INTRODUCTION

As physical therapists, we are interested in foundation sciences related to human movement. Our understanding of motor behavior serves as a basis for our work with individuals whose functional limitations arise from impairments of motor control. Among kinesiologists there are a variety of perspectives and approaches to the study of human movement. For example, biomechanists offer the theory and models of physical mechanics. These theories and models are frequently used by physical therapists to analyze and solve our patients’ movement problems. However, the biomechanical perspective represents just one approach that can be used to study human movement. Motor control, motor learning, and motor development represent three other areas of kinesiology that have much to offer physical therapy. Each of these specialized areas offers a unique perspective that can add to our abilities as physical therapists to analyze and solve patients’ movement problems.
DEFINITIONS OF MOTOR CONTROL, LEARNING, AND DEVELOPMENT

According to Brooks, a neurophysiologist, “Motor control is the study of posture and movements that are controlled by central commands and spinal reflexes, and also to the functions of mind and body that govern posture and movement.” Schmidt and Lee, as psychologists and kinesiologists, define motor learning as a set of processes associated with practice or experience that leads to relatively permanent changes in the capability for producing skilled action. And finally, the study of motor development, according to Roberton, a physical educator, is the study of life span change in motor behavior.

Motor control, learning, and development represent three distinct approaches to understanding motor behavior. Yet, scientists who study these three areas have shared ideas and themes in the past and continue to do so. Each discipline is ultimately directed toward understanding motor behavior. For motor control, the question is “How is the control of motor behavior organized?” For motor learning, the question is “How is motor behavior acquired through practice or experience?” And, for motor development, the question is “How does motor behavior change with age?” The “How?” in each of these questions refers to the search for understanding of the processes that underlie observable motor behavior.

Although motor control, learning, and development researchers have a common interest in processes that underlie motor behavior, one of the differences among them is the time scale over which the processes are studied. Motor control scientists are interested in processes lasting milliseconds or, at the most, seconds. Motor learning scientists are interested generally in processes that occur across hours, days, and weeks, although for highly practiced skills the processes of learning may extend across months or years. Those who study motor development generally are interested in processes of change that involve time periods ranging from months to decades. The relative span of time that attracts interest has to do with the rate of change in the motor behavior being studied (Table 2-1).

Motor Control—An Overview

The specialized area of motor control as we know it today grew out of the subdisciplines of neurophysiology and cognitive psychology. Early in this century, physiologists studied both motor behavior and the neural processes underlying that behavior. Since that time, and until very recently, neurophysiologists tended to concentrate exclusively on understanding microscopic internal neural processes that coordinated and controlled motor behavior of animals. Their studies were carried out in laboratories with anesthetized animals. More recently, technological advances have enabled neuroscientists to study more general processes involved in the control of natural movements of awake animals and in human subjects performing motor skills.
Over the last 30 years, cognitive psychologists brought to the study of motor control concepts derived from cybernetics and information processing. Feedback, one of these concepts, arose from cybernetic theory and has become a routine element of motor control models. Over time, neural functions were modeled as computer functions and processes such as motor programs and memory served major roles.

Physical therapists have a long-standing tradition of studying the neurosciences in order to understand how the nervous system is organized and how it controls motor behavior. The classical neurophysiologic approaches to patient care, which originated in the work of Knott and Voss, Rood, the Bobaths, Brunnstrom, and Fay, represented a distinct shift away from relying on biomechanical concepts alone to solve patient problems, to the use of a motor control model (see Chapter 1). The motor control model dominant at the time consisted of a control hierarchy, with reflexes serving as the foundation for volitional control of movements. This model is still commonly understood and often used to explain the abnormal motor behavior of individuals with impairments of the central nervous system (CNS). Simply put, individuals with brain dysfunction demonstrate reflexive motor behaviors that are no longer under volitional control. The reflexes arise from the intact lower levels of the motor control hierarchy. Physical therapists used the hierarchical model to suggest that rebuilding control after brain injury could be accomplished by activating the higher levels of control by using sensory stimulation and requests for volitional action.

When the original neurophysiologic approaches to physical therapy were developed, neurophysiologists were actively studying the electrical activity of single neurons and complex sensory receptors such as the muscle spindle. It was the study of the muscle spindle and the gamma motor system that provided a generation of physical therapists with understanding of the concept of feedback as an integral part of motor control, whereas the physiology of the muscle spindle strongly influenced the therapeutic practices advanced by Rood, as well as Knott and Voss through proprioceptive neuro-muscular facilitation (PNF). Brunnstrom and the Bobaths were less influenced by microscopic elements of motor control, focusing instead on observable elements of motor behavior theorized to represent reflexes mediated at the spinal, brainstem, and midbrain levels of the motor control hierarchy.

<table>
<thead>
<tr>
<th>Motor Control</th>
<th>Control and organization of processes underlying motor behavior</th>
<th>Milliseconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor Learning</td>
<td>Acquisition of skill through practice and experience</td>
<td>Hours, days, weeks</td>
</tr>
<tr>
<td>Motor Development</td>
<td>Age-related processes of change in motor behavior</td>
<td>Months, years, decades</td>
</tr>
</tbody>
</table>
As technology advanced, the simultaneous monitoring of electrical activity at multiple sites within the CNS became possible. This advance led to increasingly complex models of motor control developed to explain relationships among various elements of the nervous system.\textsuperscript{1,15} With this came a deeper appreciation of the complexity of the nervous system and hesitancy to assign specific functions to specific structures within the CNS (Figures 2-1 and 2-2). Neuroscientists began to adopt a notion of shared function that recognizes the contributions of multiple structures to the production of functional behaviors. This was an important trend that affects our current understanding of motor control. Gradually, network models that demonstrate this interconnectivity and interdependence of neural elements began to appear in the neuroscience literature. An example of this trend is evident in models of neural control of locomotion, in which neural networks are used to portray oscillatory processes that control the alternating phases of gait.\textsuperscript{16} The impetus for the adoption of network theory was not only the increasing appreciation of the complexity of neural processes, but also the increasing availability of computers to assist in the modeling of networks as control elements.

Current Issues in the Study of Motor Control

A general change has taken place in the way theorists view issues related to the control of motor behavior.\textsuperscript{17,18} This change in large part is the result of the publication of
the work of Bernstein, a Russian physiologist. Bernstein’s writings captured increasing attention among motor control theorists. Bernstein is most well-known for his “degrees of freedom” problem: How does the brain control so many different joints and muscles of the body? The statement of the degrees of freedom problem brought renewed focus on the physical aspects of the body, particularly the musculoskeletal system and its role in motor control. Previously, theorists focused almost exclusively on the role of the nervous system in controlling movements.

The way in which the CNS solves the degrees of freedom problem is proposed to be through muscle synergies or coordinate structures. The brain simplifies the task of controlling numerous muscles by constraining them to function collectively.

Two lines of thought have emerged to explain these muscle linkages or synergies. One emphasizes motor programs; the other emphasizes that muscle synergies are not predetermined like a computer program, rather they arise as a result of complex interactions among the individual and the environments in which the person functions. Motor programs include information that specifies fixed relationships among muscles. Programs are stored in memory and recalled to guide action. An alternate explanation is that the CNS creates solutions to the demands for action at the time they are needed. The muscle linkages emerge from the CNS, taking into account the physical structure of the body and the context in which the action must be performed.
The concept of a synergy, or muscles working in collective groups, is not a new concept to physical therapists. However, the processes that underlie the appearance of muscle linkages are new concepts. Traditionally, synergies were viewed as the behavioral manifestation of hard wired reflexes, present at birth. Synergies are viewed as either motor programs or as emergent properties of the body systems within the context of a meaningful environment.24 The nervous system, the musculoskeletal system, and the cardiopulmonary system all contribute to the production of movement. No longer is the nervous system considered the sole source of motor control.

**Synergies as Motor Programs**

A motor program simplifies the degrees of freedom problem by providing a single unit rather than many units to control. Some contemporary models of motor control constitute hierarchies that incorporate motor programs. In these models, the motor program is selected through higher level control processes but carried out by lower levels. This arrangement frees up the higher levels to engage in processes of planning actions. Those who research motor control theory from the perspective of motor programs are interested in determining what elements of the motor program are fixed and what elements can be controlled.1,2

Currently, a motor program is characterized by an invariant order in which fundamental elements come into action. Thus, if one were considering a motor program for an overarm throwing of a ball, the order in which the muscles contract would be fixed. The relative duration of the various muscular contractions would be fixed, as would the relative force levels among muscles acting in the program. What can vary in the program, and therefore would need to be controlled, are the absolute level of force and the overall duration of the program. In the overarm throwing task, this means the throw may be light or forceful or the throw may be carried out slowly or quickly.

The speed and force that can be generated within a specific program are, however, limited. For example, if speed is increased in an underarm throwing pattern, the relative timing of various muscles can change and a new program is used as the individual begins to use a windmill pattern as a windup for the throw. A similar change from one pattern to another can be seen when walking speed increases to a point where a switch to a running pattern occurs. These examples can be explained as shifts from one program to another.

One model that has evolved to explain control within the programming concept is the mass spring model of control. Support for the mass spring model has been provided by Fel'dman, a Russian motor control theorist.25 He proposed that we control the final position of a limb by specifying the relative stiffness of opposing muscles. Movements end at the point where agonist and antagonist stiffness is balanced across the limb. Noncontractile elastic properties of muscle are a part of the model, and antagonistic muscles are viewed as two opposing springs. Poli and Bizzi, two neuroscientists, found that monkeys, after having learned to perform simple one-joint movements involving pointing to targets, were able to point correctly with vision occluded and following deafferentation of the limb, regardless of the starting position.26 It appeared that the monkeys had stored information about muscle tensions at the end position of pointing at the target. This research is supportive of the theory that the motor control system solves the degrees of freedom problem by treating the musculoskeletal system as though it were a mass spring system.

The mass spring model offers a relatively simple explanation of discrete movements to an endpoint. It has been extended to relatively elaborate tasks, such as handwriting.
Hollerbach created a system of four springs arranged at right angles to each other, with each attached to the same mass or weight. This is like a four-muscle system attached around a limb segment. If the mass is displaced in any direction, the system oscillates until an equilibrium point is reached. This more complex model of springs in oscillation can produce action similar to handwriting. If the displacement of such a four-spring system happens to occur in a diagonal direction, the mass oscillates in a circular pattern. By varying the stiffness of the springs, the circular pattern can be altered to make elliptical loops. Attach a pen to the system and the product is much like the letters of cursive writing. Slight alterations to the elliptical loops produce a variety of recognizable letters. Thus, the mass spring model can be extended to explain complex tasks.

**Emergent Properties of the Nervous System**

The notion of emergent properties of a neural network is an outgrowth of application of network models to issues of motor control, particularly to the control of locomotion. By specifically placing elements depicting neurons in a series, patterns of neural function can be modeled. If one element in the chain is activated, the others will be activated in a fixed order, mimicking one of the fundamental properties of a synergy or coordinate structure: the elements are constrained to produce a fixed pattern of activity.

Not only can fixed patterns of activity result from the function of a network, but sets of neurons can be arranged in a circular pattern so that cyclic function results. Cyclic function, as a pattern of activation and rest, becomes an emergent property of the network. By constraining the relationship between the elements of the system, a new property emerges that is not an inherent property of any element of the system: that is, no element of the system possesses the property of cyclic activity, but when arranged in a network, cyclic activity can result.

Emergent network properties have disadvantages, as well as advantages. One particular disadvantage is the tendency for circularly arranged networks to produce resonating oscillatory behavior. This means that they may get progressively carried away during repetitive functions. Damping mechanisms are needed in network models to control the oscillations. Damps ultimately return oscillators to a point of static equilibrium when the energy of the system has dissipated.

While oscillatory function is quite common in biological systems, biological oscillations typically do not resonate uncontrollably. Living organisms have the ability to sustain stable levels of oscillatory function. Thus, the network model cannot be used to explain some fundamental properties of living systems. The problem with network modeling is that it is based in the physics of closed systems in which fuel or energy is not exchanged with the surrounding environment. Ultimately, closed physical systems are not well suited to modeling the functions of living systems. Biological oscillations appear to be more accurately portrayed by nonlinear or limit cycle oscillators, typical of open physical systems.

The modeling of open systems is a relatively new area of physics. Yet, the constructs of the newer models of motor control are grounded in principles related to the thermodynamics of open systems (not to be confused with open loop control of movement) and principles of nonlinear limit cycle oscillators. One important characteristic of limit cycle oscillators is the property of entrainment of one oscillating function to another, such that they share a common periodicity. Entrainment has been used to explain inter-limb coordination during locomotion. Entrainment underlies the temporally pat-
terned relationship between the limbs during their individual cyclic gait patterns. Figure 2-3 illustrates the concept of entrainment.

At first glance, the use of oscillators to model motor control appears to be limited to repetitive cyclic tasks, such as various gait patterns. Yet, oscillators also may be used to model discrete noncyclic behaviors with specific start- and endpoints.

The science of open systems that is leading to formulation of such control models is not just useful to us as therapists. The properties of nonlinear systems are being used to model a host of natural phenomenon, from shoreline formations and tornado development to the formation of biological structures such as leaves and honeycombs.30 Why is this new theory preferable to the traditional models? Simply put, complex natural patterns can be reduced to a few simple principles. These principles, when applied in the context of the physical world, lead to new understanding of a vast array of complex natural forms and patterns. Human movement is an example of an array of complex natural forms and patterns.

One aspect of the newer control models is particularly rich for physical therapists. This is the notion that synergies emerge and are constrained by the physical characteristics of the human body and characteristics of the specific environmental context in which actions are performed.31 As an example, imagine a child in a huge rocking chair (Figure 2-4A). If she were to get out of the rocker, there are several strategies she might use. She could slide off the front of the chair, extending her legs and trunk while holding fast to the armrests. Or, she could turn to lie prone on the chair and get off backwards by lowering her legs to the floor (Figure 2-4B). One action pattern that she cannot perform from this chair is the common sit-to-stand action pattern that involves flexing forward over feet contacting the floor, followed by extension to attain standing. This is because the chair is too big or she is too small to be able to sit and have her feet on the floor. But, the child can perform other actions that larger people cannot. She can curl up on her side on the seat of the chair and probably can slide out under the side arms (Figure 2-4C). Thus, the size of her body and the size of the rocking chair mutually constrain the actions possible.

Figure 2-3. This diagram demonstrates the periodic oscillation of the pectoral and dorsal fin of a fish. The relationship between the fins becomes coordinated at the X marked on the diagram. Prior to that time, the dorsal fin oscillated at a faster rate than the pectoral fin. The process of entrainment of one oscillating fin to the other resulted in a shared frequency. In this case, the dorsal fin has become entrained to the slower rhythm of the pectoral fin, and the movements of the fins are “coordinated” (adapted from Gallistel CR. The Organization of Action: A New Synthesis. Hillsdale, NJ: Lawrence Erlbaum Associates Publishers; 1980).
In the examples of throwing and locomotion patterns that were used previously to illustrate different motor programs, when the speed of the individual increased to a critical level, there was an abrupt qualitative shift from one pattern to another. In the programming concept, this shift is explained as a switch from one program to another. Newer theory, based on principles of open systems, would explain this switch as a function of scaling up a variable until a qualitatively different organizational pattern emerges from the system. Qualitative change from one action pattern to another is an emergent property. The laws and principles under which such qualitative change may occur are corollaries of theory of open systems. This newer theoretical framework is termed dynamical action theory.31

Motor Control Theory Applied to Physical Therapy

The theoretical perspective one adopts affects what aspects of patient function are evaluated and the procedures used to solve clinical problems.32,33 The classical neurophysiologic approaches to patient care were formulated from the perspective of a motor control hierarchy resting on progressively more complex levels of reflex organization. Therapists evaluated the presence of specific reflexes and reactions, presumed to be controlled at various levels of the CNS, and determined the level of neural function. Therapists facilitated and inhibited reflexes to promote advancement to a higher level of control, ultimately for the purpose of improving the patient’s functional competence in daily life.

Functional motor behaviors are of critical importance in the evaluation of patients regardless of the theoretical model adopted to explain motor control. It is important,
however, to remember that functional behavior implies that the patient acts in the context of a meaningful environment. Therefore, two basic elements that need to be assessed are functional motor behaviors and the environmental conditions under which they are performed.

A fundamental construct within the newer models of control rest on the notion of coordinate structures, synergy patterns, or muscle linkages. I suggest that the behavioral expression of these linkages within functional tasks should constitute a primary focus of physical therapy examinations. Specifically, the following question can serve as a starting point for the therapist applying motor control theory in clinical practice: “What postural and movement patterns are part of patients’ behavioral repertoire?” I would further suggest that impairments in motor control would evidence as a limited repertoire of movement patterns and difficulty when switching from one pattern to another.

The movement patterns used to perform fundamental tasks of daily life have begun to be identified as have standing postural synergies. However, the descriptions of qualitatively different patterns used to perform the fundamental of tasks of daily life are far from complete.

Another key aspect of contemporary patient evaluation is an analysis of environmental contexts in which motor behaviors are displayed. The environmental conditions under which our patients function can be systematically explored. Environments can be considered either stable or variable. Stable environments simplify demands for motor control. Stable environments are predictable and allow individuals to perform at a self-determined speed. Parallel bars are an example of a stable environment for walking. Stable environments, however, are not all the same. Home and hospital rooms can be stable, in that the elements in the room are fixed and unchanging, yet they differ from one another. We need to concern ourselves with the features of the environments in which our patients ultimately will be required to function. Walking surfaces and the heights of chairs and beds are examples of the variable features of stable environments.

Variable environments require a greater degree of motor control than do stable environments. This is because the individual must adjust movements to the changing demands of the environment. A busy city street is a good example of a variable environment, as it has a large degree of unpredictability. Yet, even variable environments can have some degree of predictability. We rely on this predictability to ensure our safety. For example, stoplights provide predictable patterns of traffic flow. But there are instances when we must be able to slow, speed up, or stop our movements in order to meet the demands of the environment. Our patients often are not given opportunities to experience variable and unpredictable environments as part of a full course of rehabilitation. Rather, we tend to teach skills in the stable environments of hospitals, rehabilitation centers, and homes. As a result, we are unsure, as our patients often are, of their ability to function across the full range of circumstances that are commonly encountered in daily life.

By viewing the individual and the environment as an interacting unit in the formation of movement patterns, the potential for structuring the environment to bring out specific patterns also becomes apparent as a therapeutic principle. Therapists are familiar with structuring patients’ environments to promote general forms of motor behavior. Common examples are arranging the room of a patient with hemiplegia to encourage turning toward the involved side of the body or positioning a toy so a child will orient and reach to touch it. But we have not fully exploited the idea of the physical environment as a constraining variable that would lead to specific motor patterns.
Conversely, we need to examine the environment to determine what actions are possible given the relative size of the patient and objects in the environment.

Several years ago, I was treating a young man recovering from head injury. He consistently postured with his right arm in elbow flexion and had developed a contracture of approximately 30 degrees. While splinting and casting had been used to prevent further contracture, active extension of this elbow, necessary to maintain functional range of motion, seldom was performed. Traditional techniques of handling and facilitating elbow extension, while effective, were hampered by his limited attention span and motivation to participate in therapy. Repeatedly asking the patient for elbow straightening or pushing him off balance to evoke protective extension were boring after multiple training sessions. Yet, the young man proved to be quite interested in trying out his abilities in a familiar and meaningful skill. I turned a sliding board into a striking board by having him hold it in a manner similar to the way in which one would hold a baseball bat. A tennis ball was tossed to him, and he swung the sliding board with appropriate timing and directional control to hit the ball. His elbow extended quite naturally, achieving in a matter of seconds what had been an underlying goal of therapy for several months. He performed a task in which he had to straighten his elbow in the context of a meaningful environment. In this example, the environmental conditions were such that the patient had to time his movement to coincide with the arrival of the tennis ball. Had he not been successful, this task could have been simplified by having him use the board to strike a stationary ball, such as in a golf swing or batting in T-ball.

In summary, newer theories of motor control lead to different examination, evaluation, and intervention strategies. The types of information gathered during examination are not the same as those we would gather using our traditional examinations. They go beyond the common view of the environment as the source of reflex stimuli. Rather, the environment is seen as both a constrainer and promoter of meaningful behavior. Motor patterns now are viewed as more than reflexive responses. They are the elements of behaviors that arise as an emergent property of a highly complex system that is tuned to function in meaningful environments.

**Motor Learning—an Overview**

The specialized area of motor learning grew out of the subdiscipline of psychology concerned with processes of learning.42 In the early part of this century, experimental studies explored three main learning issues: massing versus distributing the practice of tasks, instruction in the whole versus the parts of tasks, and the transfer of learning from one task to another.

By the middle of this century, motor learning had been established as a specialized area of study with problems that differed from those studied by researchers interested in verbal learning. Since that time, cybernetics and information processing science have exerted a major influence on the study of motor learning, as they did on the study of neurophysiology. The contribution of these new sciences to the study of learning includes recognition of the influence of feedback on the motor learning process. Both motor learning theorists and neuroscientists have applied information theory to their areas of study.1,2 This commonality and technologic advances have allowed neuroscientists to study human subjects. Additionally, neuroscientists and motor control scientists from a psychological background share ideas in interdisciplinary research focused on how skills are acquired and controlled.
Physical therapists, who work with individuals with neurologic impairments, are becoming increasingly familiar with motor learning literature. Recently, our association with medical sciences, often at the expense of behavioral sciences, tended to direct attention away from principles of learning, although there was explicit recognition of the role of learning in the restitution of functional skills.\textsuperscript{43,44} Treatment rather than teaching tended to embody the traditional way of thinking about physical therapy interventions. Regaining motor skills following CNS damage was based predominately on repetitively evoking reflexes to facilitate postures and movements. Practice involved repetition of reflexively facilitated behaviors. Rehabilitative practices involved teaching motor skills, including the breaking down of functional activities into component parts for ease of learning\textsuperscript{45} and periods of practice. Much of what therapists learned about teaching motor skills was acquired through practical experiences, rather than through reading literature related to the science of motor learning.

When Adams\textsuperscript{46} published a theory of motor learning, much attention and research was generated to investigate his theory. Adams’ closed loop theory was based on learners receiving both ongoing intrinsic feedback arising from the proprioceptive system, as well as extrinsic feedback generated as a consequence of one’s actions. The closed loop theory also included two different forms of memory as critical components. Later, Schmidt\textsuperscript{47} proposed an open loop theory that incorporated two memory structures termed the motor schema and the motor program. Schmidt’s theory is particularly relevant for skills that are performed either so rapidly or automatically that intrinsic proprioceptive feedback critical to Adams’ closed loop theory is not used for deliberate control processes.

Over the past 25 years, the theories of motor learning advanced by Adams and Schmidt have led those studying motor behavior to consider theories of motor control. Specifically, the debate of whether movements were controlled centrally or peripherally was a spark that kindled interest in contemporary motor control issues.\textsuperscript{2} This debate generated increased understanding of how different types of movements are controlled, and subsequently how different types of movements might be learned. Feedback is essential for learning, but may not be necessary for the performance of well-learned tasks.

**Current Issues in the Study of Motor Learning**

Four contemporary issues are presented to demonstrate the importance of motor learning research to physical therapists. These include the difference between motor performance and motor learning, the appropriate use of feedback, the impact of practice schedules, and the transfer of learning across tasks and conditions of practice.

**Performance and Learning**

An issue of importance to physical therapy is the differentiation between performance and learning. Performance can be observed, learning cannot. Motor learning is an internal process associated with practice or experience that produces a relatively permanent change in the capability for motor skill.\textsuperscript{2} Although we help our patients learn motor skills, generally, as therapists we are more familiar with variables that affect performance than variables that affect learning. Some of the familiar performance variables known to evoke temporary effects are fatigue, head turning that evokes a reflexive response, or an audience watching the patient perform. Learning variables, in contrast, continue to influence performance after they are removed.
Feedback

Extrinsic feedback represents information concerning performance supplied to the learner. Feedback is necessary for learning. The relative frequency with which feedback is supplied to the learner is an area of research that is germane to physical therapists. Current research suggests that contrary to what might be predicted, a relatively low frequency of providing feedback enhances learning.\(^2,48\) This is true despite the fact that performance might suffer during periods of low frequency feedback. Additionally, Weinstein has shown that the fading of feedback, or progressively decreasing the rate with which feedback is given, appears to be most effective in promoting learning.\(^49,50\)

The fading of feedback is contrary to customary practice in physical therapy in which more feedback often is considered better, particularly if performance is not up to standard. It has been suggested that the reason individuals learn better with less feedback is they do not become as dependent on feedback, rather they engage in processes that enable learning, such as reviewing their last performance of the task, and determining for themselves what should be done to improve the next performance of the task. If learning involves an improved capacity to perform a skill, opportunities to self-assess and then take corrective action are integral components of success in acquiring skills.

Practice Schedules

Among motor learning researchers, the terms blocked practice and random practice are used to denote two different practice schedules. Blocked practice refers to consistent practice of one task. Random practice means varying practice among a group of distinctly different tasks. It appears that varying practice among different tasks is more effective in promoting learning than concentrating on a single task.\(^51\) Schmidt and Lee suggested that the recall of tasks inherent in random practice seems to assist with processes that ensure learning.\(^2\)

Transfer of Learning

A final issue that arises from the motor learning research literature that is of great importance to physical therapists concerns the transfer of learning. There are two distinct types of transfer, from one task to another and from one learning condition to another. Many of our traditional neurophysiologic approaches emphasized the practice of early-appearing developmental tasks which were thought to positively affect the ability to perform later-appearing higher order tasks. For example, performance of prone extension patterns was considered fundamental and a prerequisite to the normal performance of standing. General motor abilities such as stability or extensor antigravity control, which developed in prone extension, were hypothesized to be essential to normal performance of standing. Yet, research into the existence of general motor abilities that might underlie the transfer of skill from one task to another has indicated that such transfer is very small, if it exists at all.\(^2\)

Motor Learning Theory Applied to Physical Therapy

Because physical therapists are increasingly becoming aware of the research findings of motor learning, there is an increasing trend for therapists to view their role with patients as a teacher of motor skills. This perspective is apparent in the publications of Carr and Shepherd,\(^52,53\) Weinstein,\(^48-50\) and Shumway-Cook and Woollacott.\(^54\) With the acceptance of the role of teacher comes a concern for the basic principles of motor learning and a reexamination of the traditional guiding hypotheses of physical therapy.
A common experience of therapists is that some traditional treatment procedures such as facilitation and inhibition of reflexes affect performance at the time they are applied, but have no lasting effect. The differentiation between treatment procedures that affect learning and those that affect performance should lead to more considered and appropriate use of intervention procedures and more effective outcomes.

Understanding that feedback is necessary for learning provides a different perspective on therapy sessions. In the past, feedback appears to have held a motivational role in therapy, being used as an incentive for continued participation in practice sessions. While the idea of withdrawing hands on facilitation to promote increased volitional participation is a traditional practice, the idea of withdrawing feedback to enhance learning is not. Winstein's finding, that the fading of feedback enhances learning, is important for the way we work with our patients during practice sessions. In general, we need to allow patients the opportunity to judge and correct their own performance. Accurate and timely feedback given in a frequency designed specifically to promote learning should become standard practice.

Issues related to the transfer of learning are very relevant to therapists. In traditional approaches, much time is devoted to practicing lower order tasks that are considered to positively affect performance of developmentally later-appearing tasks. Motor behavior research suggests that to the extent that the tasks are different, this practice is ineffective. Transfer between tasks appears to be dependent on the similarity between the tasks. Further, the similarity seems to rest within the elements that define motor programs. When motor programs differ, transfer of training from one task to another is quite small. Thus, the relative timing and phasing of muscle activity within a motor program is quite specific. Practice of one motor pattern is unlikely to transfer to performance of a different pattern.

How does what we know about transfer of training affect our practice as therapists? There are times in therapy when performance of the task is the primary objective, and little concern is directed toward which movement patterns are used to accomplish the task. There are other instances when patients demonstrate a stereotypic set of postural or movement patterns, and the objective of treatment may be directed toward the patient being capable of performing a very specific movement pattern. In this latter example, it is important to state clearly which pattern is the objective of treatment. And, practice must be structured to allow the patient to acquire that specific pattern.

In summary, the research findings of motor learning provide useful information for the therapist who accepts the role of a teacher of motor skills. The way we structure practice, provide feedback, and even the way our treatment objectives are stated can be influenced positively by knowledge gained through motor learning research.

**Motor Development—An Overview**

The roots of motor development as a specialized area of study can be found in the work done early in the past century by developmental psychologists and physicians. These individuals described the sequential acquisition of motor skills in infants and young children. Studies were conducted that examined the relative contributions of maturational and environmental factors to the process of age-related change in behavior. The pioneers of motor development were influenced by the motor control and learning theories of their times. For example, McGraw studied the neuromuscular development
of infants to look for the onset of cortically mediated volitional control over subcortical reflexive behaviors.\textsuperscript{55} She further studied the relative roles of maturational and experiential factors on the motor skill development of a set of twins.\textsuperscript{56,57}

The field of motor development has been defined as an area separate from developmental psychology since World War II when psychologists abandoned the study of motor development, preferring to focus on the development of cognitive skills.\textsuperscript{58} Professionals in physical education, medicine, and health disciplines including physical therapy became more involved in defining and studying the problems associated with age-related changes in motor behavior.\textsuperscript{59-61} Generally, this second generation of motor development researchers was interested in development of infants and children, although some adopted a broader perspective involving life span changes in motor behavior.

Traditional theories of motor development paralleled traditional concepts of motor control.\textsuperscript{61} In fact, the classic hierarchical model of CNS organization, originally proposed as a model of neural evolution,\textsuperscript{62} laid the groundwork for developmental theory. Processes of hierarchical integration and progressive differentiation incorporated in Jackson’s notion of neural evolution are evident in the work of McGraw.\textsuperscript{55} These processes were proposed as fundamental to changes in organismic developmental theories.\textsuperscript{63}

For about 25 years following World War II, motor development researchers tended to focus on describing the product of motor development. These products included performance measures on standardized tests of skill performance, including features such as how far and how fast children of different ages were able to throw a ball and run.\textsuperscript{59} Studies during this period carefully described the movement patterns used by children to perform a variety of motor skills.\textsuperscript{64} In the 1970s, the influence of information processing models of motor control began to be seen in the study of the development of motor skills.\textsuperscript{65,66} The information processing approach to motor development incorporates a variety of memory structures that are similar to schema and motor programs. Because feedback is an integral part of these models, they are equally well suited for and applied to the study of both motor control and learning processes.

Recently, a resurgence of interest in motor development appeared within psychology. This seems in large part to be due to the influence of dynamical action theory applied by Kugler, Kelso, and Turvey\textsuperscript{67} and Thelen.\textsuperscript{68} Their work seems to have given impetus to application of the systems theoretical perspective to infant motor development.\textsuperscript{69-71}

**Current Issues in the Study of Motor Development**

The issues in motor development that impact the practice of physical therapy include the concept of motor development as a lifelong process, a greater understanding of developmental sequences, new information concerning prenatal development of movement abilities, and the use of systems theory, particularly dynamical action theory, as a tool for research and expansion of our understanding of motor development.

**Motor Development as a Lifelong Process**

The concept of life span development had its beginnings among developmental psychologists who continued to study their young subjects well into adulthood.\textsuperscript{72} The life span concept appeared in the motor development literature in the late 60s, and now there are an increasing number of contemporary texts that adopt what is called a life span
approach to motor development. Roberton has rightfully pointed out, however, that few of these texts included chapters that cover a single topic across the life span. Rather, chapters tend to be devoted to different phases of the life span. To a large extent, this would seem to result from the paucity of research conducted from a life span perspective. It is easier to gather studies of different phases or age groups and report on them as representative of a particular period within the life span. It is more difficult to integrate the findings of studies of a single function that are carried out under a variety of conditions with representation of age groups.

We are beginning to accumulate a body of literature generated using a life span developmental perspective that describes age differences in motor performance of functional tasks. The tasks of rising to standing from the floor, rolling from supine to prone, rising from a chair, and rising from bed have been studied in a variety of age groups. Because the conditions under which the subjects perform have been kept consistent across the age groups, reasonable comparisons can be made across a wide portion of the life span. We have charted the incidence of different movement patterns used to perform these tasks from early childhood through later adulthood. The results of these studies indicate that age differences in movement patterns can be expected across the life span. We have discovered that variability in performance differs with age and with activity level. Currently, the relationship between body dimensions and motor performance in these tasks is under investigation. This line of inquiry is particularly well suited to life span study. Physical growth is a well-accepted correlate of childhood motor development. Body dimensions and movement patterns used to perform functional righting tasks demonstrate a variable relationship across the life span. The increase in weight that commonly occurs during the middle adult years alters the shape of the body and may well influence the form of functional movement patterns long after the physical growth associated with early years is finished.

The patterns of change in movements used to perform functional tasks do not entirely support the traditional concept of developmental progression during childhood to maturity in young adulthood, followed by regression during the middle and later adult years. The variable patterns of movement suggest that patterns of change in motor behavior may be more complex than the simple progression and regression hypotheses would suggest. Much is to be learned from a life span perspective toward motor development. This information will impact our expectations for individuals of different ages who require physical therapy services.

Developmental Sequences

Developmental sequences take many forms. There are sequences of tasks, such as those described by Gesell and Amatruda and Shirley. These sequences outline the order in which a variety of developmental skills are acquired, such as rolling before sitting, sitting before creeping, and so forth. There also are developmental sequences of body action within performance of a single skill or task. Developmental sequences of body movements within tasks were described by McGraw. She described how the form of body movement changes with age and outlined developmental sequences for several tasks of interest to physical therapists, including rolling, sitting, prone progression, rising to standing, and walking (Figure 2-5). Finally, there are developmental sequences of movement patterns for body regions.

Neurophysiologic approaches to patient care incorporate developmental principles as guides for the progression of patients from states of physical dependency. The predomi-
nant pattern of progression was termed the developmental sequence,\textsuperscript{12} or the skeletal function sequence,\textsuperscript{94} and comprised a sequence of motor skills predominantly selected and adapted from the work of McGraw\textsuperscript{55} and Gesell.\textsuperscript{95} Unfortunately, the ordering of developmental accomplishments was interpreted as though it were the only order for attainment of skills and led to prescriptive use of developmental sequences in physical therapy. Early-appearing developmental patterns were construed as essential preparatory steps for later-appearing functions. According to Knott and Voss “…a recapitulation of the developmental sequence is a means to the end—the ability to care for one’s body, to walk, and to engage in productive work.”\textsuperscript{12} It is worth noting, however, that Knott and Voss recognized that recapitulation of developmental tasks was not the only means to functional competence.

Careful reading of the original descriptions of developmental accomplishments\textsuperscript{93,95-97} reveals that the order in which they are accomplished varies from person to person. This finding raises serious doubts about the prerequisite nature of early-appearing tasks for later-appearing functions. If one person is able to skip a developmental step, then obviously that step is not universally essential for later functional accomplishments. The extent to which early tasks lay a foundation for later skills is a matter of conjecture. Further, if motor learning research can be used to shed light on this debate, one would have to question how performance of early-appearing skills could influence essentially different skills appearing later in development.

Prenatal Development of Movement Abilities

Ultrasonography has allowed a new perspective on fetal development. Rich descriptions of the many varied activities of the human fetus have been made possible by ultrasonography.\textsuperscript{98} Most notably, the concept of an active infant has surfaced.\textsuperscript{99-101} This new concept challenges the older idea that the infant is predominantly passive and dominated by reflexive behaviors evoked by environmental stimuli. As a result, the spontaneous
movements of the young infant are no longer ignored and have become the subject of careful study. The rhythmical patterns of infancy have been interpreted as suggesting the existence of motor programs and central pattern generators. It is not coincidental that the interpretation of these spontaneous movements has rested on concepts common to motor learning and motor control. As in the past, when reflexes were used to explain behavior, now more contemporary concepts of programs and pattern generators are being used to explain infant behavior.

**Systems Theory**

Systems theories also are influencing our understanding of motor development. This influence began gradually but has taken on intensity over the past few years. In 1964, Anokhin, a Russian neuroscientist, characterized neural development as a process of systemogenesis through which different regions of the brain develop at different rates in anticipation of the demand for vital functions. Thus, sets of brain structures collectively function to meet the specific circumstances of the individual in an ecologically appropriate context. Importantly, the ecologically appropriate context for infant development involves an interaction with a mother or caregiver. The functions of both mother and infant are matched to ensure survival and proper development.

This idea of elements collectively functioning to meet the needs of the individual in concert with environmental demands is seen in Milani-Comparetti’s interpretation of fetal movements. He characterized the emerging behavioral repertoire of the fetus as directed toward the process of being born and surviving during the early postnatal period. Thrusting and locomotor movements of the fetus were adapted to the process of birth, in which both infant and mother actively participated. Breathing and sucking patterns were developed prenatally to ensure extrauterine survival. Thus, behavioral systems were envisioned as ecologically appropriate to the context in which the fetus or infant would function.

Two contemporary systems theories are currently being used to explain a variety of developmental processes in infancy and childhood. These two theories are termed perception-action theory and dynamical action theory. Perception action theory has roots in the work of the Gibsons. Perceptual systems are considered critical for any action system. Specifically, motor development is viewed as much a function of perceptual system change as it is a function of change in motor systems.

Dynamical action theory, another example of systems theory, has been increasingly applied to explain motor development. This set of propositions central to this theory were clearly delineated by Heriza. They include the assumption that behavior represents a compression of the degrees of freedom inherent in the complexity of a developing individual. Behavior also is viewed as an emergent property of a self-organizing system. Behavior is constructed in the context of a specific task. Many subsystems of the body and environment contribute to the production of behaviors. There are preferred patterns of behaviors that are termed attractor patterns. Development can be considered to be a series of new behaviors appearing as a series of shifts between attractor patterns. What pushes the system to reorganize and produce a new pattern is termed a control parameter. Control parameters act as catalysts for change. Examples of developmental control parameters may be found in the physical characteristics of the body that change with growth, for example, the length of a limb or the weight of a body part. Control parameters may also be found in other body sys-
tems and in the physical and social environments in which individuals must function. Control parameters gradually change until a point is reached where previous behavioral patterns are unstable and the shift to a new behavioral form occurs. The idea of gradually increasing the scale of a parameter to influence motor behavior was introduced in our discussion of dynamic systems of motor control: change in locomotor patterns can be achieved by increasing the speed of locomotion, causing the system to reorganize behavior from a walk to a run. Similarly, if we reconsider the child in the rocking chair (see Figures 2-4), we begin to appreciate the role of physical growth in the emergence of new motor patterns and the potential application of dynamical action theory to advance our understanding of developmental issues. As one grows, some patterns become impossible, while others are enabled by the changing size of the individual and the changing physical and social environments in which one functions. No longer can motor development be viewed solely as a process of maturation of the CNS. Clearly the physical parameters of the body and its relationship to the physical environment contribute to the emergence of new patterns of motor behavior during development.

**Motor Development Theory Applied to Physical Therapy**

The issues of life span change in motor behavior, developmental sequences, fetal motor behavior, and constructs of dynamical action theory are impacting physical therapy. Because of a new understanding of development as a lifelong process, the concept of age-related change in motor behavior of individuals across the life span is beginning to be more widely appreciated. This broader perspective influences which motor skills and constituent motor patterns are taught to patients. A concern for the range of age-appropriate skills and movement patterns influences therapeutic programs for individuals of all ages.

Careful review of information concerning developmental sequences suggests that they be used less prescriptively. Because there is little information concerning the relationship between early- and later-appearing behaviors, the use of an early-appearing behavior, such as prone extension or creeping, to prepare for a developmentally later-appearing function, such as walking, is not well founded (Figure 2-6). As a result, therapists should carefully consider the manner in which they help patients acquire functional skills. Strict adherence to a developmental sequence as a pattern of progression no longer appears valid or appropriate. Sequences that describe the skills expected at a particular age do, however, outline the functional accomplishments that are expected of infants and children. Some of these tasks, specifically rolling, sitting, rising from supine or sitting to standing, and walking continue as integral elements of physical independence across a wide period of the life span. Each of these skills should be carefully considered when helping patients attain or regain physical independence.

The new knowledge of developmental sequences of body action and movement patterns is beginning to be applied in physical therapy. At present, the most common interpretation of this information is that age-appropriate body actions and movement patterns should be used when instructing patients in performance of functional skills.78,82,86,87

Studies of fetal movement have influenced our perception of infants as active agents in their environments. Such active infant concepts are impacting the behaviors we seek
to evaluate. The evaluation of self-control, as used in the Brazelton neonatal assessment\textsuperscript{115}, the Test of Infant Motor Performance, which includes spontaneous movements\textsuperscript{116}, and the assessment of general movements in infants\textsuperscript{117} are all examples of increasing acceptance of an active organism concept in contrast to traditional assessments that only focused on infant reflexes.

The extension of this active organism concept to our interventions requires recognition that individuals who come to treatment have a role to play in changing their behavior. We need to continue to adopt a model of intervention in which the patient is given active roles in producing action, evaluating feedback, and generating corrective action rather than considering the individual a passive recipient of our procedures.

The impact of developmental systems theories, particularly dynamical action theory, on physical therapy is just beginning to be realized. There is now greater concern for the physical constraints or determinants of motor pattern changes, such as those brought about by physical growth. The short stature of many disabled children may well be a contributing factor in determining which movement patterns are used to perform functional tasks, as is the extra body weight that inactive patients carry. No longer is the CNS considered the sole determinant of developing movements. The question of whether movement patterns emerge or if they are learned as a part of the developmental process continues to be a fertile area for debate and research. Such controversy can only lead to a greater understanding of motor control, learning, and development.

**Summary**

Motor control, motor learning, and motor development represent three different perspectives of motor behavior. The interdisciplinary sharing of ideas and themes in the past
continues to be evident today. Motor control theories are used to explain how the con-
trol of motor behavior is organized. Currently, the concept of muscle synergies or coor-
dinate structures has a central role to play in the organization of motor control. The
impact of these newer control theories on motor development and learning is strong.
The focus on coordinate structures and systems models of organization in each of these
three disciplines is evident. Coordinate structures are envisioned by some as motor pro-
grams stored in memory and by others as emergent properties of the system.

Identification of those variables in a motor program that can be controlled and those
that are fixed has implications for the motor learning theorist. By knowing what is con-
trolled, the motor learning researcher’s question “How is motor behavior acquired
through practice or experience?” begins to be answered.

For the motor development theorist, the question “How does motor behavior change
across long periods of time?” is strongly influenced by current concepts of motor con-
trol. Systems theory, which had its beginnings as a theory of control, is providing a new
understanding of the dynamic relationships in developing individuals among the envi-
rionment and perceptual, musculoskeletal, and nervous systems. Because all of these sys-
tems change across the human life span, there are multiple possibilities for explaining life
span motor development even in individuals thought to be exhibiting stable behavior.
As physical therapists, our understanding of motor behavior is expanded and our
approaches to patient care made more versatile by knowledge of theories of motor con-
trol, learning, and development.

REFERENCES

   1989;41:213-223.
5. Rood MS. Neuropathophysiologic reactions as a basis for physical therapy. Phys Ther Rev.
   1954;34:444-449.
6. Bobath K, Bobath B. Treatment of cerebral palsy by the inhibition of abnormal reflex
7. Brunnstrom S. Associated reactions of the upper extremity in adult patients with hemiple-
10. Eldred E. Functional implications of dynamic and static components of the spindle response
11. Stockmeyer SA. An interpretation of the approach of Rood to the treatment of neuromus-


