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Motor Control of Human Gait: A Dynamic Systems Perspective

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A DYNAMIC SYSTEMS PERSPECTIVE

Gary P. Austin, PT, PhD

HUMAN LOCOMOTION

Fundamentally, gait permits humans to move intentionally and independently from place to place and to interact with the environment. Human gait, as ordinary as it may seem, is a wonderful illustration of the complex, yet precise action emerging from the interplay of the organism and the environment. As a result of this precision, the locomotor system functions safely and efficiently regardless of the ever-varying environmental conditions. Successful movement ultimately depends on the control, coordination, and integration of the many resources offered by the locomotor system and the environment.

For hundreds of years, human locomotion has been the topic of inquiries by anthropologists, biologists, biomechanists, neurobiologists, orthotists, philosophers, physical therapists, physicians, physicists, physiologists, prosthetists, psychologists, and others. Of the many theoretic frameworks within which gait has been studied, the dynamic systems approach has shown great potential to provide clinical insight into human gait. This approach is based on the application of established principles of physical systems, particularly thermodynamics and nonlinear dynamics, to biologic systems. This article presents an introduction to the dynamic systems perspective of human gait with an emphasis on the more commonly used models, experimental and clinical

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variables, and applications of both to normal and dysfunctional human gait.

INTRODUCTION TO DYNAMIC SYSTEMS

The term *dynamic system* has numerous meanings in the various scientific communities that study physical and biologic phenomena. A dynamic system basically is one in which (1) the system changes or evolves over time,[75] (2) the system has developed "an immense power to evolve,"[16] (3) there are "habitual tendencies . . . to evolve from one state to another,"[1] (4) a set of differential equations describes the evolution of a particular variable over time,[48, 74] and (5) there is organism-environment interaction.[66]

The dynamic systems perspective has several basic features. Physical therapists appreciate the human body as a *complex system* composed of many interacting elements and systems at various scales. In contrast to other fields that study biologic phenomena at the *micro* scale, physical therapy is a discipline anchored in the *macro* scale, at which movements are constructed and action occurs. Regardless of whether one works at the level of the cell, neuron, motor unit, musculotendinous unit, joint, limb, or body, however, an endless number of interactions are possible. Out of this complexity at the finer levels there emerges ordered, purposeful, and remarkably successful behavior at the coarser levels. Additionally the human body is *adaptive* because of its ability to evolve, rapidly and slowly, in the direction of optimal behavior. Fundamental to the dynamic systems approach is this view of the biologic system as adaptive and inherently complex, yet capable of consistently generating simplicity from complexity (and possibly complexity from simplicity).

This biologic complexity creates the availability of many different tools with which to perform the same job. This complexity can be viewed as either a problem or a solution. Although initially referred to as the problem of motor redundancy,[6] the infinite possible solutions to a motor problem may be best referred to as *motor abundance*.[52] This abundance of solutions offers the individual countless options to perform the same intended movement, regardless of variable initial conditions and perturbations.[51] This characteristic of dynamic systems, termed *equifinality*, is essentially the preference for a particular state without regard for the path taken to achieve it. Bernstein,[7] in his discussion of motor control, refers to the capacity "to make a choice within a multitude of accessible trajectories . . . of a most appropriate trajectory." Implicit in the issues raised by Bernstein[7] are the opportunities and challenges presented by the influence of the environment and the will to move.

A more ecologic approach to dynamic systems holds *organism-environment synergy* as its central premise.[26, 59] According to this assumption, there is a mutuality and inseparability of the organism-environment system (i.e., each is defined with respect to the other, and one is never independent of the other). The unique and reciprocally dependent organism-environment relationship defines the econiche in which the organism and the environment possess resources that offer possibilities for action with functional significance.[50] Within the context of the econiche, continual exploration, discovery, and performance occur. As Riccio[66] succinctly stated, "the animal-environment interaction is a dynamical system."

The animal-environment interaction is necessarily a willful and directed experience. The *intentionality* of the organism is an essential feature of the dynamic systems approach because it speaks to the purposeful, goal-directed, and task-oriented nature of motor behavior. An intention is "a desired act"[50] or "specific information acting on the dynamics, attracting the system to the intended pattern."[48] The resources available to the organism-environment interaction, in conjunction with the intention of the organism, serve as constraints on the organization of task-oriented behavior.

The inherently complex biologic system has been referred to as a *dissipative* system.[48,50,51] Prigogine[64] introduced the thermodynamic concept of a dissipative structure, an example of which is the dynamic system (i.e., organism-environment interactions). In such a system, there occurs a periodic exchange of energy between the organism and the environment. As a function of the dissipative and intentional nature of the organism-environment interaction, dynamic systems possess the ability to coordinate and integrate the many components of the system to meet the specific demands of the task. In contrast to the purely physical dynamic system, the biologic system is a smart, special-purpose machine able to assemble itself instantaneously and softly to meet the many parallel and serial functional demands.[50,68] The ability of these mutually dependent relationships and complex processes to transform the dynamic structure into a goal-directed, functional movement pattern is referred to as *self-organization*. The system is self-organizing in the sense that it is an inherently high-dimensional system that seeks the attractors, low-dimensional states of equilibrium, which emerge from the dynamics of the system.[27]

Attractors

The behavior of a dynamic system shows tendencies or preferences, based on such constraints as the organism-environment relationship, energy states, and intention. These tendencies are referred to as *attractors*. Attractors also have been referred to as the *eventual observable behavior* or *dynamic equilibrium*,[1] the state to which a system converges regardless of the initial conditions,[48] and "the orientations and configurations for which perception and action are optimal."[66]

Originally observed in physical dynamic systems (such as pendula or springs), attactors appear to exist in the behavior of biologic dynamic systems as well. In general, there are 3 types of attractors: (1) fixed point or point attractors, (2) limit cycle or periodic attractors, and (3) chaotic or strange attractors. The fixed point attractor is a condition of static equilibrium toward which a dissipative dynamic system gravitates. A simple example of a fixed point attractor is a pendulum with friction (Fig. 1*A*). In such a system, the pendulum loses energy through dissipation to

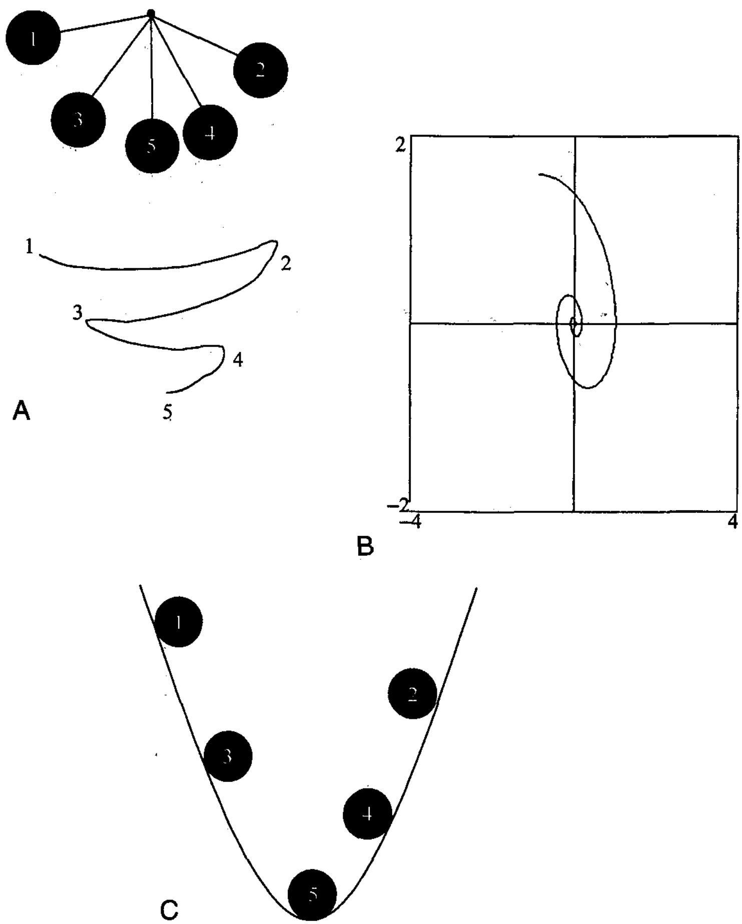

Figure 1 A simple pendulum with friction. *A*, A pendulum starting from position 1 and following a trajectory eventually coming to rest position at 5. *B*, A fixed point attractor depicted by a phase plane (velocity dependent plot) trajectory spiraling toward the origin. *C*, Motion in pendulum depicted within a potential well, from initial position 1 to final position 5.

friction, and all possible trajectories eventually converge toward a resting state. In this example, the fixed point attractor is a state of minimum energy toward which the pendulum evolves over time (Fig. 1*B*).

The potential well, a thermodynamic concept, offers a depiction of the basin of attraction within which an attractor resides (Fig. 1*C*). The slope of the walls and the depth of the well determine the strength and stability of the attractor. The dynamics of the pendulum are constrained by the basin of the fixed point attractor, and after swinging through 4 diminishing arcs, the energy available at time 1 has been lost to friction. Without an influx of additional energy, the pendulum eventually comes to rest at time 5. The fixed point attractor also is referred to as a *stable* fixed point or an energy *sink* (owing to the dissipative effect of friction). These types of attractors most commonly have been employed in the dynamic study of reaching and balance. A fixed point attractor also can be a *source* of energy, however, in the form of inverse friction or an escapement, characterized by a point from which all trajectories flee. Such an *attractor* also is referred to as an unstable fixed point attractor or a point repellor.

Another common attractor type with significant biologic relevance is the *limit cycle attractor* (Fig. 2). The limit cycle attractor (also described as a *periodic attractor*) is a sustained oscillation of minimum energy. The best example of a limit cycle or periodic attractor is a pendulum with friction that has an added energy source. Trajectories arising from within the limit cycle gather energy and travel outward to converge on the attractor. Trajectories originating from outside the limit cycle lose energy through dissipation and migrate inward, eventually

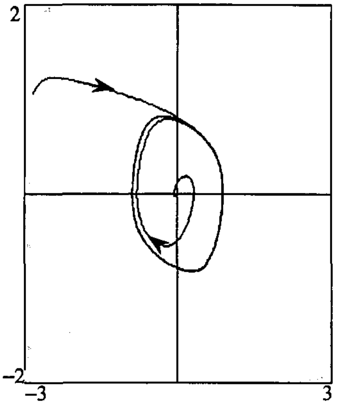

Figure 2 Limit cycle attractor in that outer trajectories travel inward, and inward trajectories travel outward, to eventually settle onto the sustained oscillation of the limit cycle.

settling into the dynamic equilibrium of the oscillation. Gait is a superb example of periodic dynamic behavior. Additional examples of limit cycle behavior abound in biology—cardiac cycle, respiratory cycle, diurnal rhythms, and life cycle to mention a few. The final attractor type is the *chaotic attractor* (neither fixed nor periodic), in which the irregularity of the system vacillates among phases and states in an orderly manner in response to changes in the initial conditions.

As a model, the limit cycle qualitatively captures the dynamic behavior present in initiating, sustaining, and changing gait patterns. The origin of the axes in Figure 2 is the resting point of the system; the system is standing still. As gait is initiated, the system intentionally draws on endogenous energy sources to push itself away from static equilibrium toward the new intended dynamic equilibrium. After several oscillations (gait cycles), the system eventually settles into a more stable, periodic pattern of movement. Dynamically speaking, the system seeks the limit cycle by following any of the infinite trajectories moving away from the origin to the periodic attractor. Conversely, if one is running and the system is functioning on a higher energy limit cycle, there exists a tendency toward dynamic equilibrium at a limit cycle in a lower energy state. The body is attracted to the walking limit cycle and undergoes a gait transition from walk to run. In dynamic terms, the system is drawn along any trajectory inward, eventually settling onto the limit cycle. The study of human movement according to the dynamic systems approach views the phase transition as a rich source of information about the control and coordination of gait.

Dynamics of Coordination

The dynamic systems approach has produced many useful analytic tools; the most useful measure of coordination and control is *relative phase*. The coordination of 2 body segments can be evaluated using the relative phase as an order parameter.[28, 30, 65] An *order parameter* is a singular, *macroscopic*, collective variable that captures the spatiotemporal assemblage of the intended movement pattern. The second major component to the investigation of dynamic phenomena is termed the *control parameter*. The most commonly used control parameters are the frequency and velocity of movement. The order parameter does not change in direct proportion to the control parameter; instead the order parameter is robust across a broad range of values of the control parameter. In adult human gait, the order parameter may have two states, walking or running, which are typified by specific coordination patterns, yet each can be maintained across the spectrum of frequencies or velocities.

Humans are able to maintain the desired gait pattern across various speeds or frequencies. With continuous upward scaling of the control parameter, however, the system is driven further away from the preferred state, and the variability shown by the system grows. Eventually the control parameter reaches a critical value, and a sudden transition, or bifurcation, in the collective behavior of the system occurs.[28,46] At this point, the system assumes the new mode of behavior to which it is attracted (i.e., a new gait pattern). These enhanced fluctuations in coordination accompanying the upward scaling of the control parameter have been shown experimentally in gait[19] and in various other classes of movements.[5,30,45–47,67,71,72]

Multistability, Transitions, and Hysteresis

When performing a goal-directed task (such as gait), the inherently complex biologic system typically has multiple simultaneous attractors, referred to as *multistability*, from which to select. Contrary to the walk-run dichotomy of human gait, Van Emmerik and Wagenaar[81] found evidence of bistable coordination dynamics during walking under conditions of increasing and decreasing velocity. With many options, the minimally stereotypic dynamic system transitions fluently from one movement pattern, or preferred state, into a different pattern. These transitions or switches in behavior sometimes are referred to as *bifurcations*. The rich dynamic behavior of the system in the vicinity of gait transitions offers great insight into normal and disordered gait.

The human gait transition has been investigated and described in various ways. Research based on anthropometric variables,[32,42] kinematic factors,[41] metabolic costs,[39,80] and kinetic factors[40,80] has yielded few reliable predictors of the transition. These investigations did yield some dynamic findings, however. Models used to investigate gait transitions have been thermodynamic,[80] dynamic,[19,49] and mathematical.[8] In particular, the findings of the models of Diedrich and Warren[19] and Turvey et al[80] appear promising. Using nonlinear dynamic modeling, Diedrich and Warren[19] found several behaviors that were characteristic of nonlinear phase transitions. Variability in relative phase, an index of the coordination, increased before the gait transition, then decreased dramatically immediately after the transition as the system settled into the new attractor state. Additionally, subjects expended less energy when in either the walking or running modes and more energy when in the gait transition. Kram et al[49] investigated the walk-run transition under reduced gravity using an inverted pendulum model. Their findings supported the contention that the transition would occur at the same value of the ratio of inertial and gravitational forces. Turvey et al[80] studied the relationship between energy storage and energy dissipation per gait cycle. These authors offered 3 predictions: (1) that energy storage-to-dissipation ratio would be 1 at the critical speed of the gait transition,

(2) that metabolic cost would be predicted from kinetic energy expenditure, and (3) that changes in kinetic energy at the critical speed of transition would predict metabolic cost at the transition speed. The findings of Turvey et al[80] supported an account of gait transition based in nonlinear dynamics, suggesting that the relationship most closely predicting the gait transition is a function of thermodynamic and mechanical factors.

Adult human gait traditionally has been dichotomized into either the walk or run. Using a dynamic systems analysis of relative phase, Van Emmerik and Wagenaar[81, 83] suggested the presence of various coordination patterns of the trunk and the arms during human walking under conditions of increasing and decreasing walking velocity. At lower walking velocities, (1) the arms were closely coupled to one another, and (2) the trunk, pelvis, and thorax were functioning in a more in-phase pattern. At higher walking velocities, (1) the arms were coupled more closely to the legs, and (2) the trunk, pelvis, and thorax were functioning in a more out-of-phase, or dissociated, pattern. Additionally the coordination of the arms and legs was more stable at higher walking velocities. The dynamic systems perspective not only exposes new movement patterns, but also it provides the clinician with novel options for the treatment of patients with movement dysfunctions. The choice of walking velocity may determine the extent to which the arms are locked onto themselves or the legs as well as the extent to which trunk rotation shows dissociation.

Dynamic systems show *hysteresis*—a dependence of the timing of the transition on the direction of the change. Evidence of directional dependence in human gait transitions is strong. In most studies, the walk-run transition occurs at a higher velocity than does the run-walk transition (Fig. 3).[8, 32, 42] Turvey et al[80] found reverse hysteresis, however, with the walk-run transition occurring at a slower walking velocity than the run-walk transition. The transitions in trunk dynamics found by Van Emmerik and Wagenaar[81] showed a similar directional influence. Rotation of the pelvis, thorax, and trunk were greater at the transition induced by decreasing velocity as opposed to increasing velocity. From a clinical standpoint, this means that the quantity of trunk rotation not only depends on the speed, but also on the direction from which that particular speed was arrived at. The advantage is the ability to induce different effects at the same speed.

DYNAMIC MODELS OF GAIT

Gait, as a periodic phenomenon, has been studied using dynamic models based on physical oscillators, such as mass-spring systems, pendula, or hybrid spring-pendulum systems. The stance phase of the gait cycle has been modeled as a mass-spring system during running and an

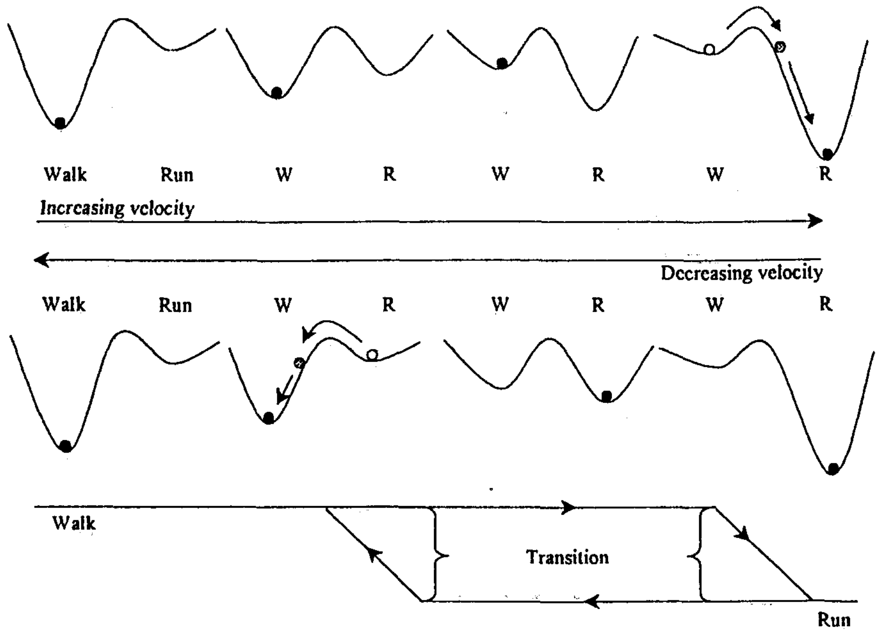

Figure 3 Hysteresis depicted by the dependence of the gait transition from walk to run with increasing velocity, or run to walk with decreasing velocity. In the upper panel, with increasing velocity during walking (W), the system eventually transitions to running (R). As the control parameter (velocity) is increased, the depth of the walking well (W) decreases. This necessitates a transition (*curved arrow*) to a new mode, running, which has a deeper well (R). In the middle panel, as velocity decreases while running (R), the system eventually transitions to walking (W). As the control parameter (velocity) decreases, the depth of the running well also decreases. This necessitates a transition (*curved arrow*) to a new mode, walking, which has a deeper well. The lower panel illustrates the complete transition from walk to run and back to walk; note that the transitions occur at different velocities.

inverted pendulum during walking. The swing phase of gait has been modeled as a pendulum and a hybrid spring-pendulum system.

A mass-spring system is a simple vibratory or oscillatory system consisting of a spring resting on a rigid surface with a mass supported atop it.[17,60] This simple model can be applied to human gait and described using parameters of force, displacement or amplitude, stiffness, mass, and frequency. The center of mass of the body is a point mass, acting downward on the neuromusculoskeletal spring. The springlike behavior of the lower extremities has great support.[2,9–12,18,20–25,53,56–58] When challenged to move at various frequencies,[2,20–23] with varying mass,[2] and on various surfaces,[24,25] the springlike lower extremity shows the ability to self-assemble into a springlike structure. In producing the appropriate stiffness, the system attempts to optimize the interaction with the environment to meet the various task demands. The complexity of the biologic spring has been shown to evolve from a linear spring at or above preferred frequencies of movement into a nonlinear spring below preferred frequencies.[2,20,22]

The analogy of the simple mass-spring system to the stance phase of gait offers great potential in terms of the conceptualization of gait and the clinical application to tests and measures and treatment intervention for gait disorders. Candidate clinical measures that arise from this model are the *frequency*, *amplitude*, and *velocity* of movement. Additionally, movement frequency offers insight into the clinical assessment of *stiffness* of biologic structures (the force-displacement relationship obtained indirectly through the spring equation). Based on the mass-spring model, potential intervention techniques might include manipulation of the mass of the system and control of the frequency, amplitude, or speed of the movement.

The stance phase of gait during walking has been studied using the inverted pendulum model, in which the lower extremity and trunk are assumed to be a rigid segment that rotates over the fixed foot in the sagittal plane around the talocrural joint axis. This model also has been referred to as *compass gait*, in which the trunk is the body supported atop the rigid leg attached to the ground (Fig. 4*A*). In addition to the investigation of the walk-run transition by Kram et al,[49] the inverted pendulum has been used in studying the storage and recovery of mechanical energy,[13] foot placement,[77] and frontal plane stability.[55,86] Expansion of the inverted pendulum model to include active neuromuscular factors suggests a dynamic system, in the general sense, in which the active

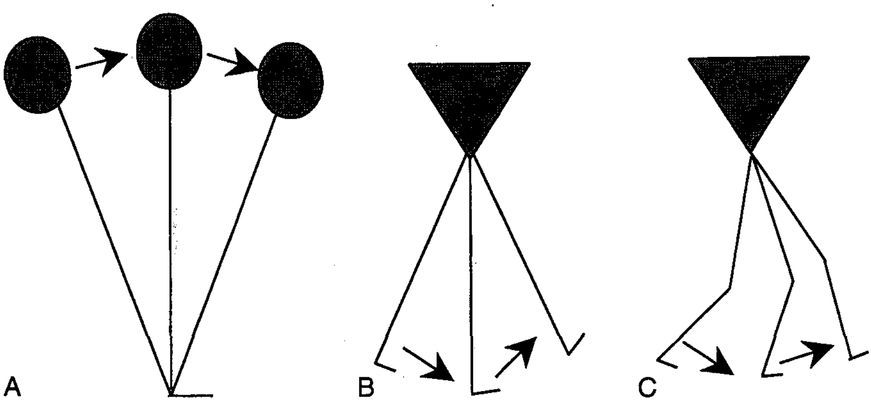

Figure 4 Various pendular models of human gait. *A*, Inverted pendulum during stance phase. *B*, Simple pendulum in swing phase. *C*, Compound pendulum during swing phase.

control of gait emerges from the interaction of the hip and foot musculature with the gravitational component.[55,86] The energetics of the inverted pendulum exhibit a distinct minimum energy state (at intermediate gait velocities) in which the recovery of energy in the stance leg was greatest.[13] The limited utility of this model with faster walking and running may suggest a dynamic transition to a more optimal springlike behavior during stance phase predicated on the new energy demands, intention, and changing relationship of the individual and the environment.

The suggestion that the motion of the leg during the swing phase of gait may approximate that of a simple pendulum was made first by Weber more than 150 years ago.[61] Forms of this model vary from simple and compound pendula to the hybrid force-driven harmonic oscillator. Mochon and McMahon[61] incorporated the stance leg as an inverted pendulum functioning in tandem with a swing leg modeled as a double pendulum system. In the most basic form, the pendulum model consists of a rigid lower extremity suspended from the pelvis (Fig. 4*B*); however, this model can be augmented to that of a compound pendulum with several linked segments (Fig. 4*C*). A current topic in the dynamic study of gait is the extent to which the swing phase of human gait is passive.[85] Although several researchers have modeled the swing phase using pendulum dynamics, work by Whittlesey et al[61,63,85] brings to light the apparent limitations of the assumptions of a passive pendular swing phase. The work done by Holt et al[35] has revealed several important dynamic principles of human gait, including (1) the force-driven harmonic oscillator model[35]; (2) the relationship between preferred stride frequency, resonance, and energetic minima,[36,43]; and (3) the role of variable stiffness in the control of the temporal behavior of the lower extremity.[63]

The force-driven harmonic oscillator model consists of a hybrid pendulum mass-spring system. This model expands on the simple pendulum model with the addition of an expression accounting for the contributions of active and passive connective tissues of the locomotor system to the stiffness of the oscillatory system.[63] The input parameters of this model are the inertial characteristics of the individual (lower extremity segmental lengths and mass). The harmonic oscillator is in a state of dynamic equilibrium when the periodic quantity of energy supplied by muscle is commensurate with the energy required to sustain the oscillation. At this point, the system functions according to the equilibrium dynamics of a limit cycle attractor. In dynamic equilibrium, a resonant frequency exists at which the oscillation can be sustained at a minimum cost to the system. Dynamic systems theory states that biologic systems are attracted to such preferred states and are capable of detecting and self-selecting the resonant frequency.

The work of Holt et al[35, 37, 63] confirmed resonance during walking by determining the resonant frequency of the force-driven harmonic oscillator model and predicting accurately the preferred stride frequency of adults and children. Numerous investigations have described the ability of humans to self-select frequencies that result in minimal energy expenditure during the performance of such tasks as walking,[62, 87, 88] running,[14] tire pumping,[15] wheelchair propulsion,[70] and upper body ergometry.[69] The force-driven harmonic oscillator model predicts the stride frequency, however, at which energy expenditure would be at a minimum based on limit cycle dynamics.[36, 38, 43] The locomotor system, as the biologic analogue of the force-driven harmonic oscillator, exhibits behavior typical of a dynamic system. Preferred movement frequencies exist and appear to be governed by energetic constraints.

The force-driven harmonic oscillator model may have potential clinical applicability. The dynamics of the force-driven harmonic oscillator depend on the inertial characteristics (length and mass) of body segments. Typically the inertial characteristics of the body change slowly, allowing adequate time for the system to adapt to such change. In the event of amputation or the application of an orthosis or cast, however, the inertial characteristics of the limb change dramatically and suddenly. Potential applications of these dynamic principles exist in such cases of temporary and permanent alterations in the locomotor apparatus. These dynamic concepts are being applied in the design and fabrication of lower extremity prostheses.[3, 4, 78] Systematically increasing the mass of the limb or changing the stride frequency may prove to be appropriate for the purpose of testing and measuring gait function or as an intervention technique in the case of lower extremity dysfunction.

Whittlesey et al[84, 85] suggested a major role for moments at the hip and knee and acceleration of the hip, which differs from the pendular models of swing phase. Implicit in their work is the active role of the hip in producing changes in the segmental acceleration of the lower leg and foot. These authors pointed out the strategy adapted by individuals with transfemoral amputations to generate increased hip acceleration to actuate the prosthetic knee and ankle joints. Whittlesey et al[85] suggested 4 reasons that it is unlikely that the swing phase of human walking is passive: (1) the prerequisite of a muscular control element in computer simulations of a normal wing phase, (2) the inadequate contribution of gravity and passive joint structures to a normal swing phase, (3) the larger relative contribution of muscle actions to the kinetic input to the limb, and (4) the inability of the force-driven harmonic oscillator to account for swing periods based solely on inertial characteristics.

Several examples of the power and utility of a dynamic systems approach in modeling phases and transitions in normal human gait have been presented. The discussion now shifts to the role of dynamic systems theory in the study of pathologies characterized by gait disorders.

STABILITY AND VARIABILITY AS MEASURES OF GAIT DYSFUNCTION

Two related properties of dynamic systems are variability and stability. The organism, environment, and task offer sources of perturbing forces. Once in a state of equilibrium, a system is considered to be *stable* if it can persist in the presence of perturbing force. A system in equilibrium is considered to exhibit *variability* to the extent that it can persist in the absence of a perturbing force. Based on the coordination dynamics approach, the control parameter can be considered, to a greater or lesser extent, to be a perturbing force. Stability and variability analyses have offered promising insight into various movement disorders.

Variability and stability can be assessed using techniques from nonlinear dynamics. The variability of a system can be measured as (1) fluctuations in relative phase using the standard deviation of relative phase,[38] (2) fluctuations in the amplitude and period of a time series,[67] (3) fluctuations in the trajectory of the limit cycle (Fig. 5),[38, 44, 76] or (4) the relaxation time—the time required for the system to return to the previous state after the introduction of a perturbing force.[73] The trajectory of the limit cycle in the phase plane (displacement-velocity plot of a point over many cycles) and the fluctuations of the time series offer the potential for qualitative analysis of the variability of a movement pattern.

Using techniques of nonlinear dynamics, researchers have found that individuals with movement disorders affecting gait lack the

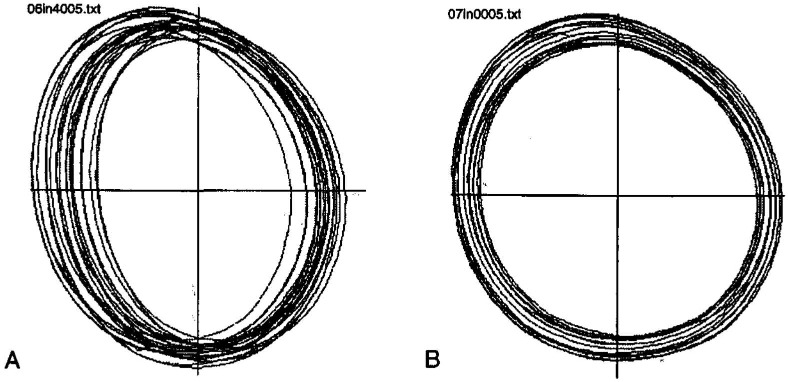

Figure 5 Variability of a sustained oscillation within the phase plane. Greater variation across trials (*A*) compared with less trial to trial variation (*B*).

variability that is the essence of a dynamic system. Walking velocity, as a control parameter, was used to detect trunk rigidity in individuals newly diagnosed with Parkinson's disease.[82] These individuals showed less variability in the relative phase of transverse plane trunk motion as well as a smaller range of trunk coordination patterns. Traditional measures of stride duration and its fluctuations were not different from those of an otherwise healthy group. Similarly, individuals with patellofemoral pain exhibited less variability in relative phase among the lower extremity segments than asymptomatic subjects.[31] Asymptomatic subjects with Q-angles exceeding 15° showed no significant difference in lower extremity segmental coupling[33] or rearfoot eversion or tibial internal rotation.[34] These findings of decreased variability are in direct opposition to the traditional perspective of movement dysfunction, which is based on the observation and description of biomechanical hypostability. It is possible that the loss of variability creates a system that is hyperstable and relies on stereotypic rather than flexible and adaptive movement patterns. To the extent that successful gait strategies are not stereotypic, this variability does not seem detrimental to the movement; rather, it is considered an indication of the adaptability of the system.

SUMMARY

The dynamic systems approach to the analysis of human gait and gait dysfunctions brings to light the rich, yet simple and successful, locomotor behavior that emerges from an intentional, complex, dynamic system. This approach has much to offer to researchers and practitioners alike, if nothing more than a novel way in which to envision human gait. The characteristic properties of a dynamic system are derived mainly from the ability of the system to respond to changes in the organism, environment, or task over various time scales. Dynamic systems are *adaptive* because of their ability to evolve, rapidly and slowly, in the direction of an optimal motor behavior based on the constraints on movement. The system is considered *flexible* because it is able to respond to changing constraints by adopting a new pattern of movement. The organism, environment, and task offer sources of perturbing forces. Once in a state of equilibrium, a system is considered to be *stable* if it can persist in the presence of perturbing force. Similarly a system in equilibrium is considered to exhibit *variability* to the extent that it can persist in the absence of a perturbing force. To achieve an optimal gait pattern, in which all of the components of the complex system are functioning toward a safe, comfortable, and energy-efficient state, the dynamic system must possess all of the abilities described. Future research employing a dynamic systems perspective should continue to emphasize the application to populations with gait dysfunctions with the ultimate goal of clinically relevant, valid, and reliable dynamic tests and measures of gait function. As clinicians begin to embrace this perspective, there will be the need to study the efficacy of the new intervention techniques evolving from the dynamic systems approach.

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