MAYO CLINIC

Brain Machine Interface and Limb Reanimation Technologies: Restoring Function After Spinal Cord Injury Through Development of a Bypass System

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Abstract

Functional restoration of limb movement after traumatic spinal cord injury (SCI) remains the ultimate goal in SCI treatment and directs the focus of current research strategies. To date, most investigations in the treatment of SCI focus on repairing the injury site. Although offering some promise, these efforts have met with significant roadblocks because treatment measures that are successful in animal trials do not yield similar results in human trials. In contrast to biologic therapies, there are now emerging neural interface technologies, such as brain machine interface (BMI) and limb reanimation through electrical stimulators, to create a bypass around the site of the SCI. The BMI systems analyze brain signals to allow control of devices that are used to assist SCI patients. Such devices may include a computer, robotic arm, or exoskeleton. Limb reanimation technologies, which include functional electrical stimulation, epidural stimulation, and intraspinal microstimulation systems, activate neuronal pathways below the level of the SCI. We present a concise review of recent advances in the BMI and limb reanimation technologies that provides the foundation for the development of a bypass system to improve functional outcome after traumatic SCI. We also discuss challenges to the practical implementation of such a bypass system in both these developing fields.

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Researchers have spent decades searching for ways to restore function to those with traumatic spinal cord injury (SCI). Development of treatment strategies must begin with understanding how injury affects the nervous system. Injury to the spinal cord prevents cortical signals generated by the brain from reaching target muscles, resulting in

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paralysis. Functional magnetic resonance imaging studies indicate that even after SCI, the brain continues to generate electrical signals in response to an individual's intention to move.[1] Additional studies indicate that electrophysiologic stimuli applied to the muscles, peripheral nerves, or spinal cord, below the level of injury, can generate muscle activity.[2] These discoveries offer a ray of hope in the treatment of SCI if we then conceive of paralysis as an information transfer lesion, where the information sent from the brain via the corticospinal tract does not reach the spinal cord.

To restore limb function to individuals with SCI, this information transfer lesion must be either repaired or bypassed. To date, current research efforts have focused on ways to repair the damaged spinal cord or to prevent further injury after the initial insult to the spinal cord. Transplantation of stem cells at the site of the injury, introduction of tissue-bridging biomatrices and peripheral nerve transfers, and targeting of methods to increase expression of neurotrophins and cytokines via viral transduction are among the strategies being investigated.[3] Although offering promise in the preclinical setting, these investigations have met with limited success in clinical trials. The lack of an adequate animal model of SCI, along with safety concerns associated with some of these therapies,[3] are cited as reasons for the poor translatability of these treatments in humans. Indeed, to date, there has been no report of restoration of limb movement using these biologic repair approaches.

In part because of the limited success of techniques to directly repair lesions due to SCI, efforts have focused in recent years on rehabilitative strategies to restore functional independence to individuals with SCI.[2] Among these efforts are the development of brain machine interface (BMI) systems. The BMI systems capture and analyze information from the brain and then deliver commands to an external device that is then able to perform the function initially intended by the patient.[4] Another strategy involves directly activating neuronal pathways below the level of the SCI lesion. In this way, we can restore function to limbs that can no longer directly receive commands from the brain. This innovative concept, known as limb reanimation, includes functional electrical stimulation (FES) of peripheral nerves or target muscles and epidural stimulation or direct intraspinal microstimulation (ISMS) of the spinal cord itself.[3] By combining the capabilities of the BMI and limb reanimation systems, a bypass of the information transfer lesion in SCI may be created, and the seemingly far-reaching goal of restoring limb function to SCI patients becomes possible (Figure 1). In this review, we discuss current advances in the BMI and limb reanimation systems and discuss how these technologies bring us closer to restoring function to paralyzed limbs in patients with traumatic SCI.

THE BMI SYSTEMS

The BMI systems are designed to restore lost neurologic functions to individuals with SCI, stroke, or a neurodegenerative disorder, such as amyotrophic lateral sclerosis.[4] A BMI first captures the electrical signals generated by the brain when the user intends to move. To operate the BMI system, a user may simply imagine certain actions, such as squeezing the hand or moving the foot, or more complex movements, such as walking. This process, known as motor imagery, produces electrical activations in the regions of the motor, premotor, and supplementary motor cortices. These signals are captured by a variety of techniques, including electroencephalography, electrocorticography, direct recordings of action potentials (known as single-unit recordings), and near-infrared spectroscopy, to cite a few.[4,5] The more invasive systems (single-unit recordings and electrocorticography) provide the best signal quality but do so at the highest risk to the patient. The least invasive systems (electroencephalography and near-infrared spectroscopy) carry minimal risk to the user but yield the poorest signal quality. Signals from such noninvasive techniques may not provide sufficient quality to operate complex devices, such as prosthetic arms or exoskeletons, which require multiple degrees of freedom of control.

Once the cortical signals are captured, they are analyzed using a computer-based algorithm to yield what is known as a *signature*. A signature is a specific pattern of electrical activity, composed of spatial-, temporal-, and frequency-based components, that is unique to a particular imagined movement. It is not necessary that the action imagined by the user correlate directly with the intended result;