

A Silicon Central Pattern Generator Controls Locomotion *in vivo*

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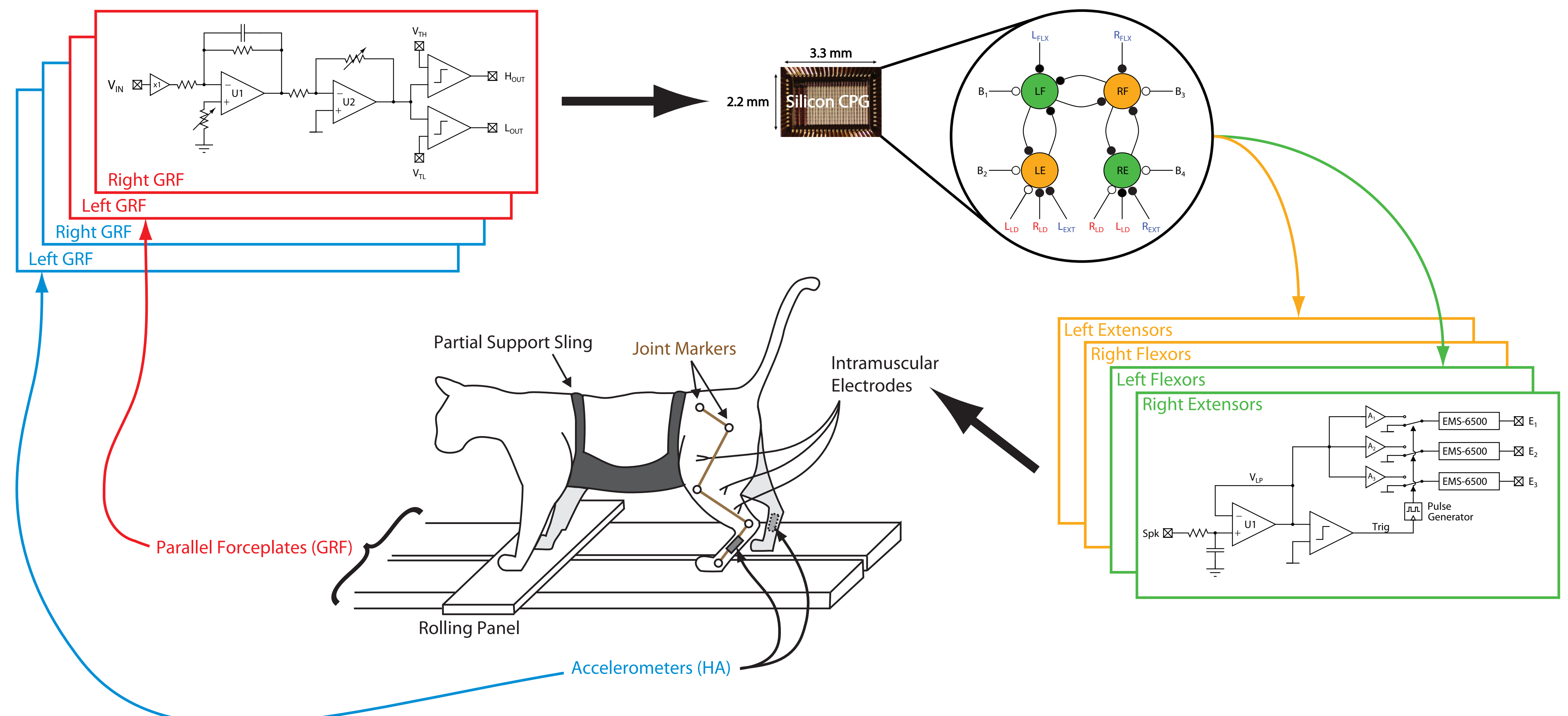
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Abstract

We present the first example of a neuromorphic device that can replace some functions of a component of the mammalian central nervous system *in vivo*. Neuromorphic systems aim to emulate the structure and function of biological neurons with silicon facsimiles. Our neuromorphic central pattern generator (CPG) microchip contains a simple neural network implementing the basic principles governing forward over-ground locomotion. An animal model of spinal cord injury (anesthetized cat) was used to demonstrate the functionality of the silicon CPG. Four on-chip silicon integrate-and-fire neurons were connected to four sets of intramuscular stimulators, each of which controlled three flexor or extensor muscles in the hindlimbs. The synaptic connections between cells in the silicon CPG enforced basic “rules” of locomotion, ensuring that antagonist muscles were not co-activated and preventing simultaneous contraction of flexors in both legs. Sensory feedback signals from hip angle and ground reaction force sensors modulated the neurons’ firing rates and triggered transitions between the stance and swing phases of locomotion.

When activated, the silicon CPG was able to restore some locomotive ability to the cat, which walked along a 3-meter platform. Kinematic and kinetic data recorded during stepping confirmed that the motor activation patterns produced by the artificial CPG were comparable to those of its natural counterpart.

Real-Time Control Loop



Biological Preparation

One adult male cat weighing 4.6 kg was used in the study. Anesthesia was induced through the inhalation of isoflurane, and an intravenous catheter was inserted for use in administering the sodium pentobarbital (Somnotol) used throughout the duration of the experiment. All experimental procedures were approved by the University of Alberta Animal Welfare Committee.

Intramuscular (IM) electrodes (9-strand stainless steel Cooner wire, insulated except for 3–4 mm tips) were implanted near the motor points of six major flexor and extensor muscles of each hindlimb: sartorius anterior (SartA, hip flexor), semimembranosus anterior (SMA, hip extensor), biceps femoris posterior (BFP, knee flexor), vastus lateralis (VL, knee extensor), tibialis anterior (TA, ankle flexor) and gastrocnemius lateralis (GL, ankle extensor). After IM wires were implanted the animal was transferred to a partial body support sling. The sling was suspended from a trolley that was allowed to roll with variable friction along the length of a 3 m walkway consisting of two parallel triaxial forceplates measuring the ground reaction force (GRF) from each leg. The two forelimbs were secured to and supported by a passive rolling panel raised slightly above the forceplates. Dual-axis accelerometers (ADXL213, Analog Devices, Inc., Norwood, MA) affixed between the ankle and metatarsal phalangeal (MTP) joint of each hindlimb were used to approximate left and right hip angle (HA). Markers for kinematic tracking were placed on the right side of the cat to indicate the iliac crest, hip, knee, ankle, and MTP joints.

Six dual-channel constant-current stimulators (EMS-6500, Electrostim Medical Services, Inc., Tampa, FL) were controlled by the silicon CPG chip and used to generate muscle contractions in the hindlimbs. Patterned trains of stimulation (biphasic, charge-balanced pulses at 0.1–20 mA, 200 μ s duration, 50 pulses/sec) were applied through the IM electrodes in order to activate flexor and extensor activity.

Hardware Infrastructure

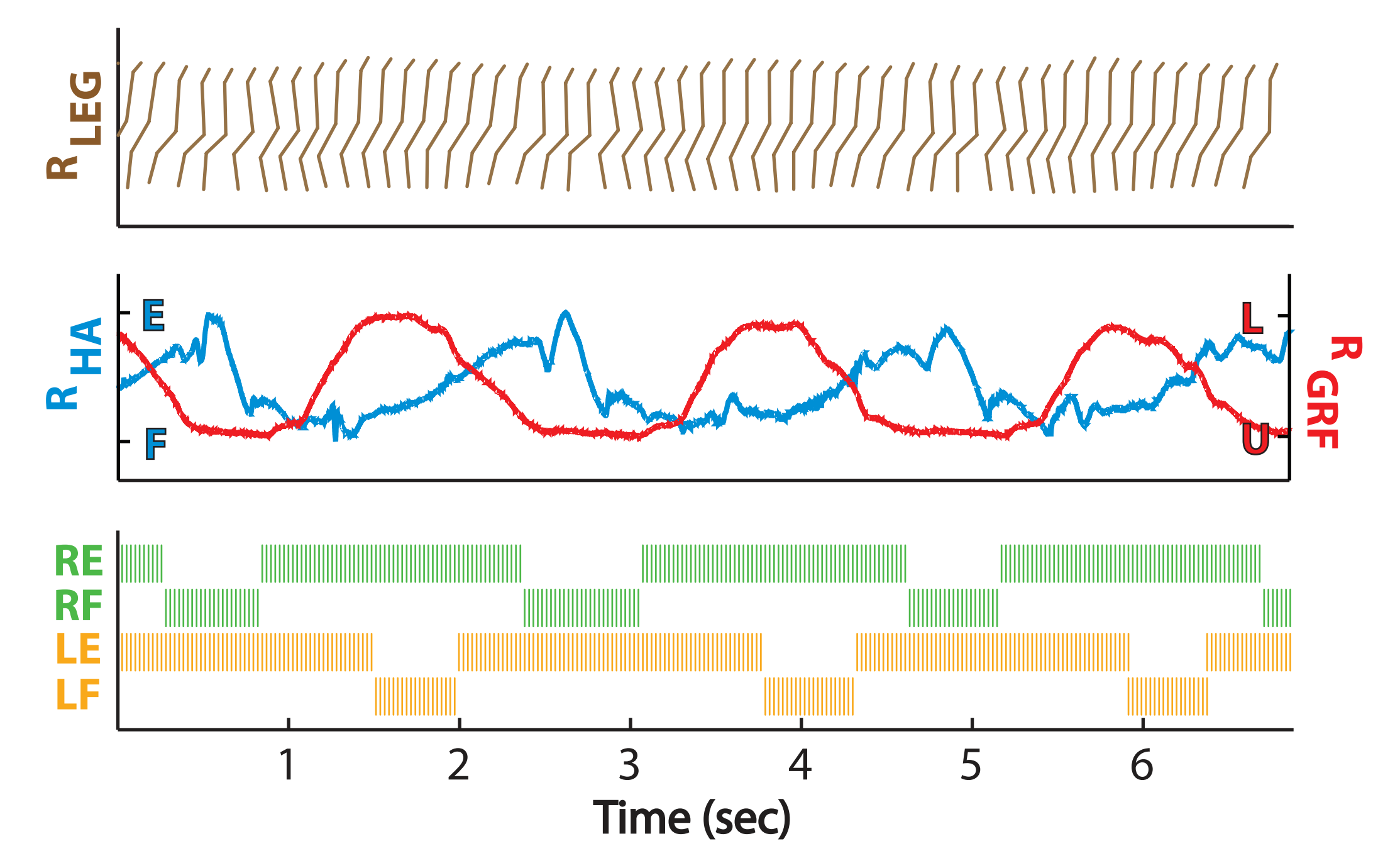
The silicon CPG is a custom-designed mixed-signal (analog and digital) VLSI microchip that occupies 3.3 mm x 2.2 mm in a 0.5 μ m three-metal, two-poly process. The chip implements ten spiking integrate-and-fire silicon neurons with programmable interconnectivity. Each neuron can make synaptic connections to any of the other neurons as well as to any of eight external input signals and one tonic bias input. Synaptic weights are controlled by 8-bit current-mode digital-to-analog converters (DACs) embedded into every synapse subcircuit. DACs are programmed over a serial bus using custom-designed software.

Six external inputs, the tonic bias, and four silicon neurons are used to form the CPG for the neuroprosthetic device. The weights on the tonic bias (B_1 – B_4) were set to excitatory levels sufficient to cause vigorous spiking from each neuron in the absence of any other inputs. However, due to the strong weighting of the reciprocal inhibitory synapses, only one neuron in each flexor/extensor pair (LF/LE and RF/RE) and only one of the two flexor neurons (LF/RF) could be active at any time. Exactly which neurons are active is determined by the six external inputs representing left hip flexion (L_{FLX}), left hip extension (L_{EXT}), right hip flexion (R_{FLX}), right hip extension (R_{EXT}), left leg loading (L_{LD}), and right leg loading (R_{LD}). The synaptic weights of each of these inputs upon the four neurons in the CPG are adjusted under manual control to generate functional propulsive locomotion.

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Results



Data observed during a few steps of locomotion controlled by the silicon CPG.

Top: Kinematic data extracted from high-speed video recordings. Stick figures of the right hindlimb were constructed using calibrated coordinates of the markers as well as the measured lengths of the limb segments.

Middle: Kinetic data from the right hip angle (HA) and ground reaction force (GRF) sensors. E = extension, F = flexion, L = leg loaded, U = leg unloaded.

Bottom: Action potentials from the four neurons in the silicon CPG. RE = right extensor neuron, LE = left extensor neuron, RF = right flexor neuron, LF = left flexor neuron.