# Motor Learning Following Stroke

## Mechanisms of Learning and Techniques to Augment Neuroplasticity

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**KEYWORDS**

• Motor learning • Neuroplasticity • Training • Stroke rehabilitation

**KEY POINTS**

- Sensorimotor impairments after stroke, such as weakness, spasticity, and decreased interjoint coordination, often cause limited use of the more affected side in daily activities.
- Motor learning (ML), or improvement in the ability to perform a skill, results in experience-dependent neuroplasticity, which is critical for those with motor deficits after stroke.
- Theories of motor control and ML inform stroke rehabilitation interventions by providing insight into the development of coordination and the effects of multiple factors on skill acquisition.
- Instructional language, augmented feedback, and practice conditions impact ML and should be carefully considered in interventions focused on skill reacquisition after stroke.
- Adjunctive strategies such as mental practice and neurostimulation techniques have been shown to improve ML for stroke survivors when combined with motor training.

## INTRODUCTION

Sensorimotor deficits following stroke often result in loss of independence and are a leading cause of long-term disability.[1,2] These impairments can include weakness, spasticity, and reduced interjoint coordination. Loss of normal muscle tone and function can result in reduced functional range of motion, leading to soft tissue abnormalities such as tendon shortening and contracture.[3] Limb movements are characterized

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by abnormal velocity profiles with reduced movement speed and smoothness and are often limited by co-contraction and difficulty decoupling movements between joints.[4] Abnormal flexor synergy patterns limit functional reaching space, leading to compensation with the trunk to access objects in the environment.[3] Impaired proximal control of the arm leads to an overhand grasping strategy, and dexterity is often limited by flexor coupling between the fingers and thumb.[3] Sensory impairments, such as loss of touch and proprioception, can also limit function and lead to increased difficulty engaging in daily activities.[3,5]

Motor recovery, which is often a goal in stroke rehabilitation, refers to the return of normal movement patterns that were present before the stroke.[6] This can be differentiated from compensation, which involves the development of new movement patterns that typically have lower efficiency and quality of movement.[7,8] The amount of motor recovery that occurs varies between individuals and is associated with clinical factors such as stroke severity, time poststroke, corticospinal tract integrity, poststroke depression, comorbidities, genetics, and quality of rehabilitation.[9] As an individual attempts to regain independence after stroke, there is potential for both motor recovery and the development of compensatory movements. As functional skills are relearned, new neural connections are created through synaptogenesis based on experience.[6] Movement compensations are commonly used to overcome daily obstacles. This can lead to learned nonuse, in which the more affected limb is not engaged functionally, or learned “bad-use,” in which maladaptive movement patterns are developed and become habitual.[10,11] Further disability can then occur in the more affected side due to lack of use and preference for the more functional limb. These changes in behavior drive neuroplasticity mechanisms to further limit use of the more affected side, as new movement patterns become neurologically ingrained.[6] Although skills can be relearned after stroke, increased numbers of repetitions are often needed for skill improvement compared with healthy individuals.[12] Additionally, spasticity may obstruct skill reacquisition.[13] To address these issues, motor learning (ML) principles have been used to guide stroke rehabilitation interventions to further enhance neural reorganization and support recovery.[4,6,14,15]

## DEFINITIONS OF MOTOR LEARNING AND SKILL ACQUISITION

ML can be defined as a change in one’s ability to perform a skill that results from practice or experience and can be demonstrated by improvements in speed and accuracy.[16] As performance becomes more stable in response to internal and external stressors, it can be generalized to different environments and situations, becoming less cognitively demanding with improved automaticity.[16] Although learning cannot be directly measured, ML is often inferred through retention and transfer tests. Motor skill retention is tested after a period of no practice to determine the persistence of the skill. Transfer tests determine the adaptability of the skill to new conditions by testing a variation of the skill or by testing it in a new context.[16,17] According to Krakauer and colleagues, different types of ML include sequence learning, novel skill acquisition, motor adaptation, and improvements in motor acuity.[18] Much of adult ML involves assembling new sequences of movements from coordination patterns that have already stabilized.[19] Daily activities are composed of sequences of motor skills that are linked together in order to achieve a task goal.[18,20,21] Coordination patterns for these underlying motor skills (grasp, reach, and transport) are acquired during childhood and then are incorporated sequentially to complete complex daily activities.[19,21] Cognitive processes are also required to efficiently organize performance and ensure that task goals are effectively met.[18,20] ML can also involve the acquisition of novel movements in which coordinative structures have not yet been developed.[16,18,19] This requires the learner to navigate numerous movement options to determine an efficient and effective method of executing the task.[22] In contrast, motor adaptation refers to involuntary adjustments that are implicitly made to maintain motor performance in response to perturbations from the environment.[18] Finally, ML can reflect improvements in motor acuity, or movement quality, such as accuracy and precision.[18] Kinematic measures can be used to quantify movement quality and compare normal patterns of movement with those that are impaired.[8]

## CONSIDERING THEORIES OF MOTOR CONTROL AND MOTOR LEARNING IN STROKE REHABILITATION

Many stroke rehabilitation interventions are informed by theories of motor control and ML, which aim to explain the production of coordinated movement and the process of skill acquisition within the context of various types of motor skills in diverse environments.[15,16,23] Here, we provide an overview of selected theories; for a full account of motor control and ML theories, please refer to Magill and Anderson[16] or Schmidt and colleagues.[24] Dynamical systems theory is a relevant theory of motor control for stroke rehabilitation. This theory states that coordinated movement patterns emerge through self-organization in response to interactions among multiple systems. Stable, energy-efficient coordination patterns are developed, which the individual will return to, following perturbation from the environment.[16,25] Skilled movement occurs through the development of functional motor synergies, where stable patterns of behavior emerge and are adapted based on the task goal.[26] Newell's complementary theory proposed that optimal coordination patterns result from the constraints of the individual, the task, and the environment; although some of these movement patterns are developed at an early age, others can be learned through intensive practice.[16,19,27] Similarly, in Gibson's theory of affordances, the individual's perception of the environment guides the development of coordinated movement patterns, based on the fit between the environmental characteristics and the individual performing the task.[16,28] This is relevant for stroke rehabilitation as lack of fit between the natural environment and the motor capacity of the individual may lead to limited arm use during daily task performance, resulting in further reductions in arm function.[29]

Theories of ML have also focused on the process of skill acquisition, which is crucial for individuals after stroke who must relearn to perform daily activities. Different models have been proposed to describe the stages of learning a new motor skill. Fitts and Posner developed a classic 3-stage model that includes cognitive, associative, and autonomous stages, whereas Gentile describes 2 stages of learning (**Fig. 1**).[30,31] In both models, early stages are characterized by greater cognitive demand as the performer must learn the basic movements required for the task while determining relevant environmental characteristics. Explicit learning processes (ie, verbalizable knowledge) are involved in understanding the goal of the task while implicit processes guide production of appropriate forces to complete smooth, efficient movements.[32] Importantly, for individuals with stroke, explicit instructions may interfere with implicit learning and have a negative impact on skill acquisition, so instructions and cues should be carefully considered.[33] In later stages of learning, movements have increased consistency and automaticity; reduced cognitive demand and improved efficiency allow for generalization to different conditions and situations.[16,30,31] Although the early stages of ML are more commonly studied after stroke,[17] it is important that the later stages of learning be attained; increased use of the more affected side during daily performance is unlikely

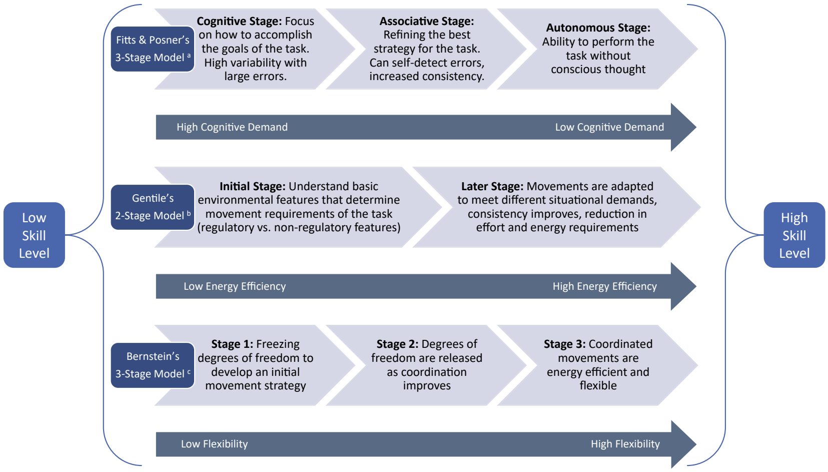


**Fig. 1.** Stages of ML.[a]Fitts and Posner.[30] [b]Gentile.[31] [c]Bernstein.[22]

unless skills can be completed with a satisfactory level of effectiveness and efficiency.[29,34,35]

Bernstein focused on the development of coordination during skill acquisition, noting that when learning a novel skill, learners reduce (or "freeze") degrees of freedom to limit the number of potential movements, resulting in movements with less efficiency and flexibility (see **Fig. 1**).[22] As coordination develops, functional motor synergies enable adaptation to different environments and contexts.[26] Based on these ideas, Newell suggested that ML is hierarchical, and skill optimization is preceded by the development of coordination and control.[19] Although healthy adults have already developed functional synergy patterns needed to carry out common tasks, new coordinative structures must be developed when learning novel skills, such as those in sports. Recently, Otte and colleagues proposed a new framework for skill development in sports that integrates Newell's stages of ML with the concept of periodization, in which training variables are systematically organized to optimize performance according to skill level, cognitive effort, and environmental demands.[36] This framework incorporates ML principles into a longitudinal training paradigm that addresses coordination, skill adaptability, and performance.[36] Although there are clear differences between sports training and motor recovery after stroke, both involve the development of functional synergy patterns that enable effective and efficient performance of a variety of skills in complex real-world situations. Specifically, for upper limb use after stroke, functional movement primitives must be performed with adequate coordination to be able to complete the wide variety of skills that comprise complex daily tasks (**Fig. 2**).[21]

Additionally, the importance of intrinsic motivation in ML has recently been emphasized in the OPTIMAL theory of ML, in which ML is enhanced by supporting autonomy, expectations for success, and focus on the task goal.[37] As individuals with stroke have reported decreased motivation to use their more affected arm in daily life,[34] incorporation of factors that support intrinsic motivation may be beneficial in stroke rehabilitation.[23,38]

## NEUROPLASTICITY AND MOTOR LEARNING

Regardless of the stage of learning, the process of learning involves changes in neural connections in the brain. Thus, what we do in stroke rehabilitation needs to be

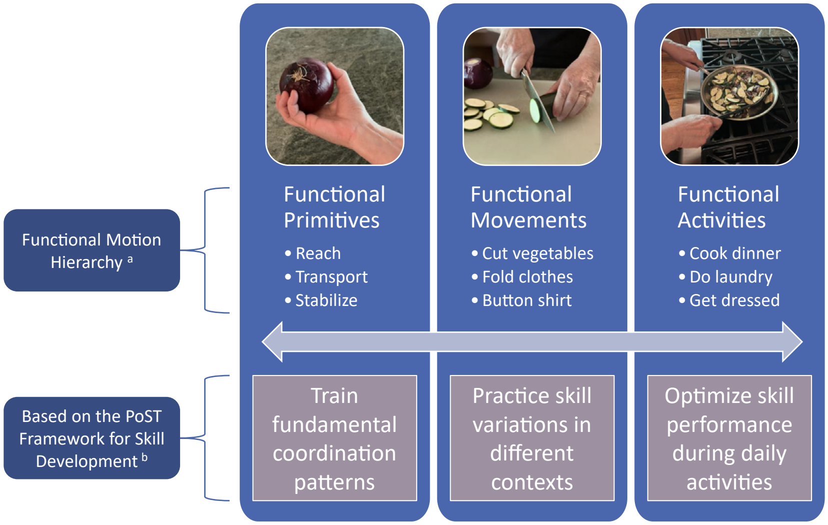


**Fig. 2.** General structure of a practice method for upper limb rehabilitation after stroke. [a]Schambra and colleagues.[21] [b]Otte and colleagues.[36]

carefully considered in light of neuroplasticity. Neuroplasticity refers to the ability of the nervous system to reorganize based on both internal and external experiences.[39] During the critical period after stroke, there is heightened potential for neuroplasticity, and motor recovery can occur both spontaneously and through functional use of the limb.[7] Neural plasticity mechanisms can also induce the development of maladaptive synergies if compensatory movement patterns are learned.[3] To counteract learned nonuse and encourage neuroplasticity that supports motor recovery, ML principles, such as specificity, intensity, frequency, salience, optimal level of difficulty, and feedback, have commonly been applied to stroke rehabilitation interventions.[6,15] Animal studies have suggested that repetitive training of a novel motor skill stimulates neural growth and reorganization of the primary motor cortex, whereas repetition of habitual movement patterns does not.[40,41] Task-specific training in animal studies leads to synaptogenesis, dendritic branching and spine formation, elimination and selective stabilization, and new long-range neural connections.[42,43] Similarly, longitudinal studies of skill acquisition in humans have found that ML results in increased gray matter density in the brain.[42] These findings have informed interventions such as constraint-induced movement therapy (CIMT), which focus on forced use of the more affected limb through task-specific, intensive practice to guide neuroplasticity toward the recovery of motor function.[11] CIMT has been shown to increase gray matter volume in bilateral sensory and motor areas of the brain, along with the hippocampus, which was correlated with increased functional use of the upper limb.[44] More recently, transcranial direct current stimulation (tDCS) combined with motor training resulted in improved ML and increased cortical gray matter volume.[42,45]

Dopamine also plays an important role in neuroplasticity related to motor control, memory, and learning. Dopaminergic neurons from the ventral tegmental area (VTA) that project to limbic and cortical regions via mesocorticolimbic pathways are associated with reward.[46] Animal studies have suggested that stimulation of the dopamine system may improve ML after stroke via dopaminergic projections from the VTA to the primary motor cortex.[47,48] Hypoactivation of the dopamine system after stroke has been linked with impaired ML.[48,49] The dopamine system modulates cognitive control, or the ability to pursue long-term goals. In diseases such as stroke where dopamine transmission is reduced, perceived efforts may be judged to outweigh perceived rewards, reducing motivation for continued engagement.[50] Thus, increasing dopamine transmission may improve motivation by increased perceived benefits and reducing perceived cost, making it easier to pursue long-term goals that require a great deal of effort.[50,51]

## TECHNIQUES TO AUGMENT MOTOR LEARNING AND NEUROPLASTICITY

### *Application of Motor Learning Principles in Stroke Rehabilitation*

ML research with healthy adults has determined numerous principles that guide instruction, feedback, and practice conditions to support optimal learning.[16] After stroke, task-specific practice using the more affected arm has been shown to improve ML and increase activation of the contralateral primary motor cortex, which is not seen when general arm use is increased.[52] Although a great deal of research has investigated the efficacy of stroke rehabilitation interventions, relatively few studies have measured the effects of individual ML principles on the acquisition of a specific skill.[15,17,53] Most of these studies investigate the effects of a single day of skill acquisition on next-day retention for individuals with chronic stroke, often excluding those with cognitive deficits or severe motor impairments.[17] More commonly, ML principles that are advantageous for healthy individuals have been applied in complex interventions aimed at improving general measures of function and capacity.[54] However, as research has also demonstrated differences in skill acquisition between healthy individuals and individuals with stroke,[12,33,55] the benefits of using several ML principles with individuals after stroke are unclear. **Table 1** includes examples of ML principles that have been investigated with individuals after stroke. See Gregor and colleagues for a more detailed analysis.[17]

### *Dosage, Intensity, and Repetition*

In stroke rehabilitation, dosage can refer to the number of hours of practice, the number of repetitions completed, or frequency and duration of practice sessions.[15] Intensity can be defined as the number of repetitions completed within a given unit of time, including the length and number of sessions and their distribution over time.[4] According to Bernstein, repetition is essential because it allows the learner to discover new ways of solving the motor problem; each repetition should be performed with focus on updating and improving the skilled movement.[56] Compared with healthy individuals, individuals with motor impairments after stroke require many more repetitions to acquire new movement patterns.[12] In animal studies of ML, hundreds of repetitions are achieved by depriving the animals of food and then offering a food reward for successful task completion in a setting that prevents compensation, leading to skill acquisition and cortical reorganization.[40,41] Research with human subjects post-stroke has found that repetitive practice of one task can transfer to improvements in other tasks.[57] However, there is not clear evidence that increasing the number of repetitions during task-specific training improves motor function, especially in chronic stroke.[53,54] Thus, precise dosage recommendations for ML after stroke have yet to be determined.[4]

### *Strategies to Augment Motor Learning (Mental Practice/Motor Imagery, Action Observation, Mirror Therapy, Aerobic Exercise, Sleep)*

Specific strategies can be combined with task practiced to enhance ML. Mental practice, or the use of motor imagery to cognitively practice a skill without performing

**Table 1**
**Motor learning principles investigated in individuals after stroke**

| ML Principle | Definition | Application with Stroke |
|---|---|---|
| **Verbal cues** | **Short phrases that direct attention to relevant aspects of the task or key movement patterns**[16] | |
| Explicit instructions | Instructions that increase verbalizable knowledge of the task, such as verbal and written information and rules[16,33] | Explicit information has a negative effect on ML after stroke[17,33] |
| Implicit instructions | Instructions that do not increase conscious awareness of the task being learned, such as movement analogies[16] | |
| External focus of attention | Instructions that direct attention to the goal of the task[37] | No significant differences were found between instructions with external or internal attentional focus after stroke[55] |
| Internal focus of attention | Instructions that direct attention to body movements[37] | |
| **Augmented feedback** | **Information about skill performance that is provided from an external source that adds to the natural sensory feedback available to the performer**[16] | |
| Knowledge of results (KR) | Information about the outcome of the task performance[16] | Both KR and KP may improve ML after stroke[15,17] |
| Knowledge of performance (KP) | Information about movement characteristics related to task performance[16] | |
| Biofeedback | Information about physiologic processes such as muscle activity[16] | Biofeedback may enhance gait retraining after stroke[79] |
| Feedback frequency | Schedule with which feedback is given; lower frequency of feedback improves ML in healthy adults[80] | No significant difference was found between 100% and 67% feedback schedules[17,80] |
| **Practice conditions** | **Variables that influence the way a task is practiced**[16] | |
| Specificity | ML is influenced by the characteristics of the task, including available sensory feedback, the environment, and cognitive requirements[16] | Practicing a single motor task can transfer to improvements in untrained tasks[57] |
| Variability | Changes in the context and movement requirements of the skill that is practiced[16] | The benefits of variable practice compared with constant practice are unclear after stroke[15,17] |
| Constant practice | Only one variation of the skill is practiced[16] | |
| Variable practice | Multiple skill variations are practiced[16] | |

(*continued on next page*)

**Table 1**
**(*continued*)**

| ML Principle | Definition | Application with Stroke |
|---|---|---|
| Practice distribution | The spacing of the practice schedule such the amount of time between sessions or trials and the number and length of sessions[16] | The benefits of massed practice compared with distributed practice are unclear after stroke[15] |
| Massed practice | Practice schedule with a short amount of rest between practice trials where each session involves more trials/ longer duration[16] | |
| Distributed practice | Practice schedule with more time between sessions or trials; sessions are shorted and spaced over a longer period of time[16] | |
| Difficulty | Task difficulty and complexity is progressively increased to provide an optimal level of challenge[15] | Progressively increasing task difficulty may promote ML after stroke[15,17] |
| Problem-solving | Use of problem-solving strategies and guided discovery for skill acquisition[68] | Combining problem-solving with task-specific training may improve transfer to untrained tasks[68] |
| Manipulating degrees of freedom | Limiting the number of joints that can simultaneously move to simplify movement options[16] | Use of a trunk restraint improves reaching performance after stroke[53] |
| Manipulating error | Error can be increased (error augmentation) or minimized (error minimization) during training to elicit adaptation[81] | Error augmentation during split-belt treadmill training may improve step length symmetry[81] |

physical movements, can augment ML and recovery when combined with physical practice for individuals with stroke.[15,17,58] Similarly, action observation involves watching a video demonstrating skilled task performance before practicing the task and has also been shown to promote ML and motor recovery.[15,17,59] Mirror therapy, which involves placing the more affected limb in a mirror box while the mirror reflection of the less affected arm is observed, has also been shown to improve upper limb recovery.[60] Aerobic exercise, such as high-intensity interval training, and sleep following motor practice can also lead to improvements in ML.[17]

### *Modalities to Augment Motor Learning (Transcranial Direct Current Stimulation, Repetitive Transcranial Magnetic Stimulation, Intermittent Theta Burst Stimulation, Vagus Nerve Stimulation)*

Noninvasive brain stimulation techniques such as tDCS and repetitive transcranial magnetic stimulation (rTMS) modulate cortical excitability and can enhance ML when combined with rehabilitation.[17,61,62] Intermittent theta burst stimulation (iTBS) is a newer type of rTMS that may also improve ML and upper limb function after stroke.[17,63] Vagus nerve stimulation (VNS), involving a surgically implanted device, is another emerging treatment that may improve upper limb function when combined with rehabilitation and has been shown to induce plasticity in the motor cortex of rodents.[64,65]

### *Psychosocial Factors*

Stroke rehabilitation interventions often require high levels of motivation and engagement, which may be difficult for individuals with stroke to maintain.[34] Studies that have used extrinsic rewards such as money have demonstrated improved outcomes in motor adaptation, retention, and sensorimotor capacity.[66,67] Participation in intrinsically motivating activities, such as those that facilitate autonomy and problem-solving, may also support engagement in self-directed practice and high-intensity interventions.[23,38] Interventions that encourage problem-solving and decision-making during skill acquisition can transfer to improvements in untrained tasks and improve self-efficacy.[68] Additionally, structuring interventions so that they provide frequent experiences of success during practice may improve motivation and support recovery.[69] Social engagement and confidence in upper limb use have also recently been linked with the amount the more affected arm is used in daily activities, highlighting the importance social context and self-efficacy.[15,70]

## DISCUSSION

Theories of motor control and ML inform many stroke rehabilitation interventions in order to drive neuroplasticity and support skill acquisition.[15] More information is needed on how people with poststroke sensorimotor impairments respond to specific ML principles.[17] Continued exploration of the most effective practice conditions for skill reacquisition following stroke can guide the development of complex interventions and ensure that the correct mechanisms of action are emphasized. Ideally, interventions would both improve underlying motor deficits and increase the skilled use of the more affected side during the performance of daily activities. However, interventions that focus on improving motor impairment often do not improve functional performance, whereas interventions that are focused on the performance of functional activities may have less impact on motor impairment.[14] Task-specific training in natural environments may promote compensatory strategies that lead to the development of maladaptive movement patterns.[15] Repetition of these movement patterns can cause them to become further ingrained and habitual.[4,38] These motor habits may develop within weeks after stroke and can limit future use of the arm even as motor function continues to improve.[71]

In order for skill development to progress once habits have formed, habits must be continually broken and replaced with improved iterations of the skill, which is known as deliberate practice.[72] Deliberate practice is associated with the development of expertise and requires professional instruction to guide optimal skill development.[18,72] Frameworks for skill acquisition in sports organize multiple levels of training within long-term programming, which may support continued skill development by focusing on both fundamental skills and application of those skills during performance.[36] In contrast, stroke rehabilitation interventions often attempt to solve a complex problem by addressing a single mechanism of action.[38] It is possible that multifaceted frameworks for stroke rehabilitation could help guide long-term skill development and support both motor recovery and functional limb use. Longitudinal studies on complex skill development after stroke are needed to assess both movement quality as well as effectiveness and efficiency of real-world skill performance.[8]

In practice, therapy doses after stroke are quite low,[73] and individuals with stroke may think that their services do not provide adequate support for recovery. For instance, they may be told to “just use” their more affected arm without being given any type of program for home practice or adequate feedback.[74] Systematic methods of practice could potentially improve efficiency during therapy time by setting up programming to support long-term self-directed practice. New technologies, such as tele-health, have the potential to support daily practice routines by monitoring activity, providing feedback, and creating environmental adaptations that offer increased opportunities for successful practice.[75] Integrating strategies that enhance ML after stroke, such as mental practice and action observation, into practice routines may also support skill acquisition and recovery.[58,59] Additionally, expanding access to neurostimulation techniques (tDCS, rTMS, VNS) and systematically integrating them into clinical practice may help improve effectiveness of current ML interventions, particularly for individuals with chronic stroke.[61,62,65]

Psychosocial factors such as motivation and self-efficacy may also help drive ML and neuroplasticity. Although motivation is frequently identified as an important factor,[6,15,38] less is known about the effects of motivation on rehabilitation outcomes. For example, although virtual reality and active video gaming interventions are designed to be motivating, constructs related to motivation are infrequently measured, and motivational outcomes are rarely compared among groups.[76] Intrinsic motivation, in which activities are performed for the sake of enjoyment and interest, may also be important for ML after stroke because it encourages curious exploration of the environment and is associated with the dopaminergic rewards system.[37,51] A study of healthy older adults found that giving participants control over the amount they practiced a novel motor task led to improvements on retention and transfer tests.[77] Similarly, when learning a novel surgical skill, medical students who were focused on skill proficiency outperformed those who were prescribed amounts of practice, even though the skill was practiced for similar amounts of time and repetitions.[78] Giving participants control over practice conditions may help elicit intrinsic motivation and stimulate dopaminergic pathways.[37,51] However, although this concept has been applied in complex stroke interventions,[23] the specific effects of self-controlled practice on poststroke ML are largely unknown.

## SUMMARY

Sensorimotor impairments after stroke pose a significant barrier to functional independence. Motor control and ML theories, and the training principles derived from them (ie, verbal cues, augmented feedback, and practice conditions), inform many stroke rehabilitation interventions promoting neuroplasticity and skill acquisition. Evidence suggests that task-specific practice improves ML after stroke and that it may be possible to augment ML by engaging stroke survivors in specific strategies (eg, mental practice, action observation) or through the application of noninvasive brain stimulation. Psychosocial factors such as motivation and self-efficacy may affect ML after stroke, although further research in this area is warranted.

## CLINICS CARE POINTS

- Task-specific training improves ML after stroke, although specific dosage recommendations are currently unknown.
- It is important to address movement quality during motor training to prevent compensatory movements from becoming habitual.
- Although more research is needed to determine effects of different practice variables on ML for stroke survivors, clinicians should be aware that explicit instructions may reduce ML, while augmented feedback may enhance it.
- Strategies such as mental practice and action observation can be combined with physical practice to enhance ML.
- Neurostimulation techniques augment ML when combined with motor training.

## DISCLOSURE

The authors report there are no competing interests to declare.

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