Motor learning is a field of study that has essentially been ignored by the sports-medicine and rehabilitation field. It is an area of research that emerged from the desire for efficiency in assembly-line tasks during the industrial revolution but has evolved to focus on the study of any skill acquisition. The investigation of upper extremity skill acquisition predominates the motor-learning literature. There is a paucity of literature on skill acquisition for the lower extremity and virtually no studies on relearning motor skills after injury. The purpose of this article is to present an overview of the field of motor learning and to suggest ways in which the fundamental principles in the motor-learning literature can be applied to orthopedic and sports-medicine rehabilitation.

**Key Points**

- Learning is measured indirectly by performance.
- Motor-skill retention is more critical than a single skill performance.
- Rehabilitation programs can be enhanced in effectiveness and variety by considering task characteristics, practice scheduling, distribution, and feedback techniques.
- Key Words: performance, retention, practice, feedback

**Historical Perspective**

Historically, interest in efficient upper extremity movement patterns was spawned by the industrial revolution in the early 1900s. Business owners wanted optimum performance, seeking ways in which their employees could produce the greatest quantity of work in the shortest period of time. The focus was on evaluating hand movement and limb positioning for optimal work efficiency. Shortly thereafter, between 1910 and 1950, a related yet unique area of study, motor control, developed. Through animal studies, Sherrington provided information on the muscle spindle, opening the door for investigation of possible neurophysiological explanations for the improved performance measured in motor-learning studies. Concurrently, in Russia, Bernstein began his work on motor control, but the work was not translated into English until the 1970s. Yet a third related area developed in the 1950s—motor development. An area of study that is very familiar to those in pediatric rehabilitation, motor development deals with how motor skills are acquired and progress during maturation. After World War II, the Army and Air Force became interested in the field of motor learning and committed scientific and financial resources to study optimal methods to train troops for high-quality and efficient performance of military duties.

By the 1960s there appeared to be three distinct yet related areas of research investigating how humans acquire motor skills. Psychologists were studying the effect of cognitive input on learning. Neurophysiologists were investigating what was happening in the brain and spinal column as motor skills were acquired or as skill levels improved. The field of physical education was combining information on cognitive skill learning from the psychologists and the physiological information from the neurophysiologists and developing practical applications of how to best teach new-skill acquisition.
During the 1970s and 1980s a more structured reorganization of the study of skill acquisition occurred. Specifically, it was divided into motor behavior, motor control, and the psychology of motor learning. Sport psychology and motor learning were combined as the psychology of motor learning. Studies focusing on motor behavior and motor control took on a more scientific profile, whereas studies in motor learning and sport psychology, which were considered to be more applied, were unfortunately referred to as “soft science” and given very little attention. Thus, the principles and knowledge of the field of motor learning were studied and used primarily by physical education instructors and ignored by the world of rehabilitation. It was an unfortunate occurrence because orthopedic and sports-medicine rehabilitation were developing very rapidly during the 1970s and 1980s and, of course, continue to develop today, but rehabilitation approaches and protocols did not consider the body of knowledge provided by the little-acknowledged area of motor learning.

In the early 1990s, Winstein, a physical therapist, tried to draw some attention to the application of motor-learning principles in orthopedic rehabilitation. More recently, Onate has begun focused work on the effect of feedback on the acquisition of motor skills. Nonetheless, the scientific study of how motor-learning principles might be applied in orthopedic and sports-medicine rehabilitation remains in its infancy.

What Is Motor Learning?

Motor learning is a result of input information that is processed by the highly complex human nervous system (central and peripheral). Some type of performance measure is used to indirectly measure the success of a motor-learning intervention. Specifically, Schmidt defined motor learning as a set of processes associated with practice or experience leading to relatively permanent changes in one’s capability for responding. In a similar fashion, Magill defined motor learning as a change in a person’s capability to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice or experience. Thus, it becomes evident that there are inherent difficulties in studying motor learning. The input parameters (the practice criteria) and the output parameters (performance) are measurable. The neurophysiology of the integration process that occurs in the human nervous system, however, is incredibly complex and very difficult to measure. Therefore, although it is possible to measure the cause and effect of the input and output parameters, it is very difficult to pin down the specifics of how and why it happened.

Motor-Skill-Acquisition Continuum

As a clinician begins to work on motor-skill development with an athlete, the expectation is that there will be changes in performance over time. Figure 1 depicts a conceptual model of motor-skill acquisition considering performance across time. Initially, the process of skill learning occurs, but what is more important is skill retention. Retention is defined as the ability to discontinue practice but still successfully execute the motor skill on demand. Finally, there is point at which the maximum threshold for performance has been met, and continued practice would lead to
overtraining, deconditioning, and, ultimately, reduced performance and injury.

Learning

During the early phases of learning, there is a reorganization of the nervous system. The human nervous system must deal with the input of new information and instruction from the selected practice paradigm. That information must be integrated into the central and peripheral nervous systems. Changes can occur in the brain, brain stem, or spinal cord or with the facilitatory or inhibitory interneurons. Feed-forward or feedback loops might be altered as joint, muscle, tendon, ligament, and cutaneous receptors adapt to enhance efficiency and performance. During this time, rapid changes might be seen in neuromuscular-recruitment patterns, posture, or dynamic-movement patterns. These early and rapid changes might be considered the adaptation phase. After the adaptation phase, changes in motor-skill acquisition might continue, but at a slower rate.

Learning is a process that is not directly observable. It is indirectly measured or inferred by measuring performance. It requires adaptation of neural circuits to allow for efficiency of movement. The early phase of learning requires cognitive input. The initial quality of the movement pattern is essential. It requires slow and controlled practice at the early stages of rehabilitation, allowing for reeducation of the feed-forward and feedback pathways.

Most motor-learning research is centered on learning new skills. What remains to be studied is the possible difference in learning or actually motor relearning there might be for clinicians working with injured athletes. Most injuries result in disrupted sensory input that alters both feedback and feed-forward loops, demonstrated by measurable changes in performance. With structures altered by injury, it is unclear whether the progression of learning after an injury is similar to or different from the progression expected when an uninjured athlete is learning a new skill.

Performance

As mentioned earlier, learning is measured by performance. We are most familiar with using outcome measures as performance criteria. That is, we measure performance by how far a ball is thrown or whether an athlete can swim a certain number of laps. Outcome measures are used by insurance companies and often by researchers as measures of successful performance. Production measures have been described in the motor-learning literature but have been significantly underused, as opposed to outcome measures, to measure successful performance. With production measures, criteria for quality of movement can be established. For example, although an athlete might throw the ball an adequate distance, he or she might be using compensatory motor-recruitment patterns to adjust for a weakness in one of the muscle groups in the shoulder or for a lack of core stability. With production measures, performance success criteria could include appropriate recruitment of the scapula stabilizers, scapula rotation rather than elevation, and appropriate mechanics of the shoulder leading the elbow, leading the hand as the ball is thrown a required distance. Researchers have begun to move toward production measures in anterior cruciate ligament injury-prevention studies. Successful jump landing has been defined as landing with the knee over the foot rather than the knee to the inside of the foot (a production measure), whereas in the past success might have been defined simply as the ability to land from the jump (an outcome measure).

Skill

Typically we talk about specific skills; in basketball, for example, we refer to dribbling, shooting, or passing. When considering acquisition of motor skills, we need to shift our frame of reference and consider the components that are imbedded in successful performance and, therefore, learning. Cognitive processing is important, along with problem-solving or perceptual ability. Psychomotor skills such as speed and accuracy are important, and, finally, neuromuscular recruitment in the desired patterns for successful performance is also required.

Retention

To determine whether the approach taken to develop a motor skill has been successful, it is important to have a “retention interval.” This interval is a period of time when no practice strategies are used to work on the skill acquisition. The length of this retention
interval is suggested to be approximately 2 weeks or more, yet there is a lot of variance in the time frame required to accurately measure retention. If the skill was truly learned, the athlete will be able to perform it at a level similar to that before the retention interval. This is the true test of success and is rarely used in the typical outpatient orthopedic setting. Once a patient has reached a performance goal, he or she is usually discharged, and it is assumed that no further intervention is necessary. In reality, there should be a follow-up assessment of skill performance, at which time success would then warrant discharge. In the athletic training setting, this retention interval is seamlessly woven into the program. As an athlete discontinues rehabilitation, the clinician has the opportunity to evaluate performance over time. If performance diminishes, the athlete is then automatically taken back into formal rehabilitation. If the expected performance persists, then rehabilitation is not reinstated.

**Overuse, Deconditioning, and Injury**

If practice persists beyond the time interval needed to learn a skill, overuse, deconditioning, and injuries will begin to set in. The symptoms clinicians will see are muscle and tendon strains, fascial changes, and subtle muscle imbalances that develop as the body attempts to compensate for fatigue and overuse. Altered motor strategies resulting from compensation will lead to tissue breakdown and the repetitive nagging injuries that are so often overlooked and ignored. Eventually the stress and strain of the altered loads result in a pathology that is now considered an injury. Intervention earlier in the overuse process would preserve the motor-learning, retention, and performance parameters needed for successful performance while avoiding the onset of pathology and the required rehabilitation that then ensues.

### The Learning Process

The learning process is complex and can be broken down into phases. The effect of practice on learning has been studied based on task characteristics, the amount and timing of practice sessions, and the effect of feedback during and after the practice sessions. Models have been developed in an attempt to define skills.

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**Skill-Acquisition Models**

Researchers have proposed models in an attempt to simplify the understanding of skill acquisition. The general motor program proposed more recently by Schmidt has longevity, and a dynamical systems model has been embraced by many (see the sidebar).

**General Motor Program Model.** Schmidt developed the concept of the general motor program during the 1970s. In an attempt to define skills, Schmidt divided the components of skill into invariant features or parameters. Three characteristics of a skill were considered invariant: the order of events, phase or relative timing, and relative force. The order of events addressed the possible order of muscle contraction. The relative timing suggested that if a muscle were active for a similar time period during the total duration of an activity or if two muscles were active in a similar time pattern during an activity, then the two events were the same skill. Relative force was the third descriptor of a skill in which the amount of muscle force produced remains in constant proportion from movement to movement. Parameters for a given skill then considered the overall duration of the event, the overall force of the event, and the muscle selection (right side vs. left side). Thus, the parameters were allowed to vary while the invariant features remained constant. Therefore, to determine whether a movement pattern was the same or a different skill, one must consider both the invariant features and the parameters of that skill. For example, if you throw a ball a short distance or a long distance, a similar muscle-firing sequence would be used, and relatively speaking, certain muscles would be active for similar amounts of time relative to the total duration of the...
throw or relative to each other, and the force required to throw the ball would be proportional to a long or short distance. Because of the nature of short and long throws, however, the parameters might vary with the overall duration of the event, overall force, and whether or not the right or the left side was used, but these would not change the skill based on the invariant features.

**Dynamical Systems Model.** The three characteristics of a skill in the dynamical systems model are self-organization, stability, and constraints. The concept of self-organization suggests that information in the environment interacts with the dynamic properties of the body and limbs to produce motor skills. The stability component suggests that a system prefers stability and that a stable system will return to a stable state after perturbation. The dynamical systems model suggests that when certain constraints are placed on the system (organismic, task-related, environmental), the system (the body) will deal with those constraints in the most efficient manner. For example, a clinician would create a situation using organismic (the body), task, and environmental constraints to produce the desired skill (movement pattern). Thus, the clinician would work with an athlete and select the appropriate amount of resistance, appropriate body position, and appropriate working surface to produce the desired outcome. Considering a goal of single-foot balance, the clinician could change the surface from a tile floor to a minitramp. The athlete could be level with the floor or on an incline and could throw a tennis ball or a medicine ball against a rebounder. Thus, maintaining single-foot balance on a level-surface, tile floor while throwing a tennis ball is the same skill as single-foot balance on a minitramp while throwing a medicine ball against a rebounder. The movement-therapy groups such as Feldenkrais® and Alexander adhere to these principles. In this example, an individual who is having difficulty with shoulder abduction might be placed supine on the floor. The body and arm would be supported by the floor, which provides postural stability. Gravity is eliminated, reducing the constraints to movement while allowing the body to work on the mechanical interaction of the scapula and the humerus at the gleno-humeral joint.

**The Phases of Learning**

Learning is thought to occur across three phases. Initially, in the cognitive phase, an athlete must think through the movement pattern, concentrating on the appropriate sequence of activities. As learning progresses, less cognitive attention is required for the learned task. Now the athlete is progressing to the associative phase. As learning is nearing completion, the athlete is capable of executing the skill without thinking at all about the components of the overall movement pattern, and the movement or skill becomes automatic. In the interest of achieving the final outcome of automaticity, clinicians often do not allow athletes adequate time for the cognitive and associative phases. Thus, athletes perform poorly after a retention interval, and the motor-learning process must begin again.

**Task Characteristics**

Motor-skill acquisition can be approached based on the type of skill to be learned (see the sidebar). Skills that are continuous (i.e., have no beginning or end), such as running or biking, should be practiced in a continuous fashion rather than broken down into arbitrary components of the movement pattern. Skills that have a defined beginning and end point, such as a tennis serve, are called discrete skills. Practicing the skill in its component pieces is encouraged. Similarly, it is recommended that serial skills, which are considered series of linked discrete-movement patterns, such as a basketball layup, be practiced similarly to discrete skills, addressing the component pieces of the skill.

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### Task Characteristics

**Continuous skill:** movement with no identifiable beginning or end  
**Discrete skill:** movement with a defined start and end  
**Serial skill:** a series of linked discrete movements  
**Open skill:** movement occurring in an a changing environment  
**Closed skill:** movement occurring in a constant environment
Skills can be characterized as either open or closed, depending on their relationship with the environment. An open skill such as playing soccer occurs in a changing environment. Thus, the skill should be practiced across a series of environmental conditions, such as taking an open shot and trying to shoot while being closely guarded. A closed skill occurs in a constant environment, for example, swimming, and therefore does not require consideration of variable environment influences in the training paradigm.

Practice Organization

The components of practice have been studied to determine approaches that would best support efficient motor-skill learning. Practice distribution, practice scheduling, skill characteristics, and use of feedback have all been studied (Table 1). Successful practice is the approach that most successfully produces learning retention and not performance. Thus, an athlete’s performance might initially be poor with some of these approaches, but the enhanced retention of the skill over time is far more important than single bouts of peak performance. The ability to recognize errors and correct them might be more valuable than actually “perfect” practice. The concept of “learning from one’s own mistakes” is evident in the motor-learning literature in regard to the benefits of practice organization and feedback.

Practice Distribution. Practice situations in which one skill is practiced over and over again, without interruption, are called mass practice. This is often used when practicing foul shots for basketball. A distributed practice session enhances retention of a skill, however, so a more appropriate way to practice foul shooting might be to have timed stations in the gym with athletes working on dribbling at one, foul shooting at another, and layups at yet another and rotating through the stations. In a similar fashion, perhaps in a rehabilitation paradigm one should consider initially rotating components of the program, promoting distributed practice of the skill-reacquisition process. For example, a clinician might want an athlete to complete three balancing activities, three strength activities, and three endurance activities. Rather than having the athlete work all three balancing activities in a row, alternate between one balancing, one strength, and one endurance activity three times.

Practice Schedule. Motor-skill practice can be scheduled in several fashions. Blocked practice provides for only a single skill to be practiced repeatedly over a given amount of time. Random scheduling allows for this skill to be practiced for the same amount of time, but the practice intervals are much shorter and interspersed with practicing other skills. Of these two, random practice has been found to enhance retention for motor-skill acquisition more than blocked practice does.

Variable practice is highly recommended to support motor-skill retention. A single movement pattern is used, but the environment is changed to challenge the athlete. For example, single-foot balance might be practiced with shoes on or off, on uneven surfaces such as a pillow, on unstable surfaces such as sand, or with the additional challenge of closed eyes. The same single-foot-balance skill is being addressed but is being practiced across a variety of settings.

Contextual interference is yet another excellent tool to enhance motor-skill retention. Contextual interference requires an athlete to be cognitively and

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physically challenged. For instance, in single-foot-balance work, playing hopscotch requires the athlete to continue to work single-foot balance, but simultaneously throwing the rock onto a square or maintaining balance while bending over to pick up the rock challenges the athlete with multitasking while working to perform the single-foot-balancing skill.

**Skill Characteristics.** Practice can be designed to perform the entire movement pattern at once (whole) or to break the movement pattern down into pieces (part). It is recommended that a “whole” practice approach be used with continuous skills and that a “part” practice approach be used with serial or discrete skills. There are three different types of part practice: fractionation—breaking the skill into components, segmentation—adding component parts of the skill one at a time, and simplification—practicing one part of the skill but varying the challenge, such as changing the size of the ball being used. These tools will provide further variety to the practice session.

**Feedback.** There are two types of feedback: internal, derived from the athlete’s proprioceptors, and external, or augmented, which is feedback drawn from an outside source. Augmented feedback might include the use of mirrors, review of videotaped sessions of the movement pattern, or simply auditory or tactile feedback from the clinician. Augmented feedback can initially be used as an adjunct tool in motor-skill acquisition. Athletes can be given feedback on the quality of their movement pattern (production measure) by performing the movement pattern in front of a mirror, or the same movement pattern could be videotaped and then later reviewed by the athlete. Eventually, the goal would be for the athlete to be able to perform the skill correctly without the need for augmented feedback. Thus, the internal, or proprioceptive, system would have taken on the responsibility of sending feedback to the athlete. Oftentimes, clinicians move too quickly from the use of augmented feedback or do not use the abundant variety of augmented-feedback tools available to supplement the rehabilitation progression.

The timing or scheduling of feedback has also been shown to influence motor-skill acquisition. The knowledge of results (KR) is used with outcome performance measures. Here an athlete is told whether the final outcome was appropriate, but no knowledge of the quality of the performance is offered. Knowledge of performance (KP) is used with production measures when the athlete is given feedback on the quality of the movement pattern. For instance, perhaps the athlete was overrotating the trunk or swinging the elbow during a tennis serve. This feedback (KP) enables the athlete to be aware of movement-pattern errors rather than simply knowing whether the serve was in or out (KR).

**Motor Learning and Rehabilitation**

There is a paucity of literature directly relating to rehabilitation and the application of motor-learning principles to skill reacquisition. One of the difficulties is the confounding factor of injury. Most motor-learning studies have used uninjured participants with intact motor systems. It is unclear whether an injured area will respond to motor-learning principles of skill acquisition in precisely the same way that an uninjured area would. With injury, both the feedback and the feedforward information loops might be altered. This might occur with minor injuries and might have an additive affect with repetitive injuries. Once an athlete has been injured, it is understood that the injured area must regain motion, strength, and endurance to allow for return to sport participation. The difficult part of rehabilitation is first determining what structures needed for skill acquisition might have been damaged, such as the proprioceptors in the ligaments of a sprained ankle. The clinician must first reactivate that feedback loop for lower level activities such as postural support and activities of daily living before progressing to higher level sport-related movement patterns. For example, it might be assumed that once pain on weight bearing has been resolved and mobility has returned to the ankle, the athlete is weight bearing symmetrically across both ankles rather than standing predominantly on the uninjured side. It is often necessary to retrain the athlete to use both feet in stance, rebalancing the postural presentation before continuing with other weight-bearing activities that would simply reinforce the asymmetry in stance developed as a result of the injury. As more research focuses on injury and subsequent skill reacquisition, the motor-skill-acquisition continuum (Figure 1) might be revised to represent a motor-skill-reacquisition continuum, reflecting more time required during the adaptation phase of learning.
Summary

Clinicians might want to consider the multifaceted principles of motor learning when structuring their orthopedic and sports-medicine rehabilitation programs. Greater emphasis on the motor-learning goals of learning and skill retention should be addressed early on in the rehabilitation phase to establish and enhance a good foundation from which to progress the rehabilitation, using overload principles for strength, power, and endurance, followed by specificity of training. Using motor-learning principles can enhance the variety of approaches to practice and reinforce skill acquisition with retention. Increasing the focus and time spent on fundamental motor-learning principles early in rehabilitation might very well enhance skill acquisition after injury and help reduce reinjuries caused by incomplete rehabilitation.

References


Marjorie King has 20 years of clinical experience in a variety of orthopedic and sports-medicine settings. As the director of athletic training graduate education at Plymouth State College, she will continue her work in core stability and motor learning.