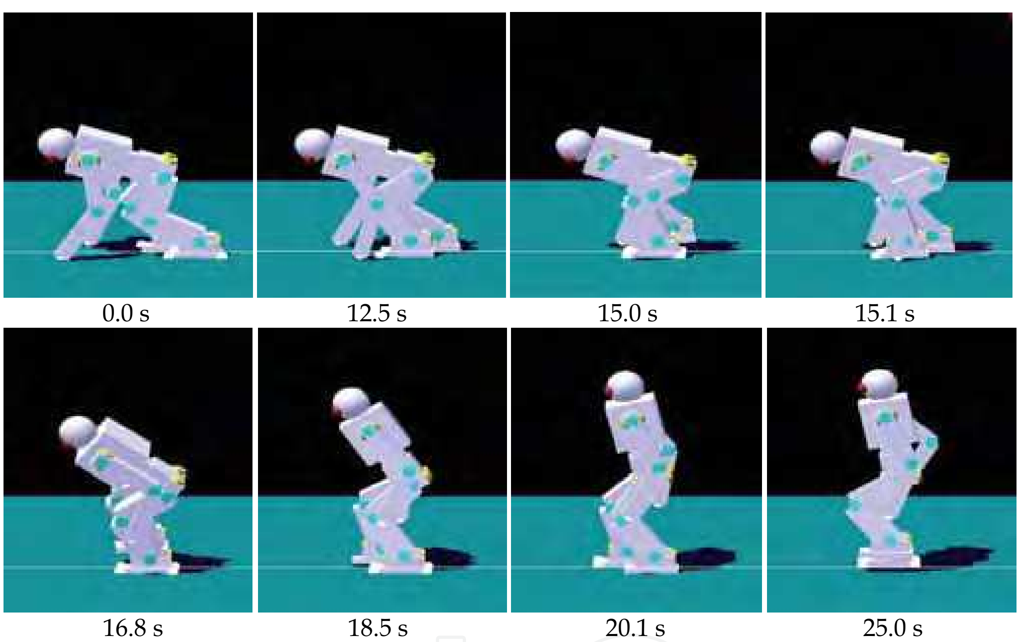


Fig. 10. Snapshots of gait transition from quadrupedal to bipedal locomotion.

5. Discussion

Kinematical and dynamical studies on biped robots are important for robot control. As described above, although model-based approaches using inverse kinematics and kinetics have generally been used, the difficulty of establishing adaptability to various environments as well as complicated computations has often been pointed out. In this paper, we employed an internal structure composed of nonlinear oscillators that generated robot kinematics and adequately responded based on environmental situations and achieved dynamically stable quadrupedal and bipedal locomotion and their transition in a biped robot. Specifically, we generated robot kinematical motions using rhythmic signals from internal oscillators. The oscillators appropriately responded to sensory signals from touch sensors and modulated the rhythmic signals and physical kinematics, resulting in dynamical stable walking of the robot. This means that a robot driven by this control system established dynamically stable and adaptive walking through the interaction between the dynamics of the mechanical system, the oscillators, and the environment. Furthermore, this control system needed neither accurate modeling of the robot and the environment nor complicated computations. It just relied on the timing of the touch sensor signals: it is a simple control system.

Since biped robots generate various motions manipulating many degrees of freedom, the key issue in control remains how to design their coordination. In this paper, we expressed two types of gait patterns using a set of several kinematical parameters and introduced two independent parameters that parameterized the kinematical parameters. Based on the introduced parameters, we changed the gait patterns and established gait transition. That is, we did not individually design the kinematical motion of all robot joints, but imposed kinematical restrictions on joint motions and contracted the degrees of freedom to achieve cooperative motions during the transition. Furthermore, we used the same control system between quadrupedal and bipedal locomotion except for the physical kinematics, which facilitated the design of such cooperative motions and established a smooth gait transition.

As mentioned above, the analysis of EMG patterns in animal motions clarified that common EMG patterns are embedded in the EMG patterns of different motions, despite generating such motions using complicated and redundant musculoskeletal systems (d'Avella & Bizzi, 2005; Patla et al., 1985; Ivanenko et al., 2004, 2006), suggesting an important coordination mechanism. In addition, kinematical studies revealed that covariation of the elevation angles of thigh, shank, and foot during walking displayed in three-dimensional space is approximately expressed on a plane (Lacquaniti et al., 1999), suggesting an important kinematical restriction for establishing cooperative motions. In designing a control system, adequate restrictions must be designed to achieve cooperative motions.

Physiological studies have investigated gait transition from quadrupedal to bipedal locomotion to elucidate the origin of bipedal locomotion. Mori et al. (1996), Mori (2003), and Nakajima et al. (2004) experimented on gait transition using monkeys and investigated the physiological differences in the control system. Animals generate highly coordinated and skillful motions as a result of the integration of nervous, sensory, and musculoskeletal systems. Such motions of animals and robots are both governed by dynamics. Studies on robotics are expected to contribute the elucidation of the mechanisms of animals and their motion generation and control from a dynamical viewpoint.

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7. References

Akimoto, K.; Watanabe, S. & Yano, M. (1999). An insect robot controlled by emergence of gait patterns. *Artificial Life and Robotics*, Vol. 3, 102–105.

Altendorfer, R.; Moore, N.; Komsuoglu, H.; Buehler, M.; Brown Jr., H.; McMordie, D.; Saranli, U.; Full, R. & Koditschek, D. (2001). RHex: A biologically inspired hexapod runner. *Autonomous Robots*, Vol. 11, No. 3, 207–213.

Aoi, S. & Tsuchiya, K. (2005). Locomotion control of a biped robot using nonlinear oscillators. *Autonomous Robots*, Vol. 19, No. 3, 219–232.

Aoi, S.; Tsuchiya, K. & Tsujita, K. (2004). Turning control of a biped locomotion robot using nonlinear oscillators. *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 3043-3048.

Cham, J.; Karpick, J. & Cutkosky, M. (2004). Stride period adaptation of a biomimetic running hexapod. *Int. J. Robotics Res.*, Vol. 23, No. 2, 141–153.

d'Avella, A. & Bizzi, E. (2005). Shared and specific muscle synergies in natural motor behaviors. *PNAS*, Vol. 102, No. 8, 3076–3081.

Fukuoka, Y.; Kimura, H. & Cohen, A. (2003). Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts. *Int. J. Robotics Res.*, Vol. 22, No. 3-4, 187–202.

Grillner, S. (1981). *Control of locomotion in bipeds, tetrapods and fish*. Handbook of Physiology, American Physiological Society, Bethesda, MD, pp. 1179–1236.

Grillner, S. (1985). Neurobiological bases of rhythmic motor acts in vertebrates. *Science*, Vol. 228, 143–149.

Hirai, K.; Hirose, M.; Haikawa, Y. & Takenaka, T. (1998). The development of the Honda humanoid robot. *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 1321-1326.

Ijspeert, A.; Crespi, A. & Cabelguen, J. (2005). Simulation and robotics studies of salamander locomotion. Applying neurobiological principles to the control of locomotion in robots. *Neuroinformatics*, Vol. 3, No. 3, 171–196.

Inagaki, S.; Yuasa, H. & Arai, T. (2003). CPG model for autonomous decentralized multi-legged robot system–generation and transition of oscillation patterns and dynamics of oscillators. *Robotics and Autonomous Systems*, Vol. 44, No. 3-4, 171–179.

Inoue, K.; Ma, S. & Jin, C. (2004). Neural oscillator network-based controller for meandering locomotion of snake-like robots. *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 5064–5069.

Ivanenko, Y.; Poppele, R. & Lacquaniti, F. (2004). Five basic muscle activation patterns account for muscle activity during human locomotion. *J. Physiol.*, Vol. 556, 267–282.

Ivanenko, Y.; Poppele, R. & Lacquaniti, F. (2006). Motor control programs and walking. *Neuroscientist*, Vol. 12, No. 4, 339–348.

Kuniyoshi, Y.; Ohmura, Y.; Terada, K.; Nagakubo, A.; Eitokua, S. & Yamamoto, T. (2004). Embodied basis of invariant features in execution and perception of whole-body dynamic actions—knacks and focuses of Roll-and-Rise motion. *Robotics and Autonomous Systems*, Vol. 48, No. 4, 189-201.

Kuroki, Y.; Fujita, M.; Ishida, T.; Nagasaka, K. & Yamaguchi, J. (2003). A small biped entertainment robot exploring attractive applications. *Proc. IEEE Int. Conf. on Robotics and Automation*, pp. 471-476.

Lacquaniti, F.; Grasso, R. & Zago, M. (1999). Motor patterns in walking. *News Physiol. Sci.*, Vol. 14, 168–174.

Lewis, M. & Bekey, G. (2002). Gait adaptation in a quadruped robot. *Autonomous Robots*, Vol. 12, No. 3, 301–312.

Lewis, M.; Etienne-Cummings, R.; Hartmann, M.; Xu, Z. & Cohen, A. (2003). An in silico central pattern generator: silicon oscillator, coupling, entrainment, and physical computation. *Biol. Cybern.*, Vol. 88, 137–151.

Löffler, K.; Gienger, M. & Pfeiffer, F. (2003). Sensors and control concept of walking ``Johnnie''. *Int. J. Robotics Res.*, Vol. 22, No. 3-4, 229–239.

Mori, S. (1987). Integration of posture and locomotion in acute decerebrate cats and in awake, free moving cats. *Prog. Neurobiol.*, Vol. 28, 161–196.
Mori, S. (2003). Higher nervous control of quadrupedal vs bipedal locomotion in non-human primates; Common and specific properties. *Proc. 2nd Int. Symp. on Adaptive Motion of Animals and Machines*.
Mori, S.; Miyashita, E.; Nakajima, K. & Asanome, M. (1996). Quadrupedal locomotor movements in monkeys (M. fuscata) on a treadmill: Kinematic analyses. *NeuroReport*, Vol. 7, 2277–2285.
Nagasaki, T.; Kajita, S.; Kaneko, K.; Yokoi, K. & Tanie, K. (2004). A running experiment of humanoid biped. *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 136-141.
Nakajima, K.; Mori, F.; Takasu, C.; Mori, M.; Matsuyama, K. & Mori, S. (2004). Biomechanical constraints in hindlimb joints during the quadrupedal versus bipedal locomotion of M. fuscata. *Prog. Brain Res.*, Vol. 143, 183–190.
Nakanishi, J.; Morimoto, J.; Endo, G.; Cheng, G.; Schaal, S. & Kawato, M. (2004). Learning from demonstration and adaptation of biped locomotion. *Robotics and Autonomous Systems*, Vol. 47, No. 2-3, 79–91.
Orlovsky, G.; Deliagina, T. & Grillner, S. (1999). *Neuronal control of locomotion: from mollusc to man*. Oxford University Press.
Patla, A.; Calvert, T. & Stein, R. (1985). Model of a pattern generator for locomotion in mammals. *Am. J. Physiol.*, Vol. 248, 484–494.
Poulakakis, I.; Smith, J. & Buehler, M. (2005). Modeling and experiments of untethered quadrupedal running with a bounding gait: The Scout II robot. *Int. J. Robotics Res.*, Vol. 24, No. 4, 239–256.
Quinn, R.; Nelson, G.; Bachmann, R.; Kingsley, D.; Offi, J.; Allen, T. & Ritzmann, R. (2003). Parallel complementary strategies for implementing biological principles into mobile robots. *Int. J. Robotics Res.*, Vol. 22, No. 3, 169–186.
Rossignol, S. (1996). *Neural control of stereotypic limb movements*. Oxford University Press.
Saranli, U.; Buehler, M. & Koditschek, D. (2001). RHex: A simple and highly mobile hexapod robot. *Int. J. Robotics Res.*, Vol. 20, No. 7, 616–631.
Taga, G. (1995a). A model of the neuro-musculo-skeletal system for human locomotion I. Emergence of basic gait. *Biol. Cybern.*, Vol. 73, 97–111.
Taga, G. (1995b). A model of the neuro-musculo-skeletal system for human locomotion II. - Real-time adaptability under various constraints. *Biol. Cybern.*, Vol. 73, 113–121.
Taga, G.; Yamaguchi, Y. & Shimizu, H. (1991). Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biol. Cybern.*, Vol. 65, 147–159.
Takakusaki, K.; Habaguchi, T.; Ohtinata-Sugimoto, J.; Saitoh, K. & Sakamoto, T. (2003). Basal ganglia efferents to the brainstem centers controlling postural muscle tone and locomotion: A new concept for understanding motor disorders in basal ganglia dysfunction. *Neuroscience*, Vol. 119, 293–308.
Takuma, T. & Hosoda, K. (2006). Controlling the walking period of a pneumatic muscle walker. *Int. J. Robotics Res.*, Vol. 25, No. 9, 861–866.
Tsujita, K.; Tsuchiya, K. & Onat, A. (2001). Adaptive gait pattern control of a quadruped locomotion robot. *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 2318–2325.
Vukobratović, M.; Borovac, B.; Surla, D. & Stokić, D. (1990). *Biped locomotion—dynamics, stability, control and application*. Springer-Verlag.
Wisse, M.; Schwab, A.; van der Linde, R. & van der Helm, F. (2005). How to keep from falling forward: elementary swing leg action for passive dynamic walkers. *IEEE Trans. Robotics*, Vol. 21, No. 3, 393–401.

Humanoid Robots: New Developments

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For many years, the human being has been trying, in all ways, to recreate the complex mechanisms that form the human body. Such task is extremely complicated and the results are not totally satisfactory. However, with increasing technological advances based on theoretical and experimental researches, man gets, in a way, to copy or to imitate some systems of the human body. These researches not only intended to create humanoid robots, great part of them constituting autonomous systems, but also, in some way, to offer a higher knowledge of the systems that form the human body, objectifying possible applications in the technology of rehabilitation of human beings, gathering in a whole studies related not only to Robotics, but also to Biomechanics, Biomimmetics, Cybernetics, among other areas. This book presents a series of researches inspired by this ideal, carried through by various researchers worldwide, looking for to analyze and to discuss diverse subjects related to humanoid robots. The presented contributions explore aspects about robotic hands, learning, language, vision and locomotion.