Nonlinear Dynamics of the Human Motor Control
-Real-Time and Anticipatory Adaptation of Locomotion and Development of Movements-

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Abstract

Nonlinear dynamics of the neuro-musculo-skeletal system and the environment play central roles for the generation and the development of human bipedal locomotion and other movements. This paper highlights a global entrainment that produces adaptive walking, freezing and freeing degrees of freedom during motor development, and chaotic dynamics of spontaneous movements in early infancy.

1. Introduction

The theory of nonlinear dynamics, which claims that spatio-temporal patterns arise spontaneously from the dynamic interaction between the components with many degrees of freedom [1,2], is progressively attracting more attention in the field of motor control. The concept of self-organization in movement was initially applied to describe motor actions such as rhythmic arm movements [3]. On the other hand, neurophysiological studies of animals have revealed that the neural system contains the central pattern generator (CPG), which generates spatio-temporal patterns of activity for the control of rhythmic movements through the interaction of coupled neural oscillators [4]. Moreover, it has been reported that the centrally generated rhythm in the CPG is entrained by the rhythm of sensory signals at rates above and below the intrinsic frequency of the rhythmic activity [4]. This phenomenon is typical for a nonlinear oscillator that is externally driven by a sinusoidal signal.

Inspired by the theoretical and experimental approaches to the motor control in terms of the self-organization, we proposed that the human bipedal locomotion emerges from a global entrainment between the neural system that contains the CPG and the musculo-skeletal system that interacts with a changing environment [5]. A growing number of simulation studies have focused on the dynamic interaction of neural oscillators with mechanical systems to understand the mechanisms of generation of adaptive movements in insects [6], fish [7] and quadruped animals [8]. In the field of robotics, an increasing number of studies have implemented neural oscillators to control movements of real robots [9-11].

The concept of the self-organization argues that movements are generated as a result of dynamic interaction between the neural system, the musculo-skeletal system and the environment. If this is the case, the implicit assumption that the neural system is a controller and that the body is a controlled system is required to be changed. This paper reviews a series of our models of the human bipedal locomotion which show nonlinear properties of the neuro-musculo-skeletal system. The aim of this paper is to provide a framework for understanding the generation of the bipedal locomotion [5, 12], the real-time flexibility in an unpredictable environment [13], the anticipatory adaptation of locomotion when confronted with a visible object [14] and the acquisition of locomotion during development [15]. Our recent study on the analysis of spontaneous movements of young infants also provides evidence that chaotic dynamics may play an important role for the development of varieties of movements [16].

2. Real-Time Adaptation of Locomotion through Global Entrainment

2.1 A model of the neuro-musculo-skeletal system for human locomotion

In principle, bipedal walking of humanoid robots can be controlled if the specific trajectory of all of the joints and of the zero moment point (ZMP) are planned in advance and the feedback mechanisms are incorporated [17]. However, it is obvious that this method of control is not robust against unpredictable changes in the environment.

Is it possible to generate bipedal locomotion by using a neural model of the CPG in a self-organized manner? Let us assume that an entire system is composed of two dynamical systems; a neural system that is responsible for generating locomotion and a musculo-skeletal system that generates forces and moves in an environment. The neural system is described by differential equations for coupled neural oscillators, which produce motor signals to induce muscle torques and which receive sensory signals indicating the current state of the musculo-skeletal system and the environment. The musculo-skeletal system is described by Newtonian equations for multiple segments of the body and input torque which is generated by the output of the neural system. We proved that a global entrainment between the neural system and the musculo-skeletal system is responsible for generating a stable walking movement by using computer simulation [5].

Here I will present a model of [12]. As shown in Fig.1, the musculo-skeletal system consists of eight segments in the saggital plane. The triangular foot interacts with the ground at its heel and/or toe. According to the output of the neural system, each of twenty "muscles" generates torque at specific joints. It is important to note that a number of studies have demonstrated examples of walking robots which exploit the natural dynamics of the body such as the passive dynamic walkers [18] and the dynamic running machines [19]. The oscillatory property of the musculo-skeletal system is an important determinant to establish the walking pattern.

The neural system was designed based on the following assumptions:

(1) The neural rhythm generator (RG) is composed of neural oscillators, each of which controls the movement of a corresponding joint. As a model neural oscillator, we adopt the half center model, which is composed of two reciprocally inhibiting neurons and which generates alternative activities between the two neurons [20].

(2) All of the relevant information about the body and the environment is taken into account. The angles of the body segments in an earth-fixed frame of reference and ground reaction forces are available to the sensory system. Global information on the position of the center of gravity (COG) with respect to the position of the center of pressure (COP) is also available. We assume that a gait is represented as a cyclic sequence of what we call global states; the double support phase, the first half of the single support phase and the second half of the single support phase. The global states are defined by the sensory information on the alternation of the foot contacting the ground and the orientation of the vector from the COP to the COG.

(3) Reciprocal inhibitions are incorporated between the neural oscillators on the contralateral side, which generates the anti-phase rhythm of muscles between the two limbs. Connections between the neural oscillators on the ipsilateral side change in a phase-dependent manner by using the global state to generate the complex phase relationships of activity among the muscles within a limb.

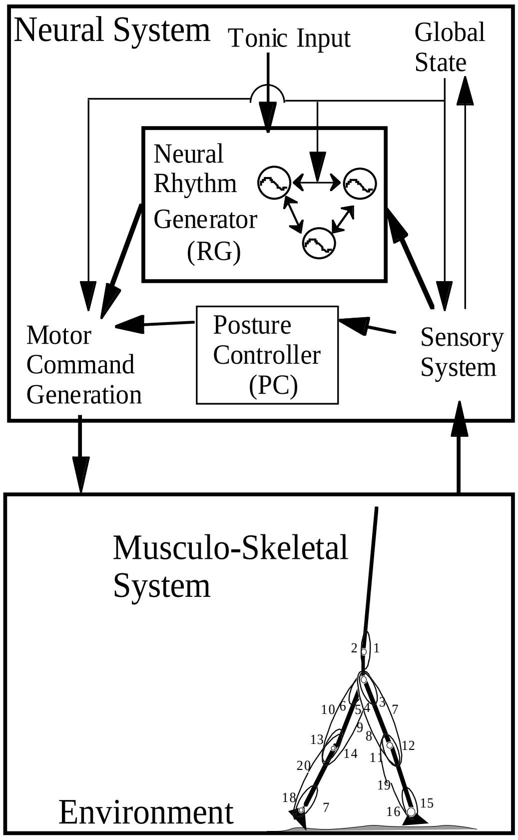


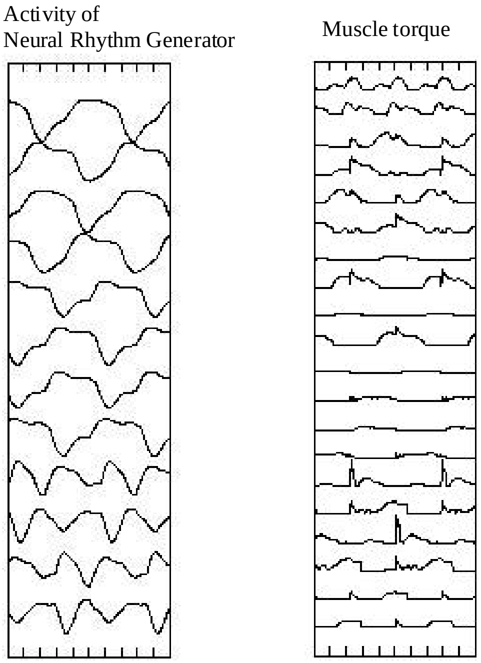
Fig. 1 A model of the neuro-musculo-skeletal system for human locomotion [12].

(4) Both the local information on the angles of the body segments and the global information on the entire body are sent to the neural oscillators in a manner similar to the functional stretch reflex, so that neural oscillation and body movement are synchronized. Sensory information is sent only during the relevant phase of the gait cycle by modulating the gains of the sensory pathways in a phase-dependent manner, which is determined by the global state.

(5) All of the neural oscillators share tonic input from the higher center, which is represented by a single parameter. By changing the value of this parameter, the excitability of each oscillator can be controlled so that different speeds of locomotion are generated.

(6) While the neural rhythm generator induces the rhythmic movement of a limb, a posture controller (PC) is responsible for maintaining the

static posture of the stance limb by producing phase-dependent changes in the impedance of specific joints. The final motor command is a summation of the signals from the neural rhythm generator and the posture controller.



Stick picture of walking

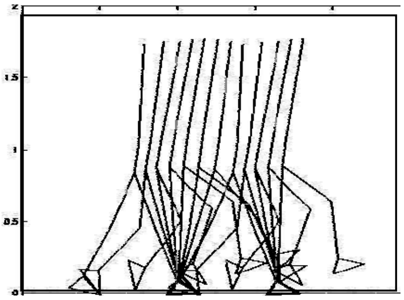


Fig.2 The results of computer simulation of emergence of neural activity, muscle torque and walking movements which are generated in a self-organized manner.

The computer simulation demonstrated that, given a set of initial conditions and values of various parameters, a stable pattern of walking emerged as an attractor which was formed in the state space of both the neural and musculo-skeletal system. Figure 2 shows neural activities, muscle torques and a stick picture of walking within one gait cycle. The attractor was generated by the global entrainment between the oscillatory activity of the neural system and rhythmic movements of the musculo-skeletal system.

When we first proposed the model of bipedal locomotion [5], there was few study to suggest the existence of spinal CPG in humans. Recently, several studies have shown evidence for a spinal CPG in human subjects with spinal cord injury [21,22]. Our model is likely to capture the essential mechanism for the generation of human bipedal locomotion.

2.2 Real-time flexibility of bipedal locomotion in an unpredictable environment

When the solution of the differential equations which were composed of the neural and musculo-skeletal systems converged to a limit cycle that was structurally stable, walking movement was maintained even with small changes in the initial conditions and parameter values [13]. For example, when part of the body was disturbed by a mechanical force, walking was maintained and the steady state was recovered due to the orbital stability of the limit cycle attractor. When part of the body was loaded by a mass, which can be applied by changing the inertial parameters of the musculo-skeletal system, the gait pattern did not change qualitatively but converged to a new steady state, where the speed of walking clearly decreased. When the walking path suddenly changed from level to uneven terrain, stability of walking was maintained but the speed and the step length spontaneously changed as shown in Fig. 3. Naturally, the stability of walking was broken for a heavy load and over a steep and irregular terrain.

Fig. 3 Walking over uneven terrain.

The real-time adaptability is attributed not only to the afferent control based on the proprioceptive information that is generated by the interaction between the body and the mechanical environment, but also to the efferent control of movements based on intention and planning. In this model, a wide range of walking speeds were available by using the nonspecific input from the higher center to the neural oscillators, which was represented by a single parameter. Changes in the parameter can produce bifurcations of attractors, which correspond to different motor patterns [5,13].

It is open whether a 3D model of the body with a similar model of the neural system will perform dynamic walking with stability and flexibility. Designing such a model is a crucial step toward constructing a humanoid robot that walks in a real environment [23].

3. Anticipatory Adaptation of Locomotion through Visuo-Motor Coordination

As long as the stability of the attractor is maintained, the locomotor system can produce adaptive movements even in an unpredictable environment. However, this way of generation of motor patterns is not sufficient when the attractor looses stability by drastic changes in the environment. For example, when we step over an obstacle during walking, the path of limb motion must be quickly and precisely controlled using visual information that is available in advance. Given the emergent properties of the neuro-musculo-skeletal system for producing the basic pattern of walking, how the anticipatory adaptation to the environment was realised? Neurophysiological studies in cats have shown that the motor cortex is involved in visuo-motor coordination during anticipatory modification of the gait pattern [24].

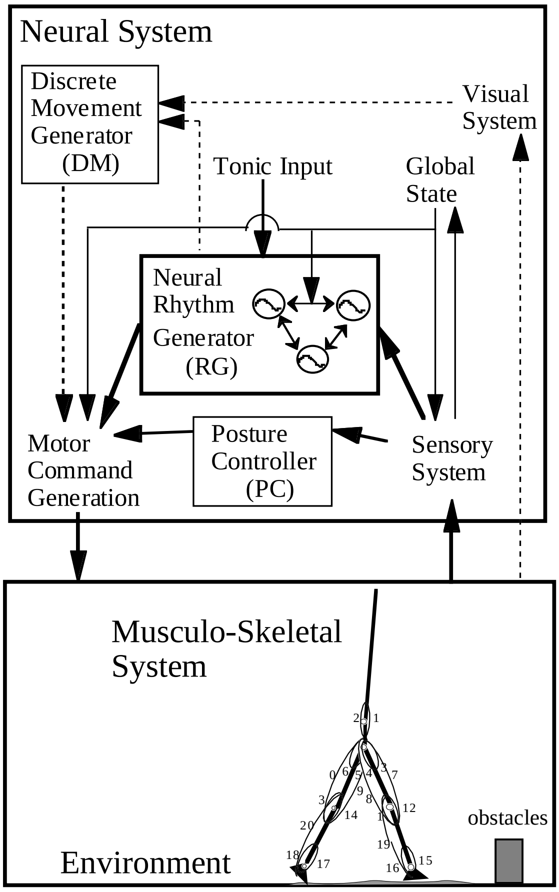


Fig.4 A model of the anticipatory adaptation of locomotion when an obstacle can be seen [15].

It was examined whether modifications of the basic gait pattern could produce rapid changes in the pattern so as to clear an obstacle placed in its path. As shown in Fig. 4, the neural rhythm generator was combined with a system referred to as a discrete movement generator, which receives both the output of the neural oscillators and visual information regarding the obstacle and generates discrete signals for modification of the basic gait pattern [14].

By computer simulation, avoidance of obstacle of varying heights and proximity was demonstrated as shown in Fig. 5. An obstacle placed at an arbitrary position can be cleared by sequential modifications of gait; modulating the step length when approaching the obstacle and modifying the trajectory of the swing limbs while stepping over it. An essential point is that a dynamic interplay between advance information about the obstacle and the on-going dynamics of the neural system produces anticipatory movements. This implies that a planning of limb trajectory is not free from the on-going dynamics of the lower levels of the neural system, the body dynamics and the environmental dynamics.

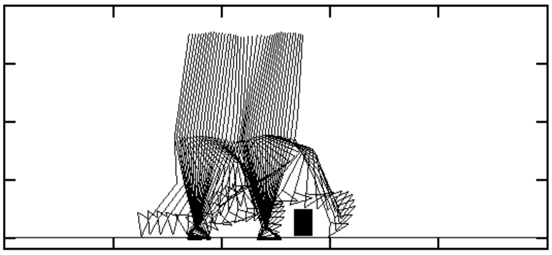


Fig. 5 Result of computer simulation of obstacle avoidance during walking [15].

4. Freezing and Freeing Degrees of Freedom in the Development of Locomotion

Once we had chosen a structure of the neural system and a set of parameter values that produced a walking movement as a stable attractor, the model exhibited the flexibility against various changes in the environmental conditions. However, it was difficult to determine the structure of the model and to tune the parameters, since the entire system was highly nonlinear. A number of studies have used a genetic algorithm to obtain a good performance of locomotion in animals [25] and in humans [26]. Another approach to overcoming the difficulty of parameter tuning of locomotor systems is to explore the motor development of infants and to unravel a developmental principle of the neuro-musculo-skeletal system. Here I show that a freezing and freeing degrees of freedom is one of the key mechanisms for the acquisition of bipedal locomotion during development.

A prominent feature of locomotor development is that newborn infants who were held erect under their arms perform locomotor-like activity [27]. The existence of the newborn stepping implies that the neural system already contains a CPG for rhythmic movements of the lower limbs. Interestingly, this behavior disappears after the first few months. At around one year of age, infants start walking independently. Why the successive appearance, disappearance and reappearance of stepping were observed in the development of locomotion? According to the traditional neurology, the disappearance of motor patterns is due to the maturation of the cerebral cortex which inhibits the generation of movements on the spinal level. However, it was reported that the stepping of infants of a few months of age can be easily induced on a treadmill [27]. It is likely that the spinal CPG is used for the generation of independent walking.

I hypothesized that this change reflects the freezing and freeing degrees of freedom of the neuro-musculo-skeletal system, which may be produced by the interaction between a neural rhythm generator (RG) with neural oscillators and a posture controller (PC). A computational model was constructed to reproduce qualitative changes in motor patterns during development of locomotion by the following sequence of changes in the structure and parameters of the model as shown in Fig.6 [14].

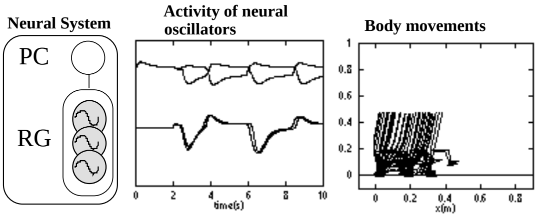
(1) It was assumed that the RG of newborn infants consists of six neural oscillators which interact through simple excitatory connections and that the PC is not yet functioning. When the body was mechanically supported and the RG was activated, the model produced a stepping movement, which was similar to the newborn stepping. Tightly synchronized movements of the joints were generated by highly synchronized activities of the neural oscillators on the ipsilateral side of the RG, which we called "dynamic freezing" of the neuro-muscular degrees of freedom.

(2) When the PC was recruited and its parameters were adjusted, the model became able to maintain static posture by "static freezing" of degrees of freedom of joints. The disappearance of the stepping was caused by interference between the RG and the PC.

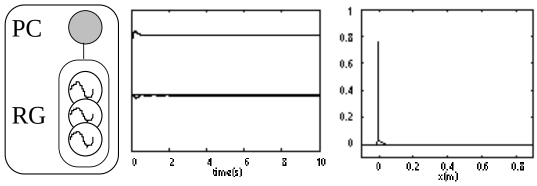
(3) When inhibitory interaction between the RG and the PC was decreased, independent stepping appeared. This movement was lacking in the ability to progress forward. We called this mechanism as "static freeing," since the frozen degrees of freedom of the musculo-skeletal system by the PC were freed.

(4) By decreasing the output of the PC and increasing the input of the sensory information on the segment displacements to the RG, a forward walking was gradually stabilized. The simply synchronized pattern of neural activity in the RG changed into a complex pattern with each neural oscillator generating rhythmic activity asynchronously with respect to one another. By this mechanism, which we called "dynamic freeing," gait patterns became more similar to those of adults.

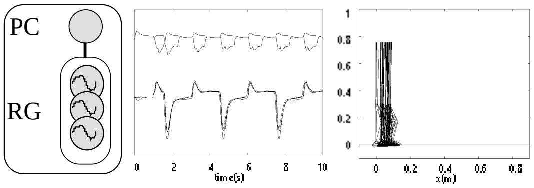
(1) Newborn Stepping



(2) Acquisition of Standing



(3) Acquisition of Walking



(4) Change to Adult-like Patttern of Walking

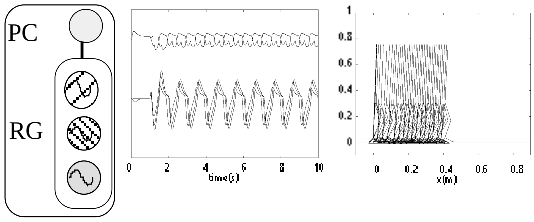


Fig. 6 A model of the development of bipedal locomotion of infants and results of computer simulation.

This model suggests that the u-shaped changes in performance of the stepping movement can be understood as the sequence of dynamic freezing, the static freezing, the static freeing and the dynamic freeing of degrees of freedom of the neuro-musculo-skeletal system. This mechanism is considered to be important to acquire both stability and complexity of movements during development. Parameter tuning for dynamic walking becomes easier after the control of the static posture is established.

5. Chaotic Dynamics of Spontaneous Movements of Young Infants

It remains to be open whether the concept of self-organization in nonlinear dynamical systems can be generalized to unravel the principle of development of complex behaviors including not only rhythmic movements such as walking but also varieties of discrete movements such as reaching arms and touching objects. We focused on what is called general movement (GM) of young infants who have not yet acquired voluntary movements [28]. The GM is a spontaneous movement, which is not just a random movement but a complex one involving head, trunk, arms and legs. The GM emerges during early fetal life and disappears around the age of 4 months post-term when voluntary motor activity gradually appears. Although the GM has attracted attention from a clinical point of view, dynamic properties of the GM have not yet been determined.

We conducted longitudinal observation of the GMs of infants at 4 weeks intervals from 1 to 4 months post-term age [16]. Subjects were 10 infants; 7 normal full-term infants, twin infants born pre-term, one of who was normal but the other was diagnosed as cerebral palsy, and one infant who had midcerebral artery thrombosis. Two-dimensional positions of four reflective markers, which were taped on each of wrists and ankles, were measured using a video camera and a computer with software for digitizing and processing of video images. We finally obtained epochs of spontaneous movements for 150 sec for each observation. Figure 7 shows examples of longitudinal changes in patterns of GMs for two normal infants.

In order to characterize the complexity and variability of GMs, we assumed that time series of GMs were generated by a dynamical system. Dynamic properties of GMs were assessed by the method of nonlinear prediction [29], in which we estimated predictability of trajectories in a phase space that was constructed by embedding of the original time series of x-y coordinate of four limbs. It should be noted that not position but velocity data were used to remove linear trends and to give greater density in phase space. Chaotic dynamics would be revealed by a decrease in the predictability with increasing prediction time steps, whereas linear process with uncorrelated noise would show a non-decreasing predictability. Statistical significance of nonlinearity was also examined using the method of surrogate data processing to exclude a possibility that high predictability can be obtained by random noises with linear auto-correlations [30].

We found evidence that the spontaneous movements of normal subjects were generated by nonlinear dynamics, which can be distinguished from linear processes and correlated noises. We also analyzed developmental trends in the motor pattern changes and detected U-shape changes in the complexity around 2 months of age for 5 infants out of 8 normal infants. Furthermore, movements of the 2 abnormal infants were characterized by loss of complexity; one showed too rhythmic pattern and the other showed a random one.

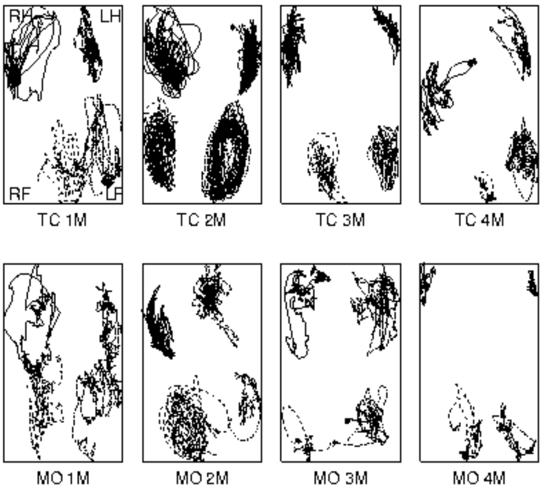


Fig. 7. Longitudinal changes in trajectories of four limbs during general movements of two normal infants for the first 4 months of age [16].

Our findings showed that the development of motor patterns is not a progressive process from a simple to a complex state nor a converging process from a random to an organized state. The developmental changes of the GM around the age of 2 months can be accounted by dynamic freezing and freeing degrees of freedom as shown in the model of development of locomotion. However, the entire processes of developmental changes in the GM are not so simple as the story of the development of locomotion, since the GM includes wide range of motor repertoire such as kicking, reaching arms, touching one's own body etc. From a point of neural mechanism, the loss of complexity in the patterns of the GM suggests that the cortex is involved in both the generation of complex motor patterns and the transformation of the GM patterns during development. This infers that the chaotic dynamics of the neuro-musuclo-skeletal system may play an important role for acquisition of movements during development. To confirm these findings, three-dimensional measurement of motion of entire body is in progress.

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