Generation and Coordination of Bipedal Locomotion through Global Entrainment

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Abstract
In order to understand biological systems as well as to design artificial systems, it is important to clarify the principle by which multidegrees of freedom can be coordinated under changeable constraints of the environment. We proposed that bipedal locomotion is realized as a global limit cycle generated through global entrainment between the neural system composed of neural oscillators and the physical system [15]. In the present paper the walking movement is shown to be robust against spatio-temporal changes in environmental constraints such as mechanical perturbations and irregular terrain. Furthermore we demonstrate that synchronization occurs between two walking bipeds through simple interaction by means of an analysis of a phase response curve and also show it by computer simulation. This implies that the principle of global entrainment is applicable to multilocomotor systems.

1 Introduction

Complexity in biological systems comes from their heterogeneous structure and intrinsic dynamics. The functional or ordered behavior of the system appears only when coordination among heterogeneous elements is established. Moreover, biological systems have to adapt to an environment which is changeable and unpredictable. This suggests that the essence in biological systems is not in any definite order as is seen in conventional artificial systems but in the ability to generate emergent order. The generation of spontaneous order has been studied typically in physical systems such as self-organizing processes [5][11]. These studies are, however, restricted to almost uniform systems with fixed constraints. Elucidation of the principle by which the heterogeneous elements can be brought into proper relation in a changeable environment is a challenging problem not only in biological studies but also in engineering studies for design of autonomous decentralized systems (ADS).

The typical example of flexibility and stability of biological systems in a changeable environment is seen in locomotion. According to neurophysiological studies, locomotor systems are characterized as a kind of ADS. The rhythmic movements of limbs are coordinated by coupled neural oscillators in the spinal cord, each of which controls groups of closely synergistic muscle [4]. Moreover the drastic change in gait pattern of a decerebrate cat on a treadmill by electrical stimulation to the midbrain [10][14] indicates that complex behavior can be controlled by a simple type of signal from the higher center of the brain.

Motor pattern generation in animals and humans have been theoretically studied at the phenomenological [13], the neural [3][7][8][19] and the biomechanical [9][17] levels. However, no theoretical studies have clarified how the motor pattern is generated through the interaction of neural, musculo-skeletal, and sensory systems to adapt to the environment.

We proposed global entrainment between the neural system and the physical system as a principle of self-organized control of motor systems in an unpredictable environment [15]. By computer simulation it was shown that bipedal locomotion is stably and flexibly performed as a global limit cycle generated by global entrainment between the rhythmic activities of the neural system composed of coupled neural oscillators and the rhythmic movements of a musculo-skeletal system interacting with its environment. Moreover, it was shown that a gradual change in speed of locomotion induces a drastic transition of the gait pattern between walking and running with hysteresis.

In the present paper we investigate the stability and flexibility of the global limit cycle generated in the model of bipedal locomotion when spatio-temporal changes in environmental constraints occur. Furthermore, applying the principle of global entrainment to multilocomotor systems, we demonstrate that two bipeds can be coordinated to walk synchronously by means of simple interaction.

2 The Model of Bipedal Locomotion

2.1 The outline of the model

Figure 1 shows the structure and information flows of our model. The physical system, which can be compared to our musculo-skeletal system, moves according to its own dynamics under the constraints of the environment and motor signals from the neural system. The neural rhythm generator composed of coupled neural oscillators generates motor signals to coordinate many degrees of freedom of the physical system. From the sensory signals which indicate the current state of the physical system and the environment, relevant signals are chosen and sent to the neural rhythm generator in an appropriate way. This reciprocal flow of information between the physical system and the neural rhythm generator enables the flexible generation of locomotor movement in a changeable environment. With global changes in the level of activity of the neural rhythm generator, the higher center controls the behavior of the whole system in a nonspecific way.

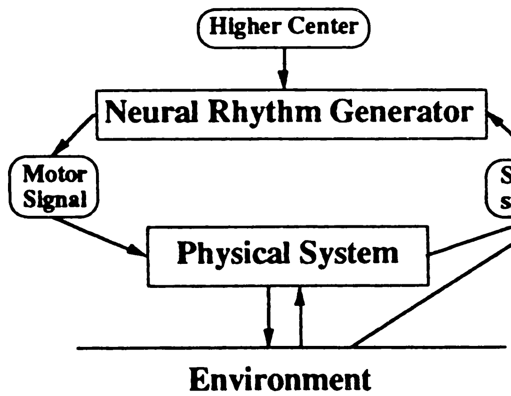

Fig.1 Model for locomotor control.

2.2 Physical system and environment

The physical system consists of an interconnected chain of rigid links in the sagittal plane, as shown in Fig.2. A leg is composed of a thigh and shank. A head represented by a point mass is attached to the hip joint. Nonlinear friction forces are assumed in the hip and knee joints, and elastic forces restrict bending of the joint in the knee. The reaction force from the ground is modeled as a two-dimensional spring and damper. Each time the ankle touches the ground, the resting position of the spring is assumed to be reset to the point at which the ankle first touches. To simulate locomotion over uneven terrain, the profile is set up on the sagittal plane such that the height of the terrain changes along the horizontal direction.

The equations of motion for the musculo-skeletal system are derived by means of the Newton-Euler method. The general form of the equations may be written as

$$\ddot{x} = P(x)F + Q(x,\dot{x},T_r(y),F_g(x,\dot{x})) , \tag{1}$$

where x is a vector of the inertial positions and angles of the links; P is a matrix; F is a vector of constraint forces; Q is a vector; T_r is a vector of torques; F_g is a vector of forces on the ankle which depend on the state of the terrain; and y is a vector of the output of the neural rhythm generator.

To obtain the constraint forces, we differentiate the equations of kinematic constraints twice with respect to time. They can be written in the general form:

$$C(x)\ddot{x} = D(x,\dot{x}) \tag{2}$$

where C is a matrix and D is a vector.

By eliminating F from (1) and (2), we get

$$\ddot{x} = P(x)[C(x)P(x)]^{-1}[D(x,\dot{x}) - C(x)Q(x,\dot{x},T_r(y),F_g(x,\dot{x}))] + Q(x,\dot{x},T_r(y),F_g(x,\dot{x})) \tag{3}$$

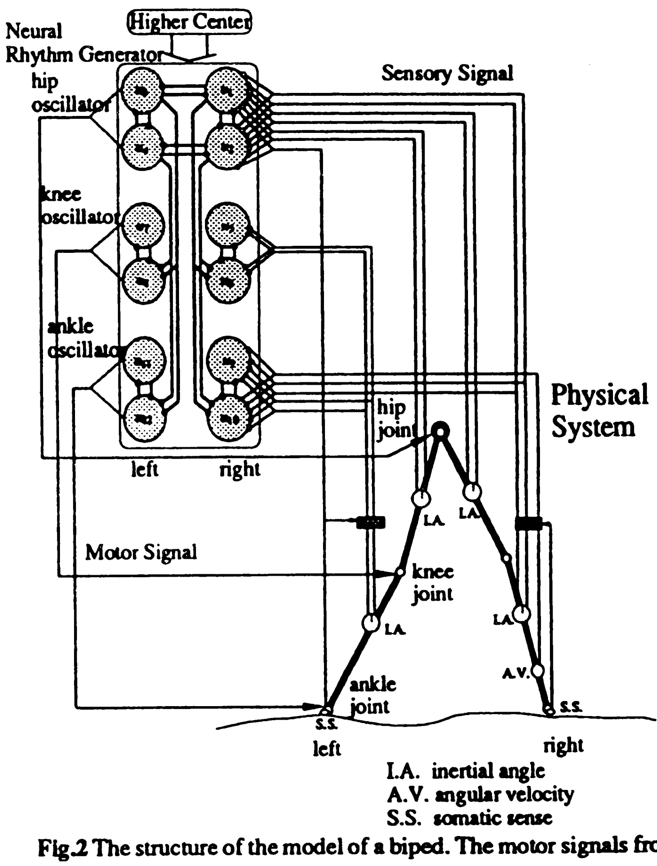

Fig.2 The structure of the model of a biped. The motor signals from the neural rhythm generator on the left side induce torques acting at the joints of the left leg. The pathways of sensory signals from the physical system to the neural rhythm generator on the right side are shown.

We are able to obtain the motion of the physical system, provided that the output of the neural rhythm generator y is given.

2.3 Neural system

One of the simplest models of a neural network generating oscillatory activity consists of two tonically excited neurons, with the adaptation or self-inhibition effect, linked reciprocally via inhibitory connections [8]. This model generates a stable limit cycle for a set of parameters. By the use of the neural oscillator model as an unit oscillator, a neural rhythm generator, composed of six unit oscillators, for bipedal locomotion is constructed as illustrated in Fig.2. Each unit oscillator induces a torque at a specific joint. The two neurons of each unit oscillator alternately induce torques in opposite directions. It is assumed that the torque generated at the joint is proportional to the output of the neurons.

The neural system is represented by the following differential equations:

$$\tau_i \dot{u}_i = -u_i + \sum_{i,j=1}^{12} w_{ij} y_j - \beta v_i + u_{0\,i} + F_{eed\,i}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{F_g}(\mathbf{x}, \dot{\mathbf{x}}))$$

$$\tau'_i \dot{v}_i = -v_i + y_i \qquad (4)$$

$$y_i = f(u_i) \quad (f(u_i) = \max(0, u_i)) \quad (i = 1, 12)$$

where u_i is the inner state of the ith neuron; y_i is the output of the ith neuron; v_i is a variable representing the degree of the adaptation or self-inhibition effect of the ith neuron; u_{0i} is a signal from the higher center; w_{ij} is a connecting weight; τ_i and τ'_i are time constants of the inner state and the adaptation effect respectively; and $F_{eed\,i}$ is a sensory signal.

In this model, we postulate explicit representations of sensory signals of inertial angles of the thigh and the shank, angular velocities of the shank, and somatic senses of making contact with the ground. Figure 2 illustrates the pathway of sensory signals to each unit oscillator. The design of the processing of sensory signals is mainly based on a simple mechanism, which is an extended form of the stretch reflex for a single joint. This is also functionally extended to the interjoint pathways of sensory signals, which are important for generating appropriate phase relationships among the joints. The signals of the somatic sense are used for modulating the signals of the inertial angles.

2.4 Method of computer simulation

By computer, equations (3) and (4) are numerically integrated using the fourth-order Runge-Kutta-Gill method. The inverse matrix in eq. (3) is solved using the Gauss-Jordan method. Given a certain set of initial conditions and a

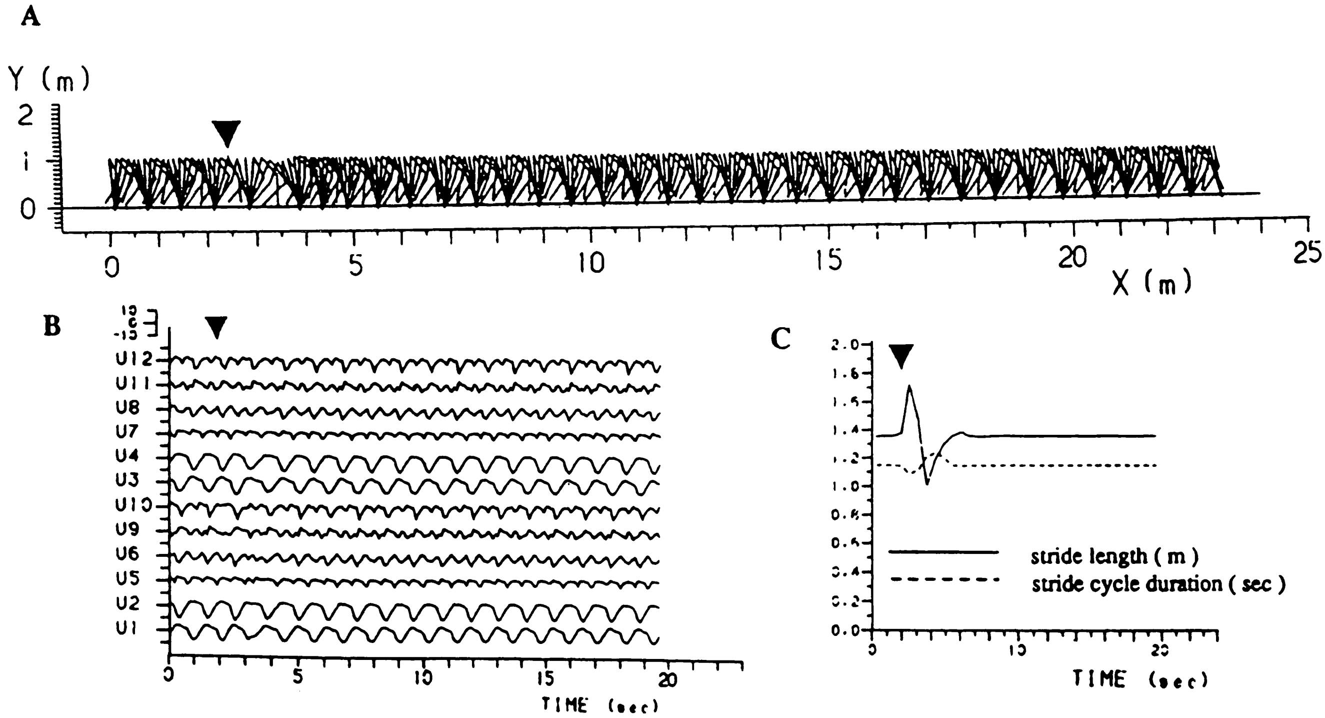

Fig.3 The response of the biped against a mechanical perturbation. A force of 280N in the forward direction is applied to the head for 0.2 s. The arrows indicate the time when a mechanical perturbation is applied. A The walking movement of the biped. The stick figure is traced every 0.1 s. B The activity of the neural rhythm generator. Each inner state of neuron u_i is shown. C Time courses of stride length and stride cycle duration (walking period). The stride length is the distance between successive contact points of the same leg with the ground.

function describing the terrain, our bipedal model generates locomotion as a completely autonomous system. The following section show the results of our simulation.

3 Robustness against Environmental Changes

3.1 Mechanical perturbation during walking

Mechanical perturbations to a part of the body during walking over flat level terrain were examined. Given a set of initial conditions, the system asymptotically converges to a steady state of walking. Afterwards a perturbation is applied to the head of the biped in the forward direction. Figure 3 shows an example of simulated motion of the biped and activity of the neural rhythm generator. The results demonstrate that the system returns to steady walking within a few step cycles after the instantaneous perturbation. The stability is attributed to the orbital stability of the global limit cycle generated through global entrainment between the neural rhythm generator and the physical system. The biped fell down for such a large perturbation as that which forces the system to move beyond the separatrix of the stable limit cycle.

To investigate the effect of perturbation on the phase of locomotor cycle, phase transition curves (PTC) [16] are measured. Figure4A shows the method by which to obtain a PTC. In the steady state of walking we define phase ϕ as $\phi = t/T \pmod 1$, where t is the time from the instance the right foot touches the ground; T is the period of one step cycle. As shown in Fig.4A, a perturbation is applied at ϕ which we call the old phase. After the system returns to the steady state, the i-th phase advance σ_i converges to σ. We define the new phase as $\phi' = \phi + \sigma$. The PTC is represented as

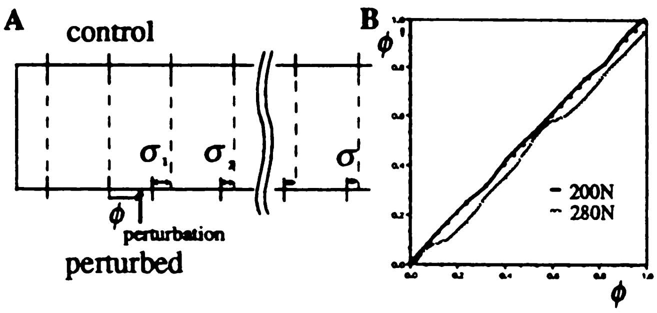

Fig.4 A Definition of phase transition curve (PTC). The upper trace shows the regular rhythm in the steady state of walking. The abscissa scales the time. The vertical bars indicate the instance at which the right leg of the biped touches the ground. The lower trace shows the perturbed locomotion. A perturbation is applied at ϕ, which is called the old phase. The old phase ϕ added by the phase delay σ makes the new phase ϕ'. B PTCs for mechanical perturbations applied to the head of the biped in the forward direction for 0.2 sec. The black and grey lines show the PTCs for forces of 200N and 280N respectively.

$\phi'(\phi)$.

Figure 4B shows PTCs obtained in cases of perturbations applied to the head of the biped in the forward direction. When the perturbation is weak, the new phase is delayed slightly at every value of the old phase. By contrast, the new phase is advanced when the perturbation is strong. In this case the degree of advancement of the new phase in the single support phase of locomotion is larger than that in the double support phase. These results indicate that the dynamical stability of the limit cycle changes according to the strength and timing of perturbations.

3.2 Locomotion over uneven terrain

The behavior of the biped was investigated when the environmental constraints were changed. The stability against environmental changes is attributed to the structural stabil-

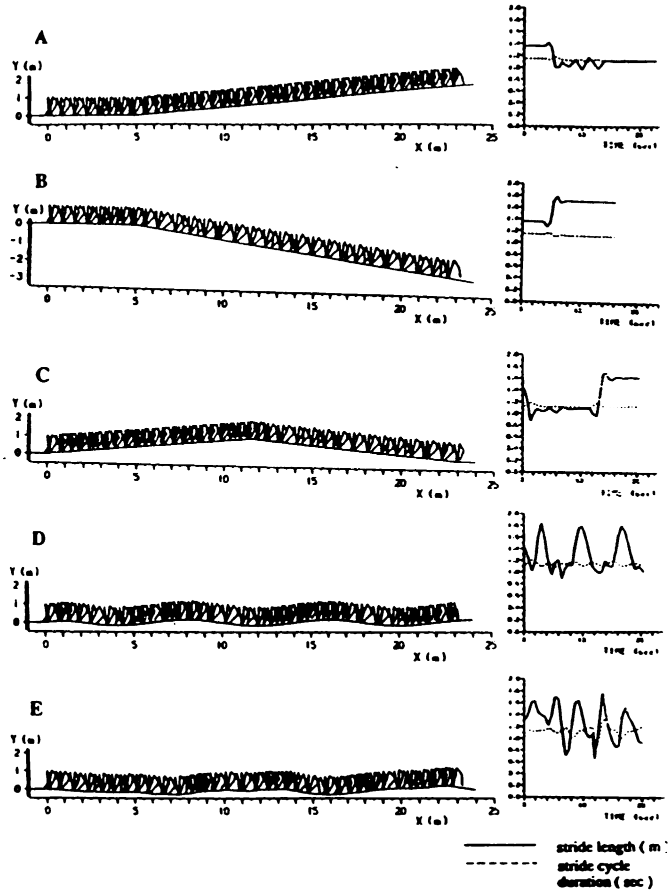

Fig.5 Walking movements over uneven terrain. The stick figures of walking movements and the time courses of the stride length and the stride cycle duration are shown. The stick figures are traced every 0.2 s. A Uphill (9%). B Downhill (-14%). C Uphill (9%) + downhill (-9%). D Terrain with a sinusoidal wave pattern (wave length: 8m; amplitude: 16cm). E Irregular terrain.

ity of the global limit cycle generated through interaction with the environment. We demonstrate how our biped generates stable locomotion over various kinds of terrain without any control specific to the environment.

Figures 5A and B show uphill and downhill walking. In the steady state of walking on a flat terrain, the terrain suddenly changes. However, the biped can continue to walk. The upper and lower limits of the slope that the biped could walk on were +10 % and -15%, respectively. Figure 5C shows walking over the hill. The movement of the legs clearly demonstrates that the stride length is automatically changed when the slope of the hill changes.

Figure 5D shows an example of walking over a terrain with a sinusoidal wave pattern. Various kinds of sinusoidal wave patterns are examined. The biped can walk stably under the condition that the spatial frequency is sufficiently low compared to the step length of the biped. In other words, the biped is stable against not rapid but slow changes in the environment.

Figure 5E shows an example of walking over irregular terrain. As in the case mentioned above, the biped does not fall down against a slowly changing terrain.

4 Coordination between two Bipeds

Everyone has experienced the unconscious synchronization of stepping motion when walking with another person. This phenomenon would be a typical example of mutual entrainment in personal communication. Perhaps this coordination is based on visual information. In this chapter we demonstrate a model of synchronization of walking as shown in Fig.6. The higher center is considered to be the coordinator with other bipeds in that dynamic changes in state originate here according to signals from other bipeds.

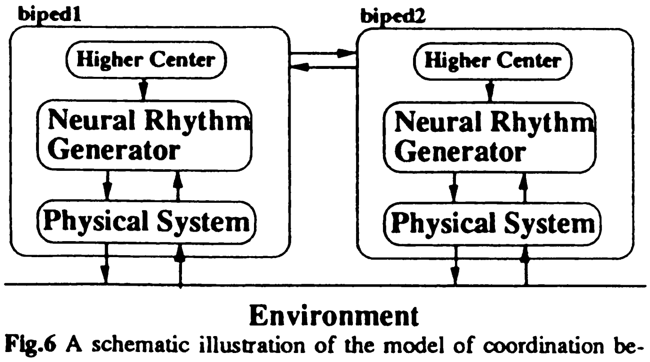

Fig.6 A schematic illustration of the model of coordination between two bipeds

4.1 Stability of phase relationship between identical bipeds

To realize synchronized walking we assume that a biped can perceive information on the timing of stepping movement of the other system. The phasic signal is expected to be responsible for phase locking between the bipeds. The higher center of each biped is assumed to generate a pulse signal at the instance the leg of the other biped touches the ground and sends it to the hip oscillators appropriately.

Effects of pulse signals to the neuron of the hip oscillator on the locomotor phase were examined and we obtained a PTC as shown in Fig.7A. Using the single PTC we can examine the stability of the coordination between the identical bipeds when they interact with each other. The stability criterion is shown in [18]. Figure 7B shows that in-phase relationship is the only stable state. Through computer simulation we obtained synchronized walking between the identical bipeds.

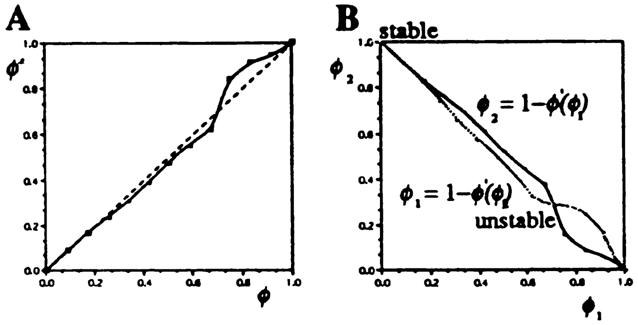

Fig.7A PTC for pulse to the flexor neuron of the hip oscillator. B Graphic solution of equilibrium point of phase relationship. The black and gray lines are derived form the PTC. The intersections show equilibrium points. The point at $\phi_1 = \phi_2 = 0.0$ is a stable equilibrium point.

4.2 The model of coordination between bipeds with slightly different character

In order that two bipeds with the same structure and slightly different parameters walk side by side, further information processing will be needed because they have not only different phases of stepping movements but also different positions and speeds in the horizontal direction when there is no interaction between them. In addition to the pulse signal responsible for phase locking, we assume that the differences in position and speed between the two bipeds in the horizontal direction are perceived and utilized for reducing the difference of step length between them. The steady input from the higher center to the hip oscillators changes according to the following differential equations:

$$\tau_0 \dot{u}_{0hip1} = c_1(x_{h2}-x_{h1}) + c_2(\dot{x}_{h2}-\dot{x}_{h1})$$
$$\tau_0 \dot{u}_{0hip2} = c_1(x_{h1}-x_{h2}) + c_2(\dot{x}_{h1}-\dot{x}_{h2}) \quad (5)$$

where u_{0hip1} and u_{0hip2} are the input signals of each biped from the higher center to the hip neural oscillator; x_{h1} and

x_{h2} are the positions of biped1 and biped2; τ_0, c_1, and c_2 are constants.

We demonstrate a typical example of the result of the computer simulation. Figure 8A shows that the two bipeds walk asynchronously in different positions when there is no interaction between them. In contrast Fig.8B shows that the two bipeds can gradually achieve and finally maintain absolute coordination when interacting with each other. In the steady state the phase relation between the two bipeds is kept exactly in phase and the step lengths are kept identical to each other.

5 Discussion

In the present paper we have shown that entrainment results in the coordination of many degrees of freedom in a complex system. In summary, entrainment works at the following different levels of control: (1) local entrainment between neural oscillators in the neural system, (2) global entrainment between the neural system and the physical system under changeable condition of the environment, and (3) entrainment in communication between bipedal locomotor systems.

Self-organized relationships among neural oscillators due to their local entrainment are the basis for the flexible generation of motor signals. According to neurophysiological studies, this type of strategy for control is generally adopted by animals. Although we have considered only rhythmic movements in the present paper, this model should be extended to deal with the problems of how motor signals of discrete movements are generated in the neural system and how rhythmic movements and discrete movements are integrated.

Global entrainment between the neural system and the physical system may serve as a principle of sensorimotor coordination in real time. Since the movement emerges as a result of dynamic interaction through global entrainment in a self-organized manner, the planning and execution are performed in parallel with continuous interactions with the environment. This is in contrast with the systems based on

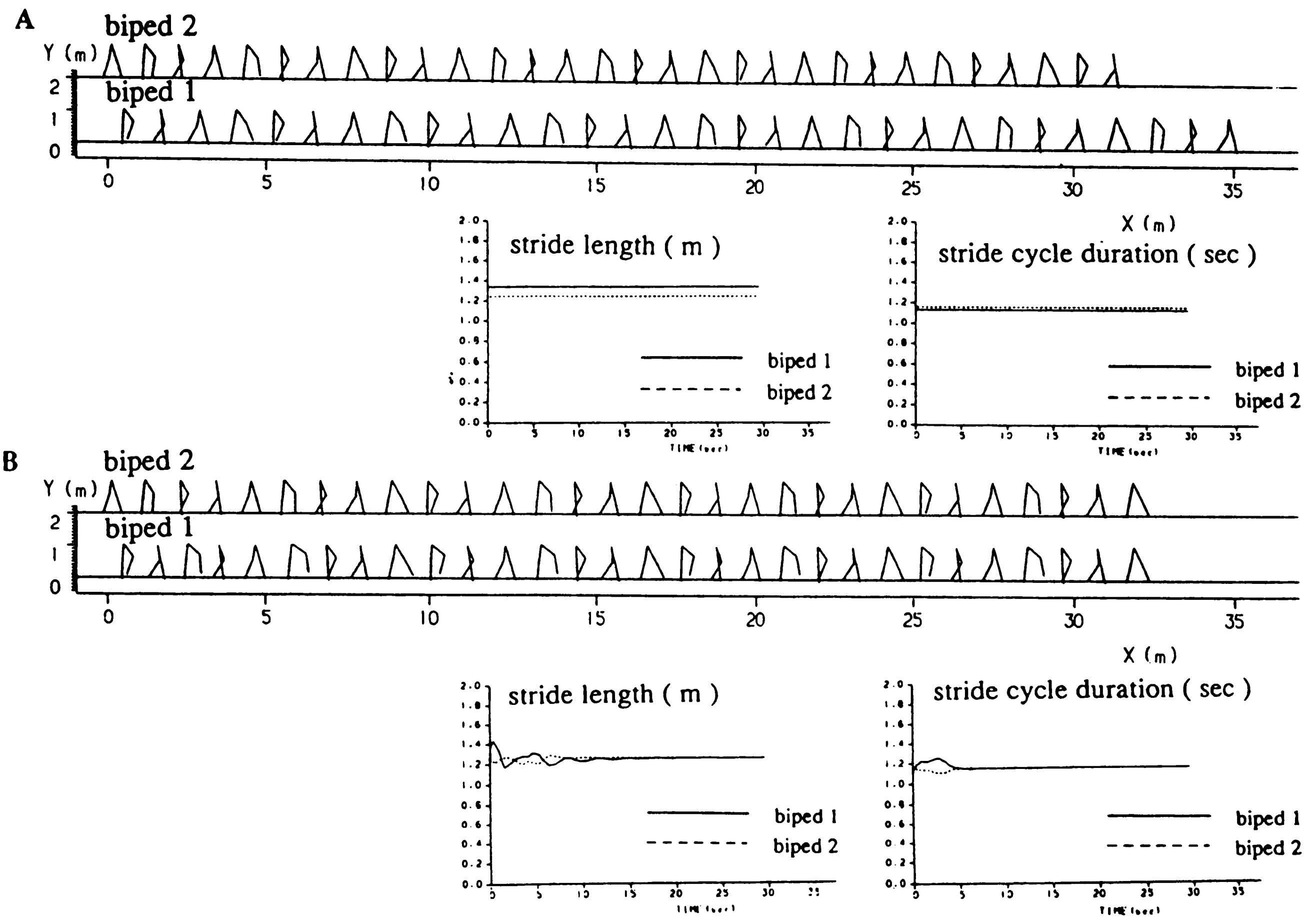

Fig.8 Synchronization of walking between two bipeds. The stick figures and the time courses of the stride length and stride cycle duration of the two bipeds are shown. The stick figures are traced every 1.0 s. A Independent walking of the two bipeds in the absence of mutual interaction. B Synchronized walking of the two bipeds in the presence of mutual interaction.

the conventional control theory, in which control systems and controlled systems are strictly separate and therefore planning and execution are solved sequentially. However, some of the studies of autonomous robots [1][2][6][12] are in agreement in the sense that movements of robots are generated as a result of dynamic interaction with the environment.

As is shown in the case of synchronized walking between two bipeds, autonomous systems can communicate with each other through entrainment. The important point of this example is that complex behavior with many degrees of freedom is coordinated by simple signals with a few degrees of freedom. Moreover it is shown that the principle of global entrainment is applicable to a group of autonomous systems. By using entrainment as a method of communication we might design new types of ADS where qualitatively different properties emerge as a result of cooperative interaction between the systems.

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