Title	DYNAMICS OF SELF-ORGANIZATION IN HUMAN LOCOMOTION
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Description	
Citation	乳幼児発達臨床センター年報, 16, 81-101
Issue Date	1994-03
Doc URL	https://hdl.handle.net/2115/25296
Type	departmental bulletin paper
File Information	16_P81-101.pdf

DYNAMICS OF SELF-ORGANIZATION IN HUMAN LOCOMOTION

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Within the framework of the dynamical systems theory of movement coordination and control we provide tools and methods to study coordination changes and stability characteristics in human locomotion. The first part of the paper offers a tutorial on dynamical systems principles, in particular what the central tenets are of a law-based approach to movement coordination. This law-based approach emphasizes the self-organizing principles that underly the formation of new movement patterns and the unity in organizing strategies across scales of observation (Kugler & Turvey, 1987). Central to the formation of new patterns is the thermodynamic theory of dissipative structures as developed by Prigogine (1980). We then turn to a description of mechanical pendular properties of the rhythmic oscillations of the limbs and assess their different stability characteristics of mechanical and dissipative processes. Different approaches (e. g., dissipative structures, synergetics theory and dynamical models) that directly relate to the formation of new movement patterns are elaborated upon. The second part of the paper provides empirical data from our own research, using dynamical systems tools and principles in studying coordination changes in healthy and pathological gait. Finally, we discuss some of the implications of this dynamical approach for the study of developmental changes in locomtory patterns.

Key words: gait transitions, nonlinear dynamics, relative phase dynamics, control parameters, pattern stability

Introduction

How does an infant discover a new locomotory pattern? How does it stabilize this newly acquired pattern? And how do transitions from standing to walking or between walking and running emerge? In this paper we would like to address these kinds of questions using principles and methods that emphasize physical descriptions of locomotion that closely approximate a pendular, clocking (limit cycle) mode of organization (Kugler & Turvey, 1987). The approach advocated by Kugler & Turvey (1987) emphasizes transformation and conservation mechanisms of energy processes as a possible source of order. These transformation and conservation processes can be observed at different frames of reference, namely the macro-mechanical and micro-thermodynamical. In the following sections it will be shown that the emergence of new patterns result from the interplay between mechanical and thermodynamical (dissipative) processes. These descriptions and formalisms are presented within the framework of the 'dynamical systems approach' to movement coordination and control, which is based on recent developments in nonlinear dynamics (e. g., Thompson & Stewart, 1986) and ecological psychology (e. g., Gibson, 1979). General principles and methods of this theory will be laid out, and we will illustrate these with data from our own work that is concerned with the evaluation and treatment of movement disorders in neurologically disabled individuals. Finally, we will discuss some of the implications of this approach for the study of coordination changes in motor development.

A Law-based Approach to Movement Coordination

One of the outstanding questions in the area of motor control is how the multiple degrees of freedom in the human body are coordinated and controlled in a coherent fashion. Bernstein (1967) was one of the first who recognized the complexity of the movement control system and systematically investigated how in the course of learning the available degrees of freedom are utilized, and, eventually mastered. Whether at a biochemical, muscular, or biomechanical level, biological systems encompass numbers of degrees of freedom that widely surpass those of artificial (engineering) systems. Also, there is no straightforward, unambiguous relation between afferent signals to muscles and corresponding movements. This implies that individual muscles and their innervational states do not have fixed movement consequences, and that movement outcomes are dependent upon contextual contingencies ('context-conditioned-variability', Turvey, 1990). This context-conditioned-variability is also visible in current mass-spring models of motor control (e. g., Feldman, 1986). In Feldman's equilibrium-point hypothesis, states of the motor system are described in equilibrium states which are dynamically assembled from the interaction of centrally regulated nonlinear thresholds on the motor neuron pool and the active loading of the musculo-skeletal system.

The dynamical systems approach provides a law-based account of how interactions between systems develop, stabilize, and change. Natural laws couple physical symmetries, which are defined by kinematic variables. Natural laws explain the stability and reproducibility of events and have only qualitative invariance, in that they identify qualitative geometric (or topological) relations which remain invariant under certain system transformations. Typically, natural laws are defined over the dimensions of mass, length, and time (see Kugler & Turvery, 1987). In traditional hierarchies in biological explanation, biological systems are considered to be holistic, whereas physical explanations are unit explanations and reductionist. The reductionism in a law-based program towards biological systems is of a fundamentally different kind because it is searching for universal organizing strategies applicable across various disciplines of the natural sciences or scales of observation (Haken, 1977 ; Kugler & Turvey, 1987 ; Soodak & Iberall, 1978).

Despite the ubiquity of cross-scale interactions, the physical and social sciences have long been preoccupied with same-scale interactions (Kugler & Shaw, 1990). The laws that have been proposed operate essentially at the same scale, refer to system dynamics that are reversible, and assume that first principles (such as the first and second laws of thermodynamics) are weakly and linearly coupled. Under this assumption, high dimensionality or variability in the movement system is viewed as a curse, to be avoided and eliminated. In the dynamical approach this variability and dimensionality is to be exploited, in that symmetry-preserving and symmetry-breaking strategies are considered as consequences of nonlinear couplings of these first principles that operate across scales (physical, biological, psychological).

Thermodynamic principles: Dissipative structures

Traditional theories of motor behavior (e.g., Adams, 1971; Schmidt, 1975) contemplate the moving organism as a closed system in which order, stability, uniformity, and equilibrium are emphasized. Linear relations in which small (large) inputs give rise to small (large) outputs dominate in these types of systems. Order, stability, and equilibrium in closed systems are fundamental aspects of classical mechanics, while in thermodynamics new models were developed in which energy, matter, and information are exchanged with the environment. Thermodynamics deals with the transactions of various forms of energy in all its possible forms, and is described by phenomena such as pressure, concentration, temperature, etc. Fluctuations and stochastic processes are essential, and in addition to conservative mechanical forces thermal flows exist which compete with the conservative forces, thereby increasing the order of the system.

In this view, macroscopic processes contain microscopic processes, and fluctuations at the micro level can fundamentally change the existing order at the macroscopic level. A system can disintegrate into chaos or jump to a higher level of organization. This higher level of organization is called a 'dissipative structure' (Prigogine, 1980). Dissipative structures require more energy to sustain their action, compared to the more simple structures from which they unfold. Prigogine (1980) emphasizes disorder instead of order, instability instead of stability, disequilibrium instead of equilibrium, and nonlinear relations in which small inputs can trigger disproportionately large outputs. These nonlinear relations are considered common whereas linear relations are considered rare.

The theoretical perspective on movement advocated by Kugler and Turvey is called the natural-physical perspective of biological organization because it is grounded in the dynamic principles of physical theory (the physical theory as outlined by Prigogine) and ecological realism (Gibson, 1979). Essential to the natural-physical perspective is the dissipative structure concept as advocated by Prigogine. In far from equilibrium conditions individual degrees of freedom (atoms, muscles, organisms) can change their behavior from unstable, chaotic, and random to a highly structured organization. In the latter stage all the degrees of freedom change or interact simultaneously, creating a sort of chemical or biological clock. The highly synchronized behavior and entrainment is an example of a self-organization process. The natural-physical perspective provides an understanding of how macroscopic patterns (whether at a molecular, biological, or social system level) can be temporarily assembled, sustained, and dissolved with no a priori set of logical constraints. What emerges is a theory of self-organizing systems, addressing directly the problem of morphogenesis in which circular interactions between low energy kinematic flow fields and high energy force fields are fundamental (e.g., see Kugler, 1986 for an application to motor development).

This intricate unity of action and perception is the hallmark of Gibson's (1979) theory of perception.

Central aspects of the theory of self-organizing systems are principles related to geometry and physics. The geometric principles are intrinsically related to the process of morphogenesis. Morphogenesis is defined by Waddington (1970) as the coming into being of characteristic or specific form in living organisms. A geometric or morphogenetic analysis focuses on intrinsic symmetries (also called 'similitudes'), and how these symmetries are sustained under some scale changes (structurally stable) and annihilated under others (structurally unstable). A physical analysis focuses on the identification of these symmetry-breaking mechanisms and on *how* qualitative changes ('bifurcations') occur (e.g., Abraham & Shaw, 1984). Nonequilibrium nonlinear thermodynamics is the area describing these symmetry-breaking mechanisms.

Any spontaneous process results in an increase in the disorder of the system and its surrounding. This is essentially what is stated in the second law of thermodynamics. Closely related to the second law is the entropy concept, which is defined as a state or condition of matter and energy identified with randomness or disorder. A corollary of the second law is that physical and chemical processes evolve in the direction of maximal entropy, i.e. maximal disorder. When the entropy of a system remains constant, the process is called reversible. This could occur theoretically in an isolated system where no change of energy and matter with the surrounding is possible. In contrast to reversible processes, the entropy production is always greater than zero in irreversible processes. These irreversible processes are unidirectional, and are the hallmark of open systems. In an open system energy and matter can be exchanged with the surrounding. In isolated systems the entropy production increases until thermodynamic equilibrium and the spontaneous formation of new states of structures is not possible (Nicolis & Prigogine, 1977; Prigogine, 1980). For an open system, however, the competition between entropy flow in the system and the exchange with the environment permits the system to adopt new structures and new forms. Open systems are in a steady state, whereas isolated systems are in true equilibrium (von Bertalanffy, 1968).

In conditions *near* equilibrium thermodynamic forces are weak and the response to small perturbations from the steady state results in a damping behavior, linearly proportional to the magnitude of the perturbation. This response to perturbations is similar to the behavior in the equilibrium condition. As a consequence, the development of a new and more complex order is impossible in this linear range of the equilibrium condition (Prigogine, 1980). When the perturbations acting on the system exceed the linear range, the independence from fluctuations and the stationary state of the system disappears. Fluxes now become more complex nonlinear functions and under certain conditions far from equilibrium fluctuations may be amplified bringing the system to a new order.

The term 'dissipative structure' emphasizes the close association between structure and order on one side, and dissipation or waste on the other (Prigogine & Stengers, 1984). In classical linear thermodynamics heat (or the incoherent transfer of energy) was considered a form of waste, but in nonlinear, nonequilibrium thermodynamics this transfer or energy dissipation becomes a source of order. Far from equilibrium a marginal state of stability is created in which a sudden transition moves the system towards instability, leading in turn to fluctuations and eventually to a new order. Symmetry-breaking instabilities can result from scaling up or down a single parameter into the nonlinear range. New stabilities may develop beyond a certain critical scale value. The critical scale value can be expressed in a dimensionless number (also called 'π-number'), which is intrinsic to the system and expresses the deviation from the internal equilibrium state.

It must be emphasized that dissipative structures are not only characterized by their ability to self-organize, but also by their ability to resist changing initial and boundary conditions that describe the relation of the system with its environment. Dissipative structures are autonomous in that they are relatively unaffected by perturbations to initial and boundary conditions. Small deviations do not change the behavioral pattern of these structures, a principle known as the equifinality principle (von Bertalanffy, 1968), which is an important aspect of dynamic mass-spring models in motor control.

Mechanical aspects: Scaling relations and pendulum models

A law-based account of the coordination and control of movement searches for a description of the rhythmic movements of the limbs in higher and lower animals in terms of the fundamental relations of mass, length, and time. Using the wrist-pendulum system as a model for the oscillatory properties of the limbs during locomotion, Kugler and Turvey (1987) derived a fundamental scaling law that captures the relation between periodic time, mass and length:

$$t_o = a_i (M^{1/16} L^{1/12})^{c_i} \cdots\cdots\cdots\cdots (1)$$

where M is the mass and L is the length of the limb or oscillator. Individual subject characteristics (e. g., anthropometric or internal control aspects) are viewed as non-uniform coordinate spaces in which the invariant law is embedded. These are evident in different scalar and vector potentials and indexed by a_i and c_i, respectively.

Kugler and Turvey (1987) analyzed the different gaits in a variety of animals from data by Pennycuick (1975). Regression analyses in double log coordinates revealed that for the walk, trot, and canter periodic times scaled, apporoximately, to mass raised to the 1/8 power (.16 for walking, .13 for trotting, and .12 for cantering) and to length raised to the 1/2 power (.49 for walking, .48 for trotting, and .44 for cantering). As animals increase or decrease locomotory speed, there is an increase in the irreversible flow of chemical energy into mechanical energy. This transformation is a scalar one, however, as the above relations between periodic time, mass, and length remain invariant.

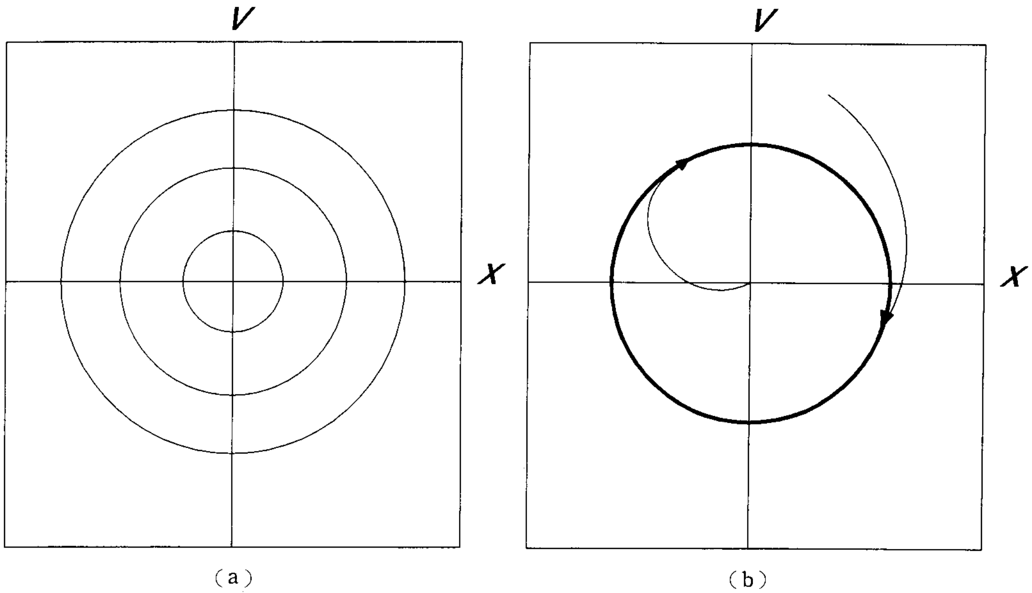
What does distinguish the different coordinative modes is that these regression lines do not overlap, i. e., not all periodicities are accessible for each gait. Kugler & Turvey suggest that it is the constant of acceleration due to gravity that governs the quantization of the different gait spectra:

$$t = 2\pi\sqrt{(L/ng)} \cdots\cdots\cdots\cdots (2)$$

For an ordinary physical pendulum, n=1. For walking, trotting, and cantering, n was found to be 1.95, 6.96, and 9.73, respectively. This suggests that different gaits are organized around integer multiples of the gravitational field intensity, and that animals organize their locomotory patterns on the basis of the reactive forces that emerge in the gravitational field.

Stability properties of mechanical and dissipative systemes

The mechanical, conservative laws describe physical conditions in which reversible energy transformation takes place (between potential and kinetic) without degradation or dissipation. This system is inherently unstable with respect to external perturbations. A perturbation leads to a change in the momentum and observed behavior of the system. This is illustrated in the 'phase-plane' configuration in Figure **1a**, in which the variable on the abscissa identifies the position variable (X) and the variable on the ordinate the velocity (V). A perturbation (small and large) applied to a conservative system will cause the system to adopt a new state (different orbit in the phase plane).



(a) (b)

FIGURE 1 Phase plane plots for a conservative (a) and nonconservative (limit cycle) system (b). The position variable is on the ordinate (X) and the velocity variable is on the abscissa (V).

In nonconservative processes on the other hand, the work cycle is formed as a result of irreversible transformations in the energy distributions from a macro to a micro frame of reference. This transfer takes place from a higher potential source to a lower potential sink. Qualitatively, the behavior of this work cycle is that of a limit cycle: a closed orbit in the phase plane (see Figure **1b**). Characteristic of the limit cycle is it's stability to perturbations and return to the same stable orbit, following different kinds of perturbations. Only very strong perturbations could possibly lead to another mode of organization. The limit cycle is therefore proposed as the basic unit of an autonomous system (Kugler et al., 1980; 1982).

The contribution of conservative (mechanical) and nonconservative (dissipative) elements is identified by a dimensionless number called the Q-factor. The number is obtained by dividing the average energy carried by mechanical processes (Em) by the average energy carried by thermodynamical processes (Et):

$$Q = Em/Et \quad \cdots\cdots\cdots\cdots (3)$$

A system with a high Q-factor stores a lot of the energy in the macroscopic force structure (the oscillations of the limbs, for example). Very little energy flows from macro to micro levels and there is no dissipation of energy. A low Q-factor is a system that stores very little energy at the macro mechanical level but absorbs most of the energy at a more micro level through dissipation. These two systems have very different stability features: high Q-factors lead to unstable systems, low Q-factors to stable systems.

The Emergence of New Movement Forms: Phase Transitions

The Interplay between mechanical and dissipative processes

A consequence of the framework presented above is that new forms can only arise from the interplay between reversible and irreversible transformations of energy. A reversible transformation occurs within a single frame of reference, for example the macroscopic mechanical. Here we only encounter transformation in the from of the energy (potential and kinetic). Irreversible processes identify the flow of energy of one frame of reference (macroscopic mechanical) to another (microscopic thermodyamical), in which constraints are broken (second law of thermodynamics) and assembled (see Kugler & Turvey, 1987 for a full discussion). This assembly arises from the emergence of long range correlations at the micro level.

An illustrative example of these different energy flows and the interchange between conservative and nonconservative processes is provided by the dynamics of a falling leaf (Kugler & Turvey, 1987; Kugler et al., 1990). When dropped from a sufficient height, a leaf might exhibit three qualitatively different modes of organization, namely: a translation, a vibration, and a spinning mode. The first is the translational mode, in which the leaf is falling down in a more or less straight path. More and more energy is absorbed while falling down (the leaf loses potential energy and gains kinetic energy) until a critical point is reached where this mode is no longer stable. At the critical point (height) the leaf self-organizes into a new vibration mode. This new mode can consume or dissipate the increasing kinetic energy that is being pumped into the system and stabilizes the dynamics. If the leaf keeps falling this mode will eventually become unstable as well, and a new mode that can contain more of the energy spontaneously emerges. This third mode is the spinning mode. Kugler and colleagues use this example to demonstrate that increasing the amount of energy flow into the system can lead to the emergence of new movement forms through a process of self-organization. In other words, new movement forms emerge through energy exchanges of the system with its environment and are not prescribed a priori in the structural elements.

In biological organisms a prereguisite for the emergence of these new forms is the coupling between high energy action fields that arise from the internal degress of freedom of the organism (micro-states) and the low energy perceptual (flow) fields. Due to their on-board energy reservoirs and ability to produce suitably large forces, biological organisms can time delay energy transactions and are not guided solely by the reactive forces that arise from the organism's presence in the environment (Kugler & Turvey, 1987). These nonmechanical interactions have been termed 'perceptual' and emerge through the availability of low-energy fields (e.g., sound, light), which are lawfully structured by the high-energy matter fields (layout of surfaces). Flow morphologies that can be defined on these low-energy fileds are potential sources of information about the dynamics that give rise to them.

New movement forms or coordinative structures do not emerge on the basis of 'hard-molded', high-energy force interactions but arise through 'soft-molded', low-energy flow morphologies present in the neural fields. New structures develop through a circular causality between the low-energy flow fields (perceptual aspects) and the high-energy action fields.

In the following sections we will elaborate on models in which this formation of coordinative structures is not construed physically but mathematically.

The Synergetics Approach

Relevant to identifying the nature of coordination changes is the distinction in synergetics (Haken, 1977; Schöner & Kelso, 1988) between order and control parameters. Order parameters identify low-dimensional qualitative states ('macro states') of the system dynamics, in which changes between modes can be induced by manipulating an aspecific control parameter, such as frequency or velocity. Phase relations between body segments are considered order parameters because of their fundamental reflection of cooperativity between components in the system ('micro states'). Relative phase between component oscillators (fins, hands, legs, etc.) can identify different qualitative states of the system dynamics (e.g., in-phase and out of phase) on which basis changes in coordination patterns can be evaluated.

Synergetics offers tools to study the nature of these phase transitions. Discontinuous transitions are characterized by abrupt jumps between different coordinative modes; these abrupt jumps can occur for very small changes in the control parameter (nonlinearity). Continuous phase transitions are more or less smooth and can occur over a larger interval of control parameter values. Critical in distinguishing these two types of transitions is the stability of the order parameter: only in abrupt transitions instability occurs before the transition point. This instability can be measured by means of fluctuations (standard deviation) in relative phase or the relaxation time after a transient perturbation. The observation of critical fluctuations and corresponding loss of stability in the order parameter is dependent upon several time scales relations: T_{obs}, the time over which the control parameter is changed or the system is measured; T_{rel}, the local relaxation time after a perturbation; and T_{equ}, the global relaxation time which is a probabilistic entity and indicates the time it would take for the system to visit all its possible states without a change in control parameter. If $T_{rel} \ll T_{obs} \ll T_{equ}$ then the different qualitative states are considered stationary stable states and transitions involve a loss of stability and increased fluctuations. If $T_{rel} \ll T_{equ} \ll$

T_{obs} then the system is not in a stationary state and no loss of stability is predicted. Control parameter changes can also lead to 'hysteresis': where and when abrupt jumps in coordination patterns occur is dependent on the way the control parameter was changed. Parametric changes in which the control parameter increases and decreases can lead to different coordinative modes at the *same* control parameter value.

Schöner et al. (1990) proposed a model of quadrupedal gaits and gait transitions based on the synergetics approach. They defined symmetry as the invariance of the phase vector representing the phases of the component oscillators. Patterns like the gallop, trot, and pace are symmetrical with respect to spatial symmetry operations of left-right limb and front-hind girdle exchanges, as well as temporal inversion, and can be considered stable independent attractors of the system dynamics. Attractors identify preferred modes of organization, and the limit cycle in the phase plane (see Figure 1b) is an example of an attractor. A pattern like the walk, however, is multistable under these symmetry requirements: two alternative modes, the 'straight' and the 'reverse' walk, can exist as dynamically equivalent degeneracies (Schöner et al., 1990), which can only become stable independent states when symmetry-breaking occurs through lowering the symmetry of the dynamics. Under certain symmetry conditions and parametric changes both abrupt and continuous changes in the coordination between homologous and nonhomologous limbs are predicted. This in contrast to observations from bimanual hand and finger movements where abrupt changes have been observed (Haken et al., 1985; Kelso et al., 1986). These different transition patterns can be related to the number of components and asymmetries in the system that reflect different stabilities in the relative phase between the component oscillators, which in turn are reflections of the overall stability and adaptability of the movement control system.

Dynamical models: The importance of control parameters

Glass and Mackey (1987) recognize the human body as a complex spatio-temporal organization, in which different diseases emerge when the normal organization breaks down and is replaced by some abnormal dynamic. This so-called 'dynamical diseases' approach investigates the nature of abnormal biological rhythms on the basis of nonlinear mathematical models, in which control parameters are essential in inducing a pattern change. Although it is evident that pathologies are related to structural abnormalities as well as system control processes, the latter have received scant attention in the medical literature.

Glass and Mackey distinguish three types of qualitative changes in dynamical diseases, i. e.: 1) the appearance of regular oscillations in a biological control system that normally does not show oscillatory behavior; 2) the appearance of new periodicities in a process that is already periodic; and 3) the disappearance of rhythmic processes. These qualitative changes can be observed in movement coordination present in standing and walking: the initiation of gait involves starting a rhythmic process, coordination changes during walking often involve introducing new periodicities, and stopping requires the disappearance of the on-going rhythm.

Akamatsu et al. (1986) have recently developed a dynamic model of the oscillatory properties of the length-tension relations in human muscle based on a population dynamics model or logistic difference equation by May (1977):

$$x_{n+1} = \alpha x_n (1 - x_n) \qquad \{0 \leq \alpha \leq 4\},$$

where x_n is the generated muscle length or joint angle at moment n, x_{n+1} the length or angle at moment n+1, and α is a control parameter, for example indicating the degree of muscle activation. This model is able to generate very different movement dynamics as a function of scaling the control parameter α. When α has low values the model predicts that from moment to moment there are no systematic changes in muscle length or joint angle. In dynamical terms, this state of organization is called a 'fixed point attractor'. When α is increased the steady state remains until α reaches a critical value, at which point the muscle length or joint angle starts to oscillate between two fixed values from one moment to the next, and the dynamic of the 'limit cycle' or 'periodic attractor' emerges (see Figure 1b). If parameter α increased even more then a period doubling occurs from a period 2 to a period 4 to a period 8 oscillation, and so on. Eventually, when α reaches a critical value the oscillations are not periodic, but almost periodic or 'quasiperiodic'. At even higher values of α there is a change to 'chaotic' dynamics in which the movement becomes more and more unpredictable. These qualitative changes from steady state to periodic to quasiperiodic to chaotic behavior are also referred to as 'bifurcations'. An example of a bifurcation diagram is presented in Figure 2. The control parameter α is plotted on the abscissa, and the variations in muscle length or joint angle on the ordinate.

This dynamic model demonstrates that a simple mathematical model for muscle or population dynamics can generate complex types of oscillatory behavior, and that bifurcations between these different dynamics occur for very specific values of a single control parameter. In the dynamical diseases approach the existence of multiple rhythms or periodicities does not have to imply that the underlying organization of the movement control variables has to be complex, i. e. that all these periodicities have to be represented in the control system. On the contrary, manipulation of only one control parameter can generate different types of dynamics, ranging from no observable periodicity to simple and complex oscillations.

Winfree (1980; 1987), one of the pioneers in research on biological rhythms, described and modelled phase resetting dynamics in a wide variety of biological organisms. Mosquitos, for example, show a circadian activity pattern of approximately 23 hours; their humming increases at sunset and sunrise. When a group of these musquitos is kept in a dark cage they exhibit their regular 23-hour cycle. After applying a strong light pulse for about 7.5 minutes, however, there is a shift in the phase or rhythm of activity; this shift is either a deceleration or an acceleration with respect to the old phase or rhythm. In the plot of old phase versus new phase these shifts can be seen as oscillations around the diagonal (representing no phase shift, where new phase equals old phase). This resetting of rhythmic behavior in which there is only a slight shift with respect to the old phase is called 'type 1' or uneven phase resetting. A different type of phase resetting occurs when a strong stimulus with a duration of 2 hours instead of 7.5 minutes resets the activity patterns of the musquitos to one complete period. This type of phase resetting is called 'type 0' or even resetting and the changes

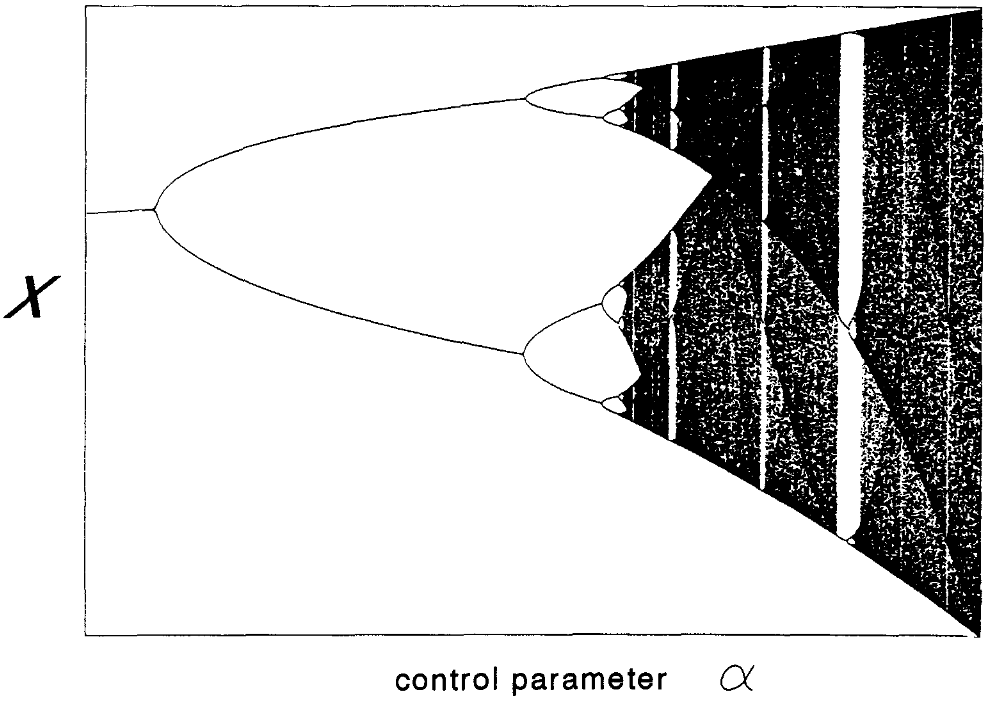


FIGURE 2 Bifurcation diagram with control parameter α on the abscissa and the variation in muscle lenght or joint angle on the ordinate. Bifurcations take place at specific values of the control parameter. At the first bifurcation point the dynamic changes from a steady state (no oscillations) to a stable limit cycle (period two oscillation) in which two different joint angle configurations are adopted during a cycle. At higher values of α a bifurcation to a period 4 oscillation emerges, and at even higher values a bifurcation to a period 8, etc.

in new phase take place around a horizontal line.

Winfree has further developed these different types of resetting in so-called 'time crystals', that represent the geometric properties of old phase versus new phase as a function of changes in a control parameter, such as the duration of the light pulse in the example above. Gradually increasing the pulse duration will change the resetting curve from uneven to even (from type 1 to type 0). The point where this transition occurs is called the 'singularity point'. If a stimulus of a particular duration and administered at a certain moment in the on-going pattern brings the system in this singularity point, then the oscillation is extinguished or can become chaotic.

These models are important in different areas of medicine, like sudden heart death in which no known structural abnormalities could be detected (Goldberger et al., 1990). They demonstrate that pathologies can arise from specific constraints on the dynamics. Winfree's time crystal models also show that different types of phase resetting do not have to be attributed to different 'clock' mechanisms in biological systems; they simply arise as a result of the same underlying dynamic when system control parameters are scaled.

We now turn to discussion of the application of dynamical systems' principles and the relevance of control parameter manipulations in the investigation of gait changes and stability of gait in normal and pathological human walking.

Empirical Data : Transitions and Stability in Locomotion

In bipedal locomotion coordination patterns like the walk and run have been identified as qualitatively different modes. It is often assumed that within these modes only linear scaling can occur : the studies were focused on changes in spatio-temporal characteristics in the step patterns of the lower extremities did find systematic linear increases in stride frequency and stride length when walking velocity was increased (e. g., Andriacchi et al., 1977 ; Larsson et al., 1980). A number of studies, however, suggest a transition in frequency and phase relations in bipedal walking within the velocity range 0.75-1.0 m/s (e. g., Craik et al., 1976 ; van Emmerik and Wagenaar, 1992 ; Wagenaar & Beek, 1992 ; Wagenaar & van Emmerik, in press).

This section focuses on the identification of different coordinative modes and the nature of transitions between these modes in human walking using tools from the dynamical systems approach. The question is whether the changes described in the model of Schöner et al. (1990) on quadrupedal locomotion also occur in the human bipedal walking mode. Coordination changes in relative phase between thoracic and pelvic rotations, as well as between arm and leg movements, were examined while movement speed and stride frequency were manipulated as control parameters. The nature of the transition and the stability of the pattern can be characterized by the variability in the order parameter relative phase : abrupt transitions between coordinative modes show large increases in variability of relative phase before and at the transition point, whereas more gradual transitions do not show these increases in variability.

Transitions in the kinematics of the trunk

Changes in coordination patterns as a function of walking velocity have also been observed for motions of the trunk and head during locomotion (e. g., Cappozzo et al., 1981). Head, thorax and pelvis move in coordinated fashion in order to minimize mechanical energy variations during the walking cycle. Coordination problems in trunk rotations have also been identified as determinants of movement pathologies in stroke patients (Wagenaar & Beek, 1992) and Parkinsonian patients (Murray, 1978 ; van Emmerik et al., 1993).

Wagenaar and Beek (1992) observed systematic changes in the phase relation between pelvic and thoracic rotations by continuously scaling walking velocity. This phase relation changes from a more in-phase pattern (about 25 degrees) at low speeds to a more out-of-phase pattern (about 120 degrees) at higher walking speeds. Dimensionless analysis revealed changes in the coordination of trunk and pelvis rotations : an optimal coupling in the coordination of the trunk and a sudden increase in transversal pelvic rotation emerged in the velocity range 0.75-1.0 m/s.

Our present data elaborate on these findings and investigated the *nature* of these coordination changes and the *stability* of the patterns. In Figure 3 is presented the changes in relative phase between pelvis and thorax as a function of walking velocity for a healthy subject and a patient with Parkinson's disease. In the healthy subject (bold solid line) relative phase changes from a more in-phase relation at lower veloc-

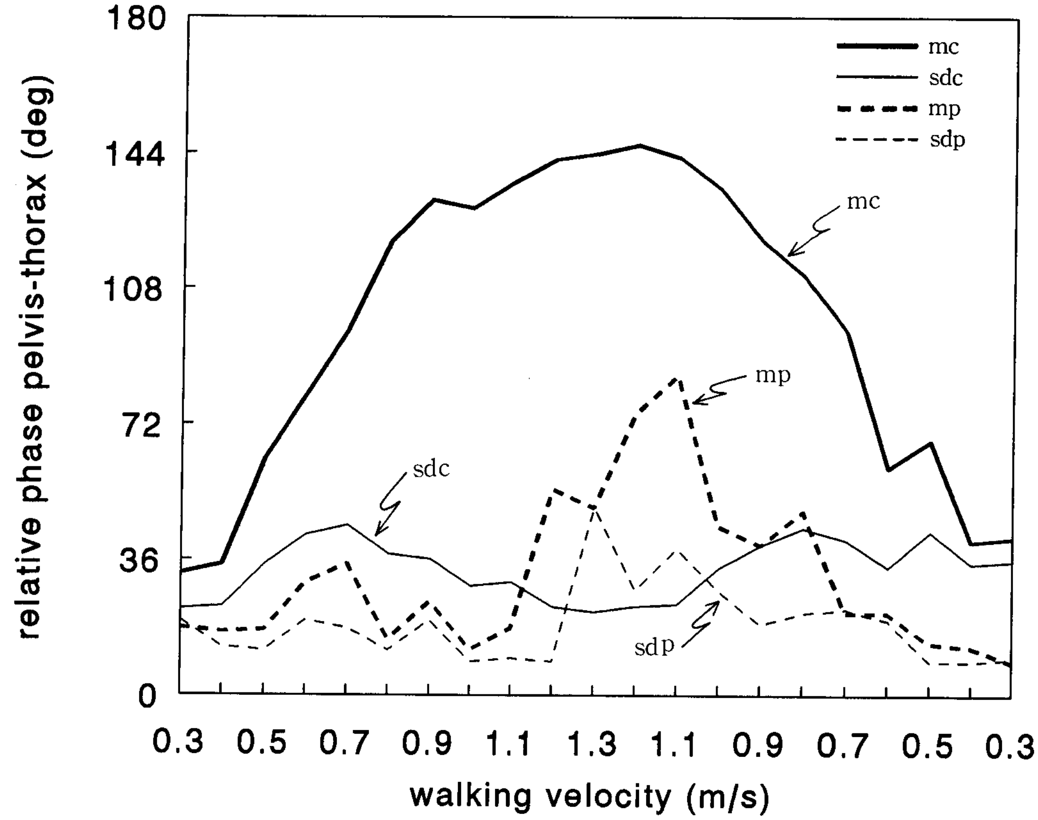


FIGURE 3 Changes in mean relative phase between pelvis and thorax for a control subject (solid lines) and a Parkinsonian patient (dashed lines) as a function of ncreasing and decreasing walking velocity on a treadmill. The mean relative phase over an entire stride cycle is plotted in bold lines, the stability in relative phase, expressed by the standard deviation, in thin lines. m=mean, sd=standard deviation, c=control, p=patient.

ities to a more out-of-phase relation at higher velocities. The standard deviation of relative phase (thin solid line) increased (stability decreased) at intermediate velocities as compared to the standard deviation at low and high walking velocities. This indicates that there are two more or less stable coordination modes, with in between a region of lesser stability. This increased standard deviation at the intermediate range could be 'critical fluctuations' as predicted from synergetics. It should be noted that not all subjects do show this same pattern of stability changes; in some subjects no systematic changes in stability as a function of walking velocity were observed. These different transition mechanisms suggest multistability (i. e., multiple stable patterns) at lower walking velocities.

In the gait dynamics of patients suffering from a variety of neurological disorders it is generally observed that the movement patterns are less adaptive. We have proposed that the movement coordination problems in patients suffering from Parkinson's disease and hemiplegia after stroke can be related to a general inability to induce phase transitions. In Parkinsons' disease patients differences related to these transition dynamics are observed (see for more detail, van Emmerik et al., 1993). In research on movement control problems in Parkinson's disease, the main clinical symptoms of rigidity, bradykinesia, and tremor have been assessed in isolation. From a dynamical perspective we have examined these symptoms in terms of a general inability to impose transitions in coordination patterns in these patients. We consequently searched for the most relevant control parameters that could be systematically scaled so that new coordination patterns can spontaneously emerge from the underlying dynamics.

An example of such a transition problem is depicted in Figure **3** : in contrast to the changes in relative phase in the healthy subject, on systematic changes in the relative phase between pelvis and thorax were observed in a patient with Parkinsons's disease (see dashed lines). The relative phase remained in an almost in-phase relation at a variety of different velocities, although decreasing the velocity resulted in larger phase differences at comparable speeds than increasing velocity (hysteresis). In addition, there was a very low variability of relative phase, indicating high stability in the relative phase between pelvis and thorax, that did not change with walking speed.

In stroke patients movement coordination problems arise as a consequence of lateral asymmetries that result from a hemiplegia. But these coordination problems are not only related to arm and leg movements; the movement of the trunk is also severely affected as was shown in a dimensionless analysis by Wagenaar and Beek (1992). We recently investigated the effects of using an imposed step frequency as the control parameter on changes in trunk rotation. No large changes in trunk rotation were observed as a function of frequency, but the type of rhythm did seem to make a difference. When the subject was instructed to move both arms and legs to the rhythm of a metronome, the observed phase difference in the trunk between pelvis and thorax was larger than when the subject was instructed to only move his legs to the rhythm of the metronome. This larger phase difference is a more stable pattern, especially for locomoting at higher velocities where it is linked to a reduced spin in trunk rotation and an increased pelvic rotation to lengthen the stride.

Transitions in kinematics of upper and lower extremities

Craik et al. (1976) observed an 'abrupt' change in the frequency relations between upper and lower extremities as a function of walking velocity: below 0.75 Hz the frequency relation was 2 : 1, above 0.75 Hz the frequency relation was 1 : 1. Jackson et al. (1978) have suggested that this switch from a 2 : 1 to 1 : 1 frequency coupling might arise within the upper extremity due to period doubling in the oscillation of the forearm. These different frequency relations are related to changes in the relative phase between the two arms.

In our research (Wagenaar & van Emmerik, in press) we observed in 6 healthy subjects a general change from an in-phase or alternating pattern at lower and intermediate velocities to a more out-of-phase pattern at higher velocities. Similar stability characteristics were observed as in the trunk: at intermediate velocities (around 0.8-0.9 m/s) loss of stability could occur. These findings are consistent with frequency changes that can occur as a function of walking velocity. At walking velocities lower than 1.0 m/s the dominant peak frequency in the arm coincides with the step frequency in the leg. At 1.0 m/s there is a transition to a synchronization with the stride frequency in the leg. Although stride and step frequency components are present at all walking velocities, the change from locking onto step to locking onto stride frequency occurs between 0.9 and 1.0 m/s.

Using the model of the simple gravitational pendulum (see equation 2), two coordinative modes with preferred frequency (0.9-1.1 Hz) were observed: one at lower walking velocities around 0.5 m/s in which the arms were locked onto the step frequency, and one at higher walking velocities around 1.2 m/s in which the arms were locked onto the stride frequency. The model predictions of the gravitational pendulum predicted the periodic data most accurately using an integer value of $n=2$ in equation (2). These data are consistent with earlier findings from Holt et al., (1990) who found a similar constant for the lower extremities while subjects walked at their preferred tempo. These data confirm Kugler and Turvey's (1987) proposed quantization of the gravitational field constant and suggest that the movement dynamics in human walking may, at least in part, be consistent with physical conservations. These two different modes were not always observed, however, but the data suggest multistability (the existence of more than one pattern) at the lower walking velocities.

Both stroke and Parkinson's patients showed less adapations in arm movements as a function of walking velocity or stride frequency as compared to normal controls. In Figure 4 the effects of an auditory rhythm (metronome) on the relative phase between the two arms are presented for a Parkinsonian patient and a control subject. Both were intructed to adapt a step frequency in tune with the rhythm. The control subject clearly shows a change to a more out-of-phase pattern at higher frequencies (a more stable pattern), but the patient does not make this transition at all.

That manipulations of control parameters such as walking velocity and imposed external rhythms can change pathological movement dynamics, is demonstrated in the effects of velocity on pathological arm tremor during treadmill locomotion. At low velocities (0.2 m/s), where arm swing was minimal, the dominant frequency in the power spectrum was the pathological tremor in the 4-6 Hz range (see Figure 5 upper right panel). Increasing the velocity reduced this pathological tremor, and at a about 0.8 m/s the pathological tremor virtually disappeared. The dominant tremor in the spectrum of frequencies was now the regular oscillatory frequency of the arm, which was closely coordinated and coupled to the rhythm of the leg (see Figure 5 middle panel). Interestingly, when walking velocity was subsequently decreased from 0.8 to 0.2 m/s, the pathological tremor did not reappear at lower velocities, and the dominant frequency in the arm was still synchronized with the oscillation in the leg (see Figure 5 lower panel). This is another example of the phenomenon of hysteresis in the control of locomotion. These observations reveal the plasticity in movement control and suggest that walking velocity is an important control parameter that can affect pathological tremors and oscillations during locomotion as predicted by the tremor models discussed above.

The data presented in the previous example indicate the flexibility in the movement control system and hysteresis in coordination of walking. Observed patterns are dependent on the nature of the control parameter, but also on the way the control

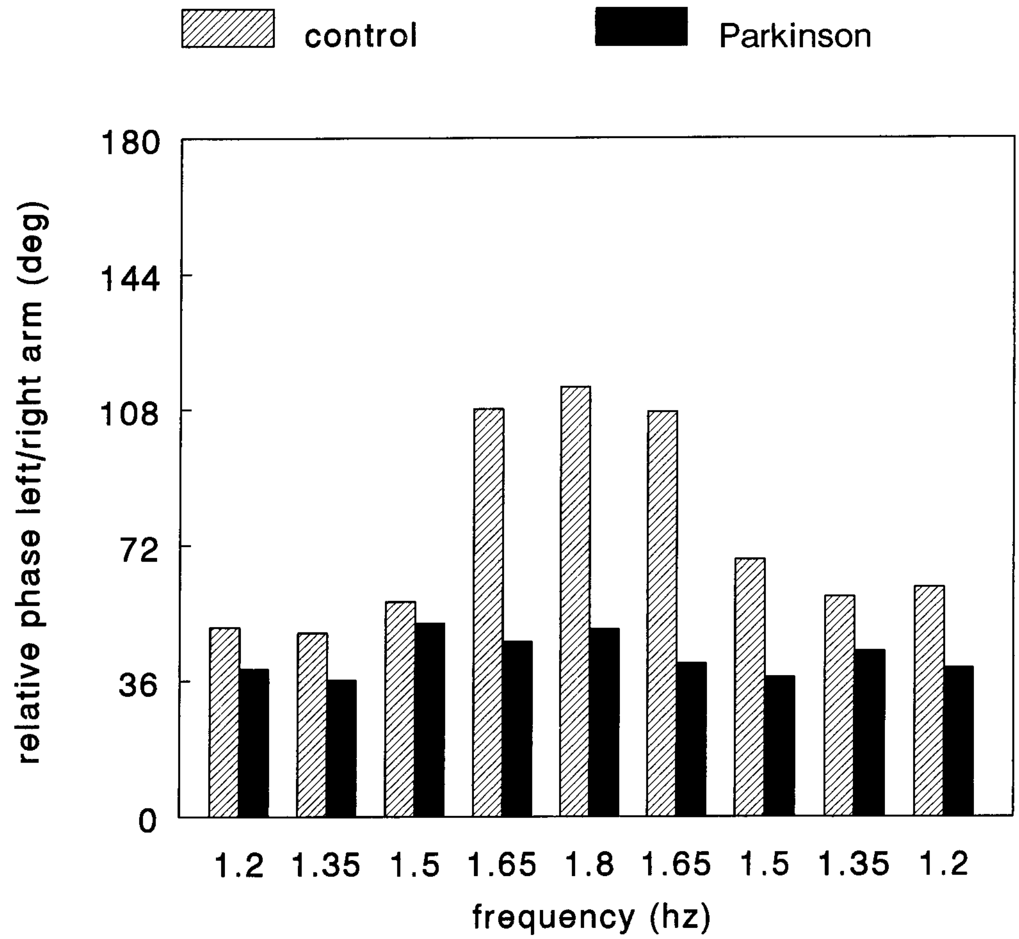


FIGURE 4 Changes in relative phase between left and right arm for a control subject and a patient with Parkinson's disease when systematically increasing and decreasing step frequency on a treadmill.

parameter is scaled, in this case whether walking velocity was increased or decreased. The data also support the predictions from logistic models of May (1977) and Akamatsu et al. (1986) in that scaling a single control parameter can systematically effect the nature of the dynamics.

The tools utilized also show the movement impairments of these patient groups and the general inability to change pattern, but suggest that with the right choice of control parameter transitions can indeed be elicited. The transition problems can arise due to an inability to impose *functional* asymmetries that are, according to Schöner et al. (1990), essential in inducing a pattern change. The pathological asymmetries in stroke patients (hemiparesis) and extreme symmetries often observed in Parkinsonian patients (rigidity) could very well interfere with imposing these functional asymmetries (e. g., disbalance when going from standing to walking).

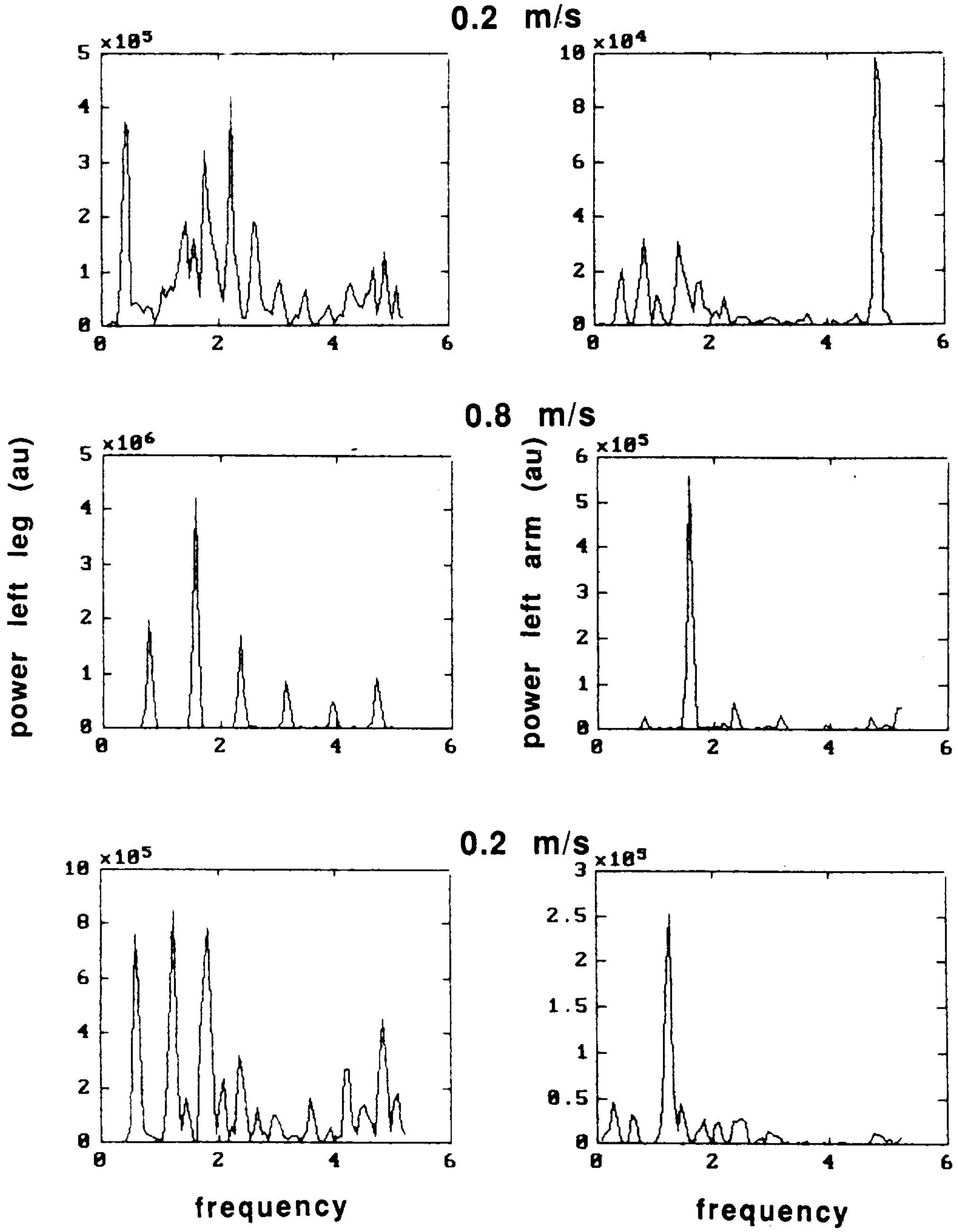


FIGURE 5 Resetting of Parkinsonian tremor during locomotion on treadmill while systematically increasing walking velocity from 0.2 m/s (upper panel) to 0.8 m/s (middle panel), and decreasing again to 0.2 m/s (lower panel). Data present the different frequency components in the movements of the left leg (left panels) and the left arm (right panels).

Implication for Motor Develoment

Relative phase dynamics

The tools from dynamical systems theory as presented adove can also be applied to the study of developmental transitions in locomotory patterns. A number of studies have emerged that examined the dynamics of movement coordination in young infants and children (e. g., Clark et al., 1988 ; Thelen, 1986). Based on relative phase analyses of interlimb and intralimb coordination, Clark and colleagues (e. g., Forrester at al., 1993) maintain that infants achieve adult coordination patterns in both walking and running. They identified the relative phase relation between footfalls as a suitable order parameter, but could not identify systematic differences between infants and adults. Both revealed on the average a 50% phase lag between the limbs' cycles. The only difference observed was that younger independent walkers with less than 3 months walking experience had higher variability in the relative phase measure. Similar observations were made concerning relative phase measures in intralimb coordination in the lower extremity. Discrete relative phase analyses of thigh and shank angles revealed similar phase angles between adults and infants at different developmental stages for both walking and running.

The conclusions of Forrester et al. (1993) regarding observed similarities in relative phase dynamics between adults and infants seem preliminary in light of the data presented above. A 50% phase lag between consecutive footfalls probably reflects more the constraints imposed on the locomotory sequence than a true difference in dynamics. Namely, in locomoting forwards one would only expect deviations from the 50% phase lag in case of clear left-right asymmetries. In addition, interlimb relative phase dynamics might differ between adults and infants when we take the dynamics of the whole body into account such as relative phase relations between upper and lower extremities or between the two arms.

Finally, the analyses were based on relative phase dynamics in the sagittal plane of motion. As our own research has demonstrated, changes in relative phase in trunk dynamics occur also in the transverse plane of motion. It is well possible that extension of relative phase analyses in infant trunk motion to these other planes of motion will reveal important differences as compared to adult patterns, and might be a distinguishing feature in movement pathologies. Indeed, Sutherland et al. (1980) observed an increased external rotation of the hip, and increased pelvic tilt in young infants as compared to adults. Given the style of locomotion of young infants, in which the movement of the center of gravity is proportionally larger in the transverse plane of motion and the infants' weight is more explicitly shifted from left to right side, changes in the relative phase dynamics in the transverse or frontal planes of motion may be expected.

Therapeutic strategies

Scholz (1990) discusses therapeutic strategies inspired by the dynamical systems approach in children with cerebral palsy. These children often locomote on all fours using a hopping pattern ('bunny hop'), a quadrupedal pattern of interlimb coordination where limbs at the same girdle (pelvis, shoulder) move in phase, and limbs at different girdles move out-of-phase. As Scholz indicates, one goal of movement therapy might be to induce a reciprocal pattern. Relative phase measures between the four limbs could be relevant order parameters to evaluate coordination changes. Possible control parameter could again be locomotory speed. Children who exhibit this hopping pattern appear extremely stiff, and this increased stiffness might make functional asymmetries and switching to a new coordination pattern difficult. One of the important aspects of dynamical systems theory is to elicit new patterns without the child's conscious effort. Control parameters play a crucial role in this process, and failure to observe treatment effects might be the result of an inappropriate choice of control parameter or, more importantly, not taking the control parameter through a sufficient range so that critical values are reached and, possibly, a pattern change.

In the preceding example, if locomotory speed turns out to be an important control parameter that can change the hopping pattern (for example by systematically manipulating speed on a treadmill), then the old pattern can be destabilized by the systematic manipulation of speed in which different patterns (i. e., the reciprocal pattern) emerge. Exercising at specifically chosen speeds can act to destabilize the old pattern, which is considered very stable given the high stiffness in these children. The result could be an increase of fluctuations in performance (i. e., in relative phase relations), which is considered essential in the creation of new patterns. This stability can be evaluated by measuring the fluctuations in relative phase or by assessing the recovery from an externally imposed mechanical perturbation. The recovery time ('local relaxation time') following such a pertubation is an indicator for the amount of stability in the system; a long recovery time implies an unstable system, a short recovery time a stable system. Close to a phase transition the relaxation time following a pertubation increases, signalling an imminent phase transition.

In summary, therapeutic strategies based on dynamic systems theory should focus on: 1) identifying the relevant order parameters that characterize the coordination dynamics; 2) identifying aspecific control parameters that can induce a pattern change; 3) manipulating the control parameters through a sufficient range so that instability emerges, a necessary prerequisite for the formation of new, stable patterns; and 4) using external rhythms or oscillators to establish synchronization or entrainment between different body segments.

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