A Dynamical Systems Approach to Motor Development
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The study of motor development has long influenced the clinical practice of physical therapy. We first review the contributions and deficiencies of two traditional maturational and reflex-based models of motor development. Second, we describe basic principles of kinematic and kinetic analyses of movement and show how we have applied these techniques to understand infant stepping and kicking. Third, we propose a theory of motor development based on a dynamical systems perspective that is consistent with our infant studies. Finally, we explore the implications of the model for physical therapists. [Kamm K, Thelen E, Jensen J. A dynamical systems approach to motor development. Phys Ther. 1990;70:763–775.]

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Basic research in movement science has influenced, and can continue to influence, clinicians in three ways: (1) to contribute to a basic understanding of the normal neuromotor system and the effects of various debilitating conditions; (2) to provide techniques for diagnosis and for assessing the effects of therapeutic interventions, and (3) to help clinicians develop theory-based regimens of treatment.

Historically, one branch of movement science, the study of motor development, has been especially influential in physical therapy in all three ways. Most important, perhaps, have been the neurologically focused, reflex-based descriptions of motor development and the behaviorist-maturational work associated with McGraw and Gesell. These approaches are well-known to all therapists, not only as bases for pediatric practice, but as guides for adult interventions as well.

One reason such developmental research has played a prominent role in physical therapy theory and practice is the widely shared assumption that the processes that underlie developmental change are the same processes that are involved in the rehabilitation of individuals with dysfunction. One purpose of this article is to examine this assumption. Is it theoretically valid to use development as a model for recovery of function? What are the benefits and limitations of developmental work for general theory and practice?

As a basis for answering these critical questions, we will review some of our recent work in early motor development and examine how our research can relate to physical therapy in the three ways mentioned previously. We will discuss how this work builds on the traditional reflex-based and maturational views and how it departs from these views, rather radically at times. We conclude by presenting a theory of motor development that may have more general therapeutic implications.

**What Motor Development Can Tell Us About the Nature of the Neuromotor System**

Historically, motor development has often been studied for the purpose of understanding the relationship between neural structure and behavior. McGraw studied infant motor development in order to determine “the relationship between behavior development and the maturation of neural tissue.” She derived her research approach from Coghill’s classic work with salamanders. Coghill studied developmental changes in motility and locomotion in the salamander, directly relating these motor changes to...
histological analyses of neural maturation. Thus, independent movement of the forelimb in locomotion was a direct result of independent innervation of that limb. Clearly, this discrete one-to-one mapping of neural structure to movement was not possible in the complex human nervous system. The power of this approach, however, promised new insights into neuro-muscular maturation. A general picture of human neural maturation was emerging from the work of Tilney (F Tilney, unpublished lecture, 1937) and Conel.6 McGraw3 related the broad changes seen in normal motor development to developmental changes in the nervous system. For example, an infant’s ability to lift the head was attributed to newly developed cortical control of the cervical region. According to McGraw, maturation of the nervous system is the unitary driving force in motor development.

Gesell4 also formulated a theory of behavioral maturation that relied on neural maturation. He documented the fluctuating dominance between extensor and flexor muscles, and between symmetric and asymmetric limb movements, in the time from birth to the acquisition of upright locomotion. He suggested that the fluctuations reflected the process of reciprocal interweaving of opposite influences into progressively more elaborate relationships. Thus, the delicate and refined coordination of flexor and extensor muscles in the dynamic balance required for walking developed in the spiraling process of reciprocal interweaving. Gesell believed that, although the environment and experience supported this process, neural maturation guided or instructed it.

Reflex-based descriptions of development explicitly referred to the role of the nervous system in behavioral development, with an emphasis on the hierarchical nature of the nervous system. According to this view, the behavioral repertoire of newborn infants is dominated by simple reflexes. These reflexes represent the functioning of subcortical, phylogenetically primitive centers in the brain. In the normally maturing infant, early reflexes diminish, disappear, or are integrated into more mature motor patterns. These changes reflect the maturation of a hierarchically organized nervous system: as the cortex increasingly assumes control of motor functions, the reflexes are inhibited or form the basis of more functional movements. A reflex-based developmental sequence received support because many infantile reflexes appear in pathological conditions of the central nervous system (CNS) and are elicited by lesions in known parts of the brain.

Both behavioral-maturationist and reflex-based descriptions of behavior have contributed to our understanding of normal and pathological development. The legacy of McGraw3 and Gesell4 has been a well-developed set of developmental norms, which have proved useful in assessment. Reflex testing has become a standard part of neurological examinations, allowing therapists to assess function, develop treatment plans, and discuss the prognosis of patients with CNS damage. Reflex testing, in particular, relates the behavioral level, at which therapists work, to the neurological level of known dysfunction. The almost exclusive dependence on neural maturation, however, suggests that experience, including therapist intervention, can have only limited effects on recovery.

Although each of these approaches offers some explanatory power, neither is able to adequately address the full range and complexity of motor development. Neural maturation explains only the broadest sequence of skill acquisition (ie, that the motor cortex matures and that skill increases), but the details of individual motor development vary tremendously. No genetically determined map can account for this. Furthermore, infants produce exquisitely complex, adaptive actions in the context of a changing, and often unpredictable, environment. Reflexes may provide a bias or general framework for movement, but they do not address the dynamic and adaptive nature of early infant behavior. It is widely recognized that theories that rely heavily, if not exclusively, on neural explanations of behavior are incomplete. How is it that they have been able to dominate developmental motor theory for so many decades?

First, the field of motor development had its beginning in questions about the relationship between the brain and behavior. Second, all of these theories were developed in parallel with our greatly expanding knowledge of the nervous system. The quantitative and qualitative study of principles of neural functioning has become a major focus in science. Each new insight revealed a system of greater complexity and adaptability. From this perspective, it sometimes seemed realistic to expect that the details of behavior could indeed be revealed through understanding the details of the nervous system. Until recently, our knowledge of the details of the nervous system was expanding rapidly, whereas the study of behavior development remained relatively qualitative and descriptive of global phenomena.

This disparity between the sophistication of neural analyses and behavioral analyses has now changed with recent advances in the quantitative study of movement, as represented by this series of articles on movement science. In turn, new theories and methods used to understand adult movement science can be applied to the questions of motor development. In the 1940s and 1950s, Bernstein7 applied elegant quantitative procedures to developmental questions, and, although his work was published in English in 1967, it went unnoticed for several years. In recent years, the study of motor development has been resurgent with the application of these quantitative methods to developing motor systems. The ability to quantify movement and to understand the details of movement organization released researchers from much of the dependence on neural explanations and has allowed for analyses of multiple interacting factors in motor development.

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The relationship of muscle activity to movement can be analyzed by collecting kinematic data in combination with electromyographic (EMG) data. The pattern of muscle activity does not always have a one-to-one relationship to the kinematics. The use of kinematics and EMG, in combination and alone, has altered the way motor development is viewed.

To illustrate how movement analysis can be used to understand motor development, we will review some of the published research on infant leg movements. This review will serve to describe the application of these methods to motor development and to provide a basis for exploring alternative explanations for motor development.

**Newborn Stepping—A Model for Developmental Motor Analyses**

Infants move their legs under a variety of conditions. One behavior, newborn stepping, has been the subject of controversy for many years. This newborn behavior is elicited when an infant is held vertically with the trunk slightly forward, allowing the feet to touch a firm surface. In this position, the newborn will make alternating flexion and extension movements of the legs that appear similar to the adult alternating pattern of walking. This response normally declines or "disappears" at about 4 to 6 weeks of age. Reflex-based and neural-maturation theories regard the behavior as a primitive reflex, which would be expected to disappear as the brain matures. There are reports, however, of situations in which the reflex does not disappear. One is the experiment of Zelazo et al, who trained the reflex with daily exercise. Super reported that some cultures naturally provide infants with vigorous exercise. In both studies, not only did the "reflex" not disappear, but the infants were reported to have somewhat precocious motor development.

Is newborn stepping then a reflex or a precursor to mature function? In therapeutic terms, this question is not at all academic. The persistence of primitive reflexes can interfere with normal maturation. Alternatively, the practice of early precursors to mature behavior may serve to facilitate development. Facilitating the expression of this stepping pattern to promote functional development is in direct conflict with the reflex-theory-based recommendation to inhibit the pattern. The controversy over the nature of newborn stepping and other developmental phenomena points to the necessity of addressing these conflicting explanations with empirical studies in order to provide coherent theory-based explanations and intervention strategies.

Theelen and colleagues have used kinematics, EMG, and behavioral observation to analyze infant leg movements. They found that spontaneous kicking, which is generally observed in supine infants, exhibited similar kinematic patterns to those involved in newborn stepping. This similarity suggests that the two apparently different behaviors are actually isomorphic, or one behavioral pattern. Unlike newborn stepping behavior, however, spontaneous kicking does not disappear. Indeed, the frequency of spontaneous kicking in infants increases during the period when the stepping behavior disappears (ie, 4–6 weeks of age). Thus, stepping and kicking appeared to be isomorphic behaviors with different developmental profiles.

Thelen and Fisher compared stepping and kicking in eight healthy 2-week-old infants. They found stepping and kicking to be similar on a number of measures. The frequency of both stepping and kicking was more highly correlated with arousal measures than with position of the infant. Both behaviors were initiated with a synergistic, simultaneous flexion of hip, knee, and ankle, followed by a forward swing of the lower leg and plantar flexion of the ankle. The infants' EMG records identified a phasic activation of the tibialis anterior muscle (ankle dorsiflexor) and the rectus femoris muscle (hip flexor), with less consistent firing of hamstring muscles (knee flexors). Significantly, little or no activation of extensors was seen in the extension phase. Extension resulted from a passive re-
was the best predictor of the number of measures, supported the hypothesis that newborn stepping and spontaneous kicking in infants are isomorphic.

Further insight into the relationship of kicking and stepping can be found in their differences. Although the duration of hip flexion was the same for both behaviors, the active range of motion for hip flexion was greater for kicking than for stepping. In addition, the infants had longer hip extension durations during supine kicking, with smaller excursions in the extension direction. These differences can be explained by considering changes in the biomechanics of the movement associated with the posture of the infant in relation to gravity. In a supine position, hip flexion is assisted by gravity once the thigh reaches a 90-degree angle, which results in greater flexion. When the infant is held vertically, hip extension is assisted by gravity throughout the entire movement, resulting in greater extension angles. Thus, the kinematic differences between kicking and stepping may be the result of contextual differences in relation to gravitational forces. Spontaneous leg movements are molded and shaped by the forces that act on them.

This sensitivity to the contextual changes of posture also offers clues to the differences in the ontogenetic course of kicking and stepping. Thelen and colleagues conducted three studies to examine these differences. Their first study examined the relationship between body-build changes that infants normally experience between 2 and 6 weeks of age and the rate of newborn stepping. They found that the level of arousal was the best predictor of the number of steps. Furthermore, infants who gained weight most rapidly stepped less. This finding suggests that the weight gain of infants is faster than the accompanying improvement in strength. Infants may simply be too weak to step when they experience their most rapid weight gain between 2 and 4 months of age.

In their second study, Thelen et al. manipulated the weight-to-muscle ratio of 12 healthy, 4-week-old infants by adding small weights to the infants' legs. The amount of weight added was proportional to the infants' expected weight gain between 4 and 6 weeks of age. Each infant was held upright for 1 minute, both with and without weights, with a 5-minute rest period between conditions. In the weighted condition, the infants stepped significantly less than they had in the unweighted condition. There were no arousal differences between the two conditions. Strength and apparent limited the infants' expression of stepping behavior.

Advocates of the reflex-based and neural-maturation approaches have paid scant attention to the biomechanical aspects of movement development. Their emphasis has been on neural control, via muscle activation, of movement. We know from the analyses of Bernstein, however, that movement can occur from forces other than those generated by muscles. First, some forces originate from the environment, with gravity being the most pervasive of this type of force. Gravity is most frequently treated as a constant, but the influence of gravity varies for a body in motion. To illustrate this variance, consider the infant's stepping or kicking behavior (Fig. 1). Infants kick by decreasing the hip angle (ie, increased flexion) and increasing the hip angle (ie, increased extension). In a supine position, with the leg resting on the support surface, gravity is assisting extension. As the hip angle decreases, the influence of gravity toward extension decreases. When the angle of the hip is less than 90 degrees, gravity assists flexion. This relationship of gravity to the moving body results in dynamically changing external forces acting on the body.
Foot COM

Shank COM

Thigh COM

Figure 1. Torque is the product of two factors: the force and the perpendicular distance between the axes of rotation and the line of action of the force. For example, gravity is a constant vertical force that acts through the limb’s center of mass (COM). When the hip is extended in the supine kick, the distance between the thigh COM and the hip joint is at a maximum, and the effect of the gravitational torque is large (position 1). As the perpendicular distance between the thigh COM and the hip joint decreases (positions 2 and 3), the gravitational torque decreases. When the hip is fully flexed (position 4), the force of gravity is unchanged, but gravitational torque assists flexion. Thus, torque magnitudes vary as a function of changing force magnitudes as well as distance fluctuations.

A second source of non-muscularly generated forces that the neuromuscular system must contend with at a given joint are those produced in one body segment that act on linked segments. These motion-dependent forces also change dynamically as a movement progresses. For example, if you place your right hand on your left shoulder and then actively abduct with the right shoulder, your right elbow will first tend to flex as the upper arm moves into alignment with the body and then start to extend because of the force transferred from the upper arm to the forearm. The magnitude and pattern of motion-dependent forces vary with the speed or vigor of movement, the orientation of the limb, the stiffness of the system, and presumably many other factors. With even simple single-limb movements, the patterns of motion-dependent forces are complex and nonlinear and vary with each individual trajectory. The combination of gravitational forces and a complex set of motion-dependent torques results in highly irregular patterns of force acting on the body. The neuromuscular system must work in concert with these forces to produce smooth and efficient movement. To understand this process, we have to analyze the kinetics, or forces, of movement and examine how these multiple influences assemble to achieve coordinated movement.

Kinetic Analysis of Infant Movement

Kinetic analyses reveal the pattern of forces that produce movement. Although kinematic variables may provide a comprehensive description of movement, they give us no information about the motivating forces. Two identical end-point trajectories can be produced by substantially different patterns of forces and their associated torques (torque is the rotary effect caused by application of a force to a segment that rotates about a point). Thus, a full understanding of movement production comes only when descriptive kinematics are coupled with kinetic analyses that identify the forces acting on the body.

We have been using an intersegmental dynamics analysis to determine the kinetic features of infant movements. Based on the mathematical techniques of inverse dynamics and Newtonian equations of motion, this analysis allows us to determine the net torque acting at each joint, that is, the resultant tendency for the body segment to rotate about the joint. For example, we can calculate the dynamics of the infant’s kicking limb by using a three-link, rigid-body model (representing thigh, shank, and foot); an appropriate anthropometric model; and velocity and acceleration data derived from position-time data. The mathematical techniques rely on the basic Newtonian expression of force (ie, force = mass x acceleration).

The net torque (NET), can be further broken down into three components. First, there is the torque produced by the force of gravity (GRA). Second, there are motion-dependent torques (MDT). These are the torques created by the mechanical interaction of linked segments (recall the abduction example). The final component of the NET is the contribution of the muscles (MUS). The relationship of this set of variables can be expressed as

\[ \text{NET} = \text{GRA} + \text{MDT} + \text{MUS} \]

Inverse dynamics enables us to directly determine the contributions of the motion-dependent torques and the force of gravity. When these two components are subtracted from the net torque, the residual serves as an estimate of the contribution of the muscles. Note that this residual is the only part of the system that the ner-
Muscle torque can be actively regulated by the nervous system and also result from the viscoelastic properties of the muscles. The viscoelastic properties account for the observations, familiar to physical therapists, that a muscle can often exert more force when it is lengthened and that muscles offer resistance to quiet stretch. Thus, the muscles can be both actively regulated and passively responsive to changes in the other forces, which vary in complex and nonlinear ways.

We know that infants produce smooth, coordinated kicking movements in this environment of complex, interacting forces. By what means are they able to do this? To begin to answer this question, Jensen and colleagues (1989) studied spontaneous leg movements produced by 3-month-old infants who were positioned supine, held vertically, and reclined at a 45° angle. In addition to the three gravitational contexts produced by the postural manipulation, the infants themselves naturally produced kicks of various degrees of vigor and ROM. Despite their diversity, the kicks shared a common kinematic point at which the hip reversed direction by slowing to zero velocity and then changing direction. We will focus on this point in time to compare torque patterns and movement strategies across a variety of kicks.

To illustrate the relationship between kinematics and kinetics, we have plotted torque profiles of individual infants' kicks with their associated kinematic data (Fig. 2). Two kicks (ie, a nonvigorous kick and a vigorous kick) from each postural condition (ie, supine, angled, and vertical) were selected. The torque profiles of the nonvigorous kicks (graphs A, B, and C) show that muscle flexion predominated throughout the movement. In the supine and angled postures (graphs A and B), the motion-dependent torques were relatively small and the modulation of the muscles served primarily to counteract changes in the force of gravity as the movement evolved. In the vertical posture (graph C), the motion-dependent torques were more complex. Although the muscles primarily still counteracted the force of gravity, the force of gravity was responsive to modulations in the motion-dependent torques as well. The role of the neuromuscular system in these kicks seemed to be to get the movement started and then to counteract fluctuations, primarily in the force of gravity, as the movement evolved.

Vigorous kicks occurred in the same gravitational contexts, but the motion-dependent torques were larger and more complex (graphs D, E, and F) compared with those of the nonvigorous kicks. In the supine condition (graph D), the hip angle decreased to less than 90° degrees, as in the Figure 1 example, and the force of gravity assisted flexion for that portion of the movement. The action of the muscles changed to extension, counteracting both the force of gravity and the motion-dependent torques, until the hip again extended and muscle flexion returned to counteract the pull of gravity. In the angled posture (graph E), the muscles again produced extension, but this time in response to large motion-dependent torques. In the vertical posture (graph F), the motion-dependent torques changed dynamically, but were not as large. The muscles again produced flexion, and the force of gravity continued to act on the hip. When infants kick vigorously, the neuromuscular system must contribute in a precise and contextually sensitive manner as a number of other factors dynamically change.

The six graphs in Figure 2 represent only a small number of the almost infinite number of ways and contexts in which infants kick. The torque profiles of this small sample of infants demonstrate that the neuromuscular system utilizes many contextually sensitive and efficient strategies. In one instance, the neuromuscular system primarily complemented the force of gravity; at another time, the system complemented motion-dependent torques or the combination of both components. The nervous system clearly contributes to movement, but it seems unlikely, if not impossible, that it can program and fully specify the topology, or form, of a movement. These kicks reveal instead times at which the force of gravity and the motion-dependent torques seemed to drive the neuromuscular system.

Much of the adaptability of the neuromuscular system in these spontaneous kicks appears to stem from the viscoelastic properties of the muscles. Figure 2 (graphs E and F) shows that the muscles' peak torque corresponds to the maximum joint angle or muscle length. There were, however, exceptions to this pattern in which the force produced by the muscles suggests they were actively modulated by the neuromuscular system. When the hip extends, the extensor muscle torque should decrease as the muscle length shortens. Instead, the extensor muscle torque continued to increase as the hip extended with active modulation of the muscles (graph D). Hip reversal, which is the common element across kicks, was achieved both with flexor torques of muscle resisting gravity (graphs A, B, and C) and with extensor torques of muscle resisting gravity but also actively extending the hip (graph D). If these topologically similar kicks were determined by executive instructions from the nervous system, then we would expect the active modulation of muscle torques to have been similar across kicks as well. What we saw instead was a nervous system acting in concert with multiple other subsystems in a flexible manner in the assembly of coherent movement. Clearly, the traditional neuromaturational or reflex-based theories are inadequate to account for these phenomena, and, we believe, these theories are also insufficient to explain their development.

**Toward a Dynamic Theory of Motor Development**

A systems description of behavior does not assume any one of the contributing factors (eg, arousal of the infant, the infant's neuromuscular sys-
Figure 2. Torque profiles of individual infants' kicks with their associated kinematic data. Both vigorous and nonvigorouse kicks are represented in three postures (supine, 45° angle, and vertical). The kinematic variable is angle of the hip (measured in radians). Kinetic variables are muscles (MUS), force of gravity (GRA), and motion-dependent torques (MDT) (measured in newton-meters). Flexion and extension are indicated by decreasing and increasing hip angles, respectively. (A=nonvigorouse kick in supine position; B=nonvigorouse kick in angled position; C=nonvigorouse kick in vertical position; D=vigorouse kick in supine position; E=vigorouse kick in angled position; F=vigorouse kick in vertical position.)
system, gravity) has some privileged status over the other subsystems in determining the nature of the kick. As orientation of the infant changes, gravity contributes more or less to the topology, motion-dependent torques vary with both gravity and vigor, the role of muscle torque adapts to each change, and the entire system varies with arousal. No one subsystem contains the instructions for a kick, any more than the water in the study of Thelen et al. contained instructions for flexing and extending the legs.

The behavior of the system is instead an emergent property of the interaction of multiple subsystems. Because the behavior is not specified, but emergent, the system can be said to be self-organizing.

The concept of self-organizing systems may, at first, seem strange to therapists who received their training using the more traditional conceptual models of input-output mechanisms. Self-organization, in which order and pattern arise from the cooperativeness of many elements, however, is a feature of complex, dynamical (or nonlinear) systems. Such systems have been the subject of much scientific (and popular) interest in recent years. Not only are mathematical dynamical systems such as fractals and Mandelbrot sets fascinating, but these analyses are being applied to a wide variety of natural physical and biological phenomena, including laser lights, cloud formations, weather patterns, neural networks, and cardiac physiology. (Two recent nonmathematical books about diverse dynamical systems are Chaos: Making a New Science, by Gleick, and The Cosmic Blueprint: New Discoveries in Nature's Creative Ability to Order the Universe, by Davies.)

The principles and tools of dynamical systems have also been used to understand human motor behavior. The dynamic approach builds on the work of Bernstein and uses concepts from contemporary theories of synergetics and nonlinear dynamics. It is beyond the scope of this article to detail all of the principles of dynamical systems that apply to motor behavior; readers are referred to the article by Scholz in this issue and to the works of Kelso and Fuller, Kugler and Turvey, and Schön and Kelso for a more detailed discussion.

In our laboratory, we have been using dynamical systems principles to characterize both the organization of movement coordination and its development. We will present an overview of the approach, with an emphasis on how a dynamical view of developmental change can inform clinical practice in physical therapy. (See works by Thelen and colleagues for a full explication of a dynamical approach to development.)

The underlying assumption of a dynamical approach to behavior and development is that biological organisms are complex, multidimensional, cooperative systems. No one subsystem has logical priority for organizing the behavior of the system. For infant leg movements, this assumption means that the multiple subsystems described previously and their component parts cooperate in each behavior. Within the musculoskeletal system alone there are many muscles spanning multiple joints that must be linked cooperatively for coherent action. We have shown that the musculoskeletal system does not operate in isolation, but is sensitive to weight of the legs, orientation with respect to gravity, arousal, and a number of contextual variables. This sensitivity cannot be programmed prior to action because, as we have shown with gravitational and motion-dependent torques, the status of each variable changes with ongoing movement. Furthermore, the sensitivity of the system is far too precise and quick to be the result of corrections made from feedback. If, however, we consider that each subsystem contributes to the behavior of the infant in a cooperative, interdependent relationship with other subsystems, then the sensitivity of the musculoskeletal system can be understood as an emergent property of the interaction of subsystems. The interaction of these multiple subsystems can vary in an almost infinite variety of ways, yet the topology of behavior takes relatively stable forms.

This assumption means that the behavior of the system at any point in time results from the confluence, or coming together, of all of the functionally related components. Each of these components may initially be free to vary, resulting in many degrees of freedom to be controlled. Behavior represents a compression of the degrees of freedom as the system assembles into a functional pattern. Most functional tasks can be achieved with a variety of movement patterns, but we tend to use the one that requires the least amount of energy and that is the most efficient melding of the many parts involved. Like a ball rolling into a pit in the sand, the system will return to certain configurations. Alternating kicking is an example of a pattern that consistently appears when infants are aroused and spontaneously move their legs. Infants alternate their legs when they see their mother or a brightly colored mobile, when they are angry, and later when they begin to walk. Kicking is not the only movement infants perform with their legs, but it is the most common and predictable response. In dynamical systems, this pattern is called an attractor because the system falls into the pattern easily and returns to that pattern even when perturbed or interrupted.

An attractor is a preferred, but not an obligatory, configuration of the system. If we could make a diagram of the almost infinite number of possible ways infants coordinate the movement of their legs, this diagram would be a map of the state space of infant leg movements. This hypothetical state space is represented in Figure 3. The temporal relationship between the right leg and the left leg is represented by plotting the location of each leg with respect to the other in
the course of a movement. The x-axis represents the position of the left leg, ranging from maximum flexion to maximum extension for any given movement. The y-axis represents the same range of positions for the right leg. Alternate kicking, which is identified by the 180-degree phase relationship between the movement of the two limbs, would occupy only a small part of that state space. In the example of alternate kicking, the right leg is at maximum flexion when the left leg is at maximum extension. If the legs maintain a 180-degree phase relationship throughout a kick, each point measured in time will fall on or near a diagonal line. Bilaterally, symmetric kicks would fall on the opposite diagonal. We know infants prefer the alternating pattern of coordination, so the area of this diagonal line is a preferred area in the state space, or an attractor.

Like the ball rolling into a pit in the sand, attractors are described as having relatively deep or shallow attractor wells, based on the ease with which the system returns to the attractor and on how difficult it is to move the system away from or out of the attractor well. To illustrate this concept, it is helpful to think of the state space as a three-dimensional space. If the hypothetical marble of behavior is placed on a flat surface such as a tabletop, it is as likely to roll to one spot on the table as to any other spot; there is no attractor. If the surface has even a slight concavity, however, the marble is likely to return to the lowest point under a number of conditions, but it can also roll in other areas as conditions vary (Fig. 3B). This shallow attractor well gives the behavior a preferred, but flexible, configuration. When an attractor well is very deep, the behavior of the system becomes limited to this area and is often described as hard-wired, stereotyped, or obligatory (Fig. 3C). For example, infants with cerebral palsy often have difficulty dissociating movement of their legs and may only kick symmetrically. These infants would be said to have a deep attractor well in the area associated with symmetric kicking. Describing the behavior as hard-wired fails to recognize that behavior can be constrained by multiple influences and attributes the stability of the behavior to the status of only one subsystem, the nervous system. Dynamical systems principles allow for alternate explanations of this phenomenon that include the status of other subsystems. In the example of the infant with cerebral palsy, other subsystems may include arousal level, posture or position of the infant, and the task constraints. These alternate subsystems are ones that physical therapists use and manipulate in the therapeutic process. A dynamical systems perspective would agree that CNS damage places constraints on the system but also recognizes that other subsystems influence the behavior as well.

The context of behavior and the task are important parts of the system. Both the general context (eg, postural, gravitational, social) and the particular task are important organizing influences. As one reaches for a cup, one cannot choose to perform the movement over just a bit to the

Figure 3. (A) State space of interlimb coordination for infant leg movements. The x-axis represents the position of the left leg with a range from maximum extension to maximum flexion. The y-axis represents the position of the right leg. The temporal relationship between limbs is represented by plotting the position of one limb with respect to the other limb. Alternate kicking (with 180° phase relationship between limbs) is represented by solid line (——). Bilateral symmetric kicks are represented by dashed line (— — — —). (B) Shallow attractor well. (C) Deep attractor well.
left and still be successful. The task-reaching for the cup—places constraints on complex systems, which act like a funnel to organize behavior. If we release a handful of marbles into a funnel, they will fall into it in a random fashion, but they will fall out below, one at a time, in an ordered procession. Widen the neck of the funnel to lessen the constraints, and behavior becomes less ordered. The task and the context engage the entire sensory-perceptual apparatus as functionally related subsystems in response to these constraints.

The concept that the organism, the task, and the context self-organize behavior to a preferred form, or attractor, is central to a dynamical approach. Attractors, in turn, can be very stable—so stable that the behavior looks like it is wired in—or quite unstable. Reconsider the so-called primitive reflexes, indeed not as hard-wiring, but as the infant’s propensity under certain circumstances to exhibit a particular motor response. Reflexes, even primitive reflexes, are not inevitable. Their performance depends, for example, on the infant’s state and position. If we conceive of actions as these dynamic attractors, assembled on the spot, rather than as the play-out of a tape, we are in the position to suggest a theory of how these behaviors change that is more general than neural maturation.

Until now, we have used motor actions such as kicking and stepping to illustrate the many ways in which behavior is dynamically organized. We are fundamentally interested, however, not only in stable forms of action, but also in a theory of behavioral change, because development is the continual acquisition (and loss) of forms. A dynamical approach states that during development, new forms of behavior emerge as old forms lose stability. Loss of stability, in turn, can result from changes in any of the contributing subsystems.

These predictions come from the more general property of complex, dynamical systems: their nonlinearity. Nonlinearity means that small causes can have large effects. An example of nonlinearity is adding weight onto a camel’s back. Imagine gradually adding weight and watching the camel slowly buckle its knees in direct proportion to the weight. Finally, when a crucial weight—the “last straw”—is added, the camel collapses. We are suggesting that the acquisition of qualitatively new behaviors during development is a similar phase transition. Contributing subsystems develop continuously, but behaviors appear discontinuously. In the example of the loss of infant stepping discussed previously, we suggested that, as infants gain weight, their stepping declines proportionally. At a critical fat-muscle ratio, however, a new movement pattern appears—no stepping at all. The gain of fat could be considered in dynamical terms the control parameter (see article by Scholz in this issue) for loss of stepping; it is the part of the system whose changes made the whole system unstable. Fat gain is not specific to stepping, but it specifically reordered the assembly of the stepping behavior.

Thus, as subsystems—including contexts and tasks—themselves change, they threaten the integrity of the behavioral attractor. Primitive reflexes may be dissolved because the cortex matures, but perhaps also because competing behaviors or even peripheral strength interfere with their stability. During these transitions among stable states, dynamical theory predicts that the system is especially vulnerable to perturbation. For example, adding equal proportions of weights to the legs of older infants or children may not depress their stepping abilities, because they are no longer at a critical strength threshold and their legs can handle much added weight and still step.

At the time of reorganization, even small influences may have large effects. Developmental outcome itself is nonlinear. Therapists often observe neonates on intensive care who are at grave risk, yet who develop normally, whereas other neonates at apparently lesser risk have a poorer outcome. These are frustrating cases to all, but from a dynamical perspective, we may not be able to improve our predictability. If the development course is nonlinear, then perhaps even factors so small as to be immeasurable at certain critical points of transition can shift the developmental course. This developmental shift is much like a ball balanced on the top of a hill. The destination can be determined by the slightest puff of wind.

Part of the nonlinearity of developing systems may be explained, in part, by the asynchrony of the developmental course of the subsystems that comprise it. Although many subsystems cooperate to produce behavior, at any time they can be at different functional states of maturity. In addition, their rates of change may also differ. For example, newborn stepping is inhibited by lack of strength, but later in the first year, stepping may be inhibited by lack of balance ability. We cannot assume that the control parameters engendering developmental shifts are the same at different points in time. At the later age, the whole cooperative system is likely to be different and it will prefer different stable states.

This asynchrony is often exaggerated in children with developmental disabilities. Therapists may be familiar with the child who demonstrates all of the motor components of walking but who lacks the cognitive or perceptual abilities to be interested in the environment beyond his or her arms’ length. Alternatively, children with motor dysfunction who want to move may find a number of ways to locomote that compensate for their disability. A compensation that works for the child at one age, however, may interfere with development of normal locomotor patterns at a later time, when other subsystems have matured and changed. Any behavior represents a particular assembly of all of the relevant subsystems and their developmental status at the time.

The process of development, therefore, is envisioned as a series of phase shifts in which some stable solutions, such as primitive reflexes and early
rhythmicities, dissolve and infants must find a number of new stable motor solutions as each subsystem develops on its own time line. Any solution that is too stable or inflexible, however, can interfere with developmental progress. For example, sitting is a stable and adaptive solution for exploration when the infant has a given level of trunk control, arm strength, and perceptual skill. To progress, however, infants must explore the limits of this posture. If they never try out the biomechanical and adaptive limits of the posture by reaching forward or to their sides and sometimes falling over, they may be locked into a rigid sitting behavior and may never acquire the ability to assume the sit-to-hands-and-knees position.29 This hypothesis suggests that, even though the system is in transition, infants explore the perceptual and biomechanical dynamics of their own movement while engaged in adaptive play. It is within the context of a task that the dynamic coupling of motor and perceptual components takes place in the continuing organization and reorganization of behavior that we observe as development.30

Implications for Physical Therapy

A dynamical view of development leads to a number of implications for treatment. Treatment is change that involves seeking new, and more adaptive, movement configurations, just as development is change that involves the same goal.

We suggested that, just as neural maturation may be an insufficient cause for developmental change, therapists should seek more system-wide, multi-determined bases for treatment. If the behavioral pattern is what is to be changed, then identifying the dysfunctional pattern and a more functional goal is a first step. Contemporary movement science may be of great assistance in the performance of this task. The emphasis should be not on the abstract capabilities of the system under artificial testing situations, but on the patterns that the subject prefers, on the stability of those patterns, and on the contexts and tasks that are normally encountered. Clinical case studies, often criticized for not being generalizable, are of great value with a dynamical systems approach. The course of therapy, like that of development, is likely highly nonlinear; thus, we need to preserve the variability of the course of recovery. Average outcomes from large populations obscure the heterogeneity of both the starting points of diverse patients and their pathways of change.

The value of charting the pathways of change during the recovery process (as well as noting the outcome) allows the therapist to discover the points at which the system is in transition from one stable mode (perhaps dysfunctional) to another (which may be functional or another dysfunctional pattern). It is only at these junctures that the therapist may discover the control parameters, or what is pushing the system into a new realm. Control parameters may be highly specific, like CNS changes or particular muscle strength, or nonspecific, like emotional or motivational aspects, but they cannot be known a priori because of the nonlinearity of the system. Once the putative control parameter is identified, a principled program of manipulating that control parameter can be started.

In reality, many physical therapy regimens follow a dynamical systems approach. Assessments of patient strengths and weaknesses are inherently systems analyses. From this evaluation, therapists anticipate under what conditions and how patients will change. Therapists often also anticipate systemwide responses to small changes in a control parameter. For example, an orthotic device placed in the shoe may alter the pattern of weight-bearing and thus influence the posture of the knee, hip, pelvis, and trunk. Therapists know that improving general strength may be a control parameter for many new functional abilities. An orthotic device does not contain instructions for a different locomotion pattern, and strength does not instruct a patient in more functional actions. Nonetheless, these small changes disrupt the current functioning and allow the system to seek other and potentially better patterns of movement.

Can a dynamical systems approach help patients with damaged or poorly developing nervous systems? We can imagine that the CNS damage imposes especially tight constraints on movement and perception, limiting the ability of the system to free its inherent degrees of freedom and to explore functional movement solutions. One clear consequence of a dynamical approach is that intervention must be started while the system is still plastic, so that the movement attractors can be channeled into more adaptive patterns. Often, patients' movement disorders are not diagnosed and the patients are not treated until the patterns are well-practiced and rigid. Over time, for example, in infants at risk for cerebral palsy or other motor delays, abnormal patterns may be self-sustaining and reinforced by caregiving practices. Early intervention has the potential to channel the still-plastic system into more functional organizations. Similarly, a patient with a recent cardiovascular accident may be immobilized in bed during the flaccid stage of recovery, but without the proprioceptive, social, visual, and movement consequences of ongoing activity, movement may be reorganized in an atypical way. The early recovery process may take place in a condition of relative sensory deprivation. In this condition, the damaged nervous system exerts the most pervasive influence on the system as it reorganizes. Providing stimulation within a functional task context should help to balance these influences and facilitate optimal recovery.

Thus, the goal of treatment, according to a dynamical view, is to work on the system when it is in transition. The synergy patterns that patients exhibit are stable configurations of damaged systems. Patients who have experienced the bias of one organization longer will have developed a deeper well of this preferred organization, pulling further subsystems into a less
flexible pattern. If poor patterns are already in a deep attractor well, interventions are required that disrupt this current stability, if possible. Once the system has alternative patterns available, the therapist can assist the patient in discovering, through natural movements, the range of possible solutions. This is particularly effective tool from a dynamical view, for example, is the exploration of dynamic balance. Therapists provide the opportunity for patients to discover the biomechanical dynamics of their own actions by introducing instability into the context of movement. In this dynamic context, therapists use handling techniques to precisely control the amount of instability and the degrees of freedom. For every posture, and for every patient, there will be a critical point at which the patient will either reorganize the movement adaptively or regress to a less adaptive, stable posture. Increased stretch reflexes and synergy patterns may be one way of trying to control the many degrees of freedom. Therapeutic handling should allow as many degrees of freedom to vary as the patient can flexibly explore. The task of maintaining head control, balancing the whole body in standing, or reaching for an object in this dynamic context demands flexible adaptive exploration and discovery of alternative movement solutions. Just as infants explore the limits of each posture, so must patients. Control around these transition points is one key to adaptive behavior. When patients are able to explore and use the limits of postures to actively engage in tasks, they are adaptive and independent.

Conclusion

The physical therapy profession has a good descriptive literature in case studies and single-subject experiments to serve as the basis for investigation into the processes of recovery with a dynamical systems approach. In addition, therapists have developed intervention techniques that incorporate multiple subsystems into the process. The dynamical systems approach to understanding development should be a fruitful model for physical therapists. The asynchronous development of subsystems in development results in the emergence of different organizations of the system as the status of each subsystem changes. Patients experience changes in individual subsystems as well in the process of recovery. Therapists should be sensitive to the transitions their patients make and look for the control parameter responsible for the shift. The nervous system, as one subsystem, will always be changing, but need not be the reason for all of the transitions patients experience. Quantitative analyses of movement should be used to investigate multiple reasons for changes in recovery, just as the quantitative techniques freed developmentalists from strictly neural explanations. The control parameter may be different at each transition. A dynamical systems approach, however, predicts that therapists will have a number of entry points into the system and a number of subsystems to explore for intervention.

Acknowledgments

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