Characterization of multisite spinal cord stimulation to improve locomotion in rats with complete spinal cord injury

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EPIDURAL electrical stimulation (EES) of the lumbosacral spinal cord has been shown to improve standing and walking following spinal cord injury in rats, cats, and humans. In these applications, stimulation paradigms were typically composed of continuous EES delivered through one or two electrodes. The potential of EES applied through multiple electrodes at distinct locations and at specific time of the gait cycle remain unknown. Here we introduce an integrated neuroprosthetic system composed of a real-time kinematic feedback and a multi-electrode array covering the entire extent of the lumbosacral spinal cord. The underlying objective was to enable the design of multisite EES paradigms capable of improving movement execution with EES in spinal rats.

We first conducted a comprehensive characterization of the functional effects mediated by each monopolar and bipolar electrode configuration in the multi-electrode array. We found that the recruitment of flexor and extensor muscles depended on the amplitude and location of EES, which correlated with the amount of whole limb extension and flexion. Second, we evaluated the ability of distinct sensory states, such as suspended in the air, standing, and stepping, to modulate EES-evoked motor response in hindlimb muscles. We obtained, for each electrode, a function that linked EES amplitude to a certain kinematic movement based upon limb-dependent position and task-specific feature: hindlimb movement = f (electrode, amplitude, limb state, task).

We next leveraged this mapping to design multisite EES paradigms whereby bursts of stimulation are delivered through specific electrode configurations and at specific time of the gait cycle based on real-time kinematic feedbacks in order to promote near-optimal gait patterns in the otherwise paralyzed rats. We thus developed stimulation algorithms that tuned EES features through 5 independent electrode configurations promoting side-dependent movements of flexion and extension during continuous locomotion. Detailed analysis of kinematic, kinetic and muscle activity revealed significantly increased modulations of gait features and more physiologically relevant stepping patterns during multisite, burst-like EES compared to tonic (continuous) stimulation.

These combined results pave the way towards the development of neuroprosthetic systems to improve the recovery of standing and walking in spinal cord injured subjects.

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