SPECIAL COMMUNICATION

# Basic Concepts of Activity-Based Interventions for Improved Recovery of Motor Function After Spinal Cord Injury

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Spinal cord injury (SCI) is a devastating condition that affects a large number of individuals. Historically, the recovery process after an SCI has been slow and with limited success. Recently, a number of advances have been made in the strategies used for rehabilitation, resulting in marked improved recovery, even after a complete SCI. Several rehabilitative interventions, that is, assisted motor training, spinal cord epidural stimulation, and/or administration of pharmacologic agents, alone or in combination, have produced remarkable recovery in motor function in both humans and animals. The success with each of these interventions appears to be related to the fact that the spinal cord is smart, in that it can use ensembles of sensory information to generate appropriate motor responses without input from supraspinal centers, a property commonly referred to as central pattern generation. This ability of the spinal cord reflects a level of automaticity, that is, the ability of the neural circuitry of the spinal cord to interpret complex sensory information and to make appropriate decisions to generate successful postural and locomotor tasks. Herein, we provide a brief review of some of the neurophysiologic rationale for the success of these interventions.

**Key Words:** Rehabilitation; Spinal cord injuries.



THE CONCEPTS OF neural control of locomotion that underlie the activity-based therapy locomotor training include (1) the level of automaticity of the spinal cord networks; (2) the importance of sensory input to the spinal cord automaticity; (3) neuromodulation of the physiologic state and the learning capacity of the spinal cord locomotor circuitry; and (4) the role of descending pathways in the control of locomotion.

## AUTOMATICITY OF THE SPINAL CORD NETWORKS

The overriding general concept of the neural control of locomotion that makes locomotor training an effective therapeutic strategy is the high level of automaticity of the nervous system.[1-12] The automaticity of the spinal networks is identified by the properties of self-regulation and functioning without volition or conscious control. An essential component of automaticity of motor control is central pattern generating networks that elicit neural activity in response to sensory input that is task specific for posture and locomotion.[2,3,13-25] Effective standing and walking occurs with considerable precision and discrimination without conscious thought, suggesting that there is significant potential for recovery if these networks or their residual components are optimized functionally, even after a severe spinal cord injury (SCI).

### Evidence of Automaticity in Biological Systems

The idea that networks of neurons within biological systems could generate a cyclic motor output is centuries old, as key experiments demonstrating automaticity in the mammalian spinal cord were performed by Brown in 1911.[26] Orlovsky et al[27] hypothesized that each limb is modulated by supraspinal input via groups of spinal neurons called controllers. These controllers respond to a tonic drive from the brain by generating a relatively complex rhythmic pattern that activates the limb musculature in a coordinated pattern to generate locomotion. Shik and Orlovsky[12] proposed a 2-level automatism control system for locomotion. One level provides nonspecific tonic input that determines the intensity of locomotion (speed and grade), while the other is responsible for making fine adjustments in the control of the limbs, including maintaining equilibrium. This fine control system normally interacts with sources of sensory information, such as proprioceptive and visual inputs, to execute fine adjustments in the locomotor pattern (fig 1). These observations[6,7,28,29] were followed by an explosion of studies attempting to define the mechanisms underlying the phenomenon of central pattern generation (CPG).[3,8,30-37]

From a teleological perspective, one might question the concept of automaticity with respect to its usefulness. Similar sensory and motor components among a wide range of animals with vastly different musculoskeletal structures have evolved in a 1G environment in a manner that has enabled postural and locomotor tasks to occur quite automatically among all complex animals.[38] The automatic aspects of these functions reflect successful evolution that enables postural and locomotor responses to be generated by the lower nervous system without relying on more complicated, and probably more unpredictable, delayed decision-making by higher neural centers. A greater reliance on the brain would require additional time and would impose disadvantages in the execution of a variety of postural and locomotor tasks, particularly when the response time is critical for survival. In this sense, evolutionary learning has played a key role in the automaticity of neural control exhibited during the execution of motor tasks. Thus, the nervous system, even without conscious control, demonstrates

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**List of Abbreviations**

| | |
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| CPG | central pattern generation |
| EMG | electromyogram |
| SCI | spinal cord injury |

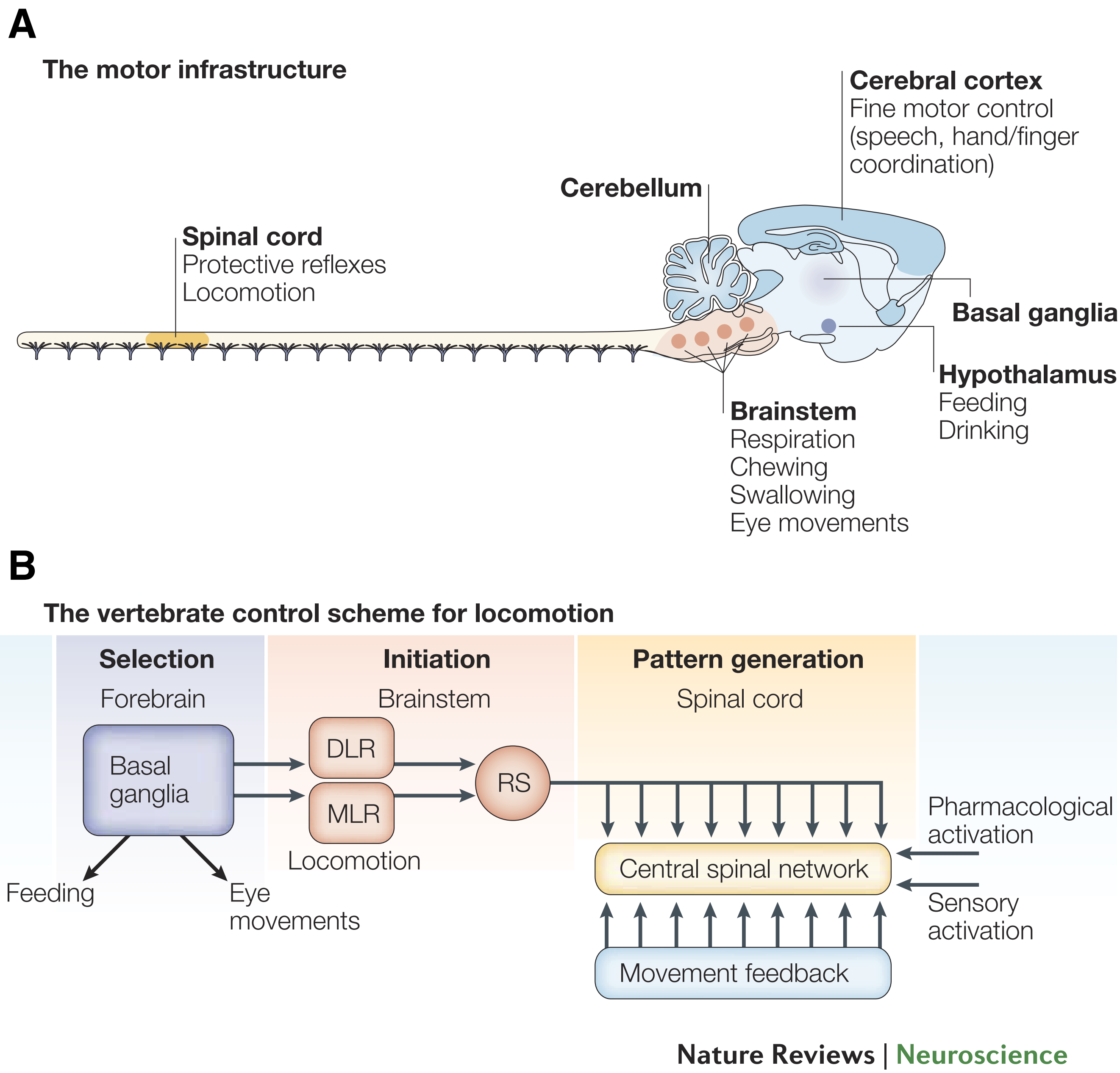


**Fig 1. The motor infrastructure. (A) Location of different networks (CPGs) that coordinate different motor patterns in vertebrates. These areas can coordinate the activation of different CPGs in a behaviorally relevant order. For instance, if the fluid intake area is activated, an animal will look for water, walk toward it, position itself, and start drinking. The cerebral cortex is important in particular for fine motor coordination involving hands and fingers and for speech. (B) General control strategy for vertebrate locomotion. Locomotion is initiated by activity in RSs of the brainstem locomotor center, which produces the locomotor pattern in close interaction with sensory feedback. With increased activation of the locomotor center, the speed of locomotion increases and interlimb coordination can change (eg, from a walk to a gallop). The basal ganglia exert a tonic inhibitory influence on motor centers that is released when a motor pattern is selected. Experimentally, locomotion can also be elicited pharmacologically by administration of excitatory amino-acid agonists and by sensory input. Abbreviations: DLR, diencephalic locomotor area; MLR, mesopontine locomotor area; RS, reticulospinal neuron. Reprinted with permission from Macmillan Publishers Ltd: Nature Reviews Neuroscience. Grillner S. The motor infrastructure: from ion channels to neuronal networks. Nat Rev Neurosci 2003;4:573-86.[39] Copyright 2003.**

a sophisticated level of automaticity and also is smart and highly adaptable or plastic.

## Spinal Cord Automaticity and Plasticity in the Control of Locomotion

Historically, the spinal cord's level of control over postural and locomotor tasks has been substantially underestimated. New insights continue to be gained into the properties of the spinal cord that enable it to execute these tasks, often with minimal conscious supraspinal control. The phenomenon of CPG within the spinal cord has magnified the importance of the concept of spinal automaticity, that is, the ability of the neural circuitry of the spinal cord to interpret complex sensory information and to make appropriate decisions to generate successful postural and locomotor tasks.[38,40] There is a high predict-