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Analog chip could be Rx for spinal cord injury

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There's a reason that a broken neck or back is considered to be one of the most tragic of injuries. If the spinal cord snaps, the brain loses its ability to communicate with the rest of the body, and the limbs to talk to each other. What most people don't realize is that when it comes to locomotion, the second problem is actually worse than the first. The chicken with its head cut off can still run around, thanks to its spinal cord: The brain gave the signal to get going, then became superfluous to requirements. But if the limbs can't "speak" to each other to coordinate, then walking is impossible.

Researchers at Johns Hopkins University (JHU; Baltimore) saw a way of getting around the problem. It turns out that the coordinated movements of limbs in all sorts of animals (including chickens) are produced by a central pattern generator (CPG). Sensors and actuators feed signals into the neurons of the spinal cord and then respond to the output. Because of the cyclical nature of walking, the spinal cord neurons learn to coordinate the inputs and outputs to produce a regular pattern: they become a CPG as the creature learns to walk. So, to give locomotion to an animal with a severed spinal cord, you need to reproduce this neural process.

If you could do so with an embedded chip, the researchers reasoned, you could enable walking at the flip of a switch.

Now they've shown that it really works. In a recent experiment with colleagues at the University of Alberta, Edmonton, they used a chip with analog neurons to control the walking of a temporarily paralyzed cat. Not only were signals from the chip used to stimulate the muscles, but the movement of the limbs was detected and fed back into the artificial neural network. The resulting movement might not have been completely natural, but it proved the concept. And this solution, unlike a more brute-force digital approach, has the potential of actually being implantable in the medium term.

Reggie Edgerton, a professor at the Department of Physiological Science and Neurobiology, University of California at Los Angeles, studies the neural control of movement and neuromuscular plasticity (adaptability and learning). He sees the new work as a step forward: "It provides a compact device that not only can stimulate the muscle but has some ability to modulate the stimulation amplitudes based on kinetic and kinematic feedback of the limbs." The difficulty of what the JHU accomplished should not be underestimated, he said. "Perhaps the most important point from the present data is the suggestion of some success in proof of concept of recording sensory information, processing it, and then generating a reasonably successful adapted activation pattern of specific muscles."

The neuromorphic approach
Ralph Etienne-Cummings, the JHU associate professor who has been in charge of the electronics work, has been working with CPG-based locomotion for several years. With his colleague Tony Lewis at Iguana Robotics (Mahomet, Ill.), he showed back in 2000 that a central pattern generator can be used to efficiently control walking in engineering as well as nature. Together, Lewis and Etienne-Cummings built a small robot: just a pair of legs driven at the hip. The knees were left to move freely, swinging forward under their own momentum like pendulums.

Locomotion was simple. The analog CPG chip designed by Etienne-Cummings would produce a burst of spikes that would drive the left/right hips forward/back. Position sensors on the hips would send spikes to the chip when their extremes had been reached, which would modify the output of the CPG and cause the left/right hips to start moving back/forward instead. Essentially, the sensors helped to feed in information about the real-time physics of the legs into the CPG, and it in turn coordinated the actions of the legs.

This particular CPG chip worked through the charge and discharge of an analog capacitor, so incoming spikes supplied by the extreme hip position sensors had the effect of either charging the CPG faster (in the first phase) or allowing it to discharge more slowly than it would have otherwise. Because that would change the period of the CPG, the next 'extreme' spikes would hit at a different part of the cycle, altering its pattern again. However, eventually, the CPG pattern would converge to that of the sensor spike pattern (a process known as entrainment), and the walking pattern would be set. Thus, as soon as one leg was fully extended, the other hip would start to push forward, producing a gait that exactly matched the physics of the legs. The researchers were also able to make the legs step over obstacles by adding a camera, appropriately converting its output into spikes, and feeding those into the CPG.

For this experiment, the CPG chip itself consumed less than 1µW.

From robotics to biology
According to Jacob Vogelstein, a researcher who has been working as part of Etienne-Cummings' team for several years, the advantages of applying this approach to those with spinal-cord injuries was obvious: The current state of the art for patients is primitive. "Commercially available locomotor prostheses require the user to press a button each time he or she wants to take a step. A specially outfitted walker is sold with this system and has one button on the left side and one button on the right. When the user wants to move his or her left foot, he or she depresses the left button. When the user wants to move his or her right foot, he or she depresses the right button. There is no sensory feedback loop to control the locomotion."

There are better systems available in the lab, he says, but they require "a fast PC, a whole rack of signal processing hardware, an analog-to-digital converter card and specialized software written in C. If you took all of the hardware and crammed it in a box, you'd probably need 8 cubic feet."

By contrast, the JHU electronics fit on a printed-circuit board. Most of the components are commercially available: an analog signal processor chip, to process signals to be fed into the CPG; a microprocessor, to control the output to the subject; and constant-current stimulator output stages. Of course, the core of the system is the analog CPG chip. In the experiment with the cat, the researchers' custom device had four sets of neural circuitry that corresponded to four muscle areas: the left and right hind leg flexor and extensor muscles.

As with the robotics experiments, hip angle and ground-reaction force sensors were used to send information into the CPG, which prevented opposing muscles from operating at the same time and generally coordinated the movement. The chip was used to directly stimulate the muscles of a cat whose spinal cord had been anaesthetized so that it could not participate in the motion control.

Vivian Mushahwar, an assistant professor in the Center for Neuroscience at the University of Alberta, was in charge of doing the in vivo experiment. Though the locomotion was slow, she was impressed with the quality of movement the chip produced. "This walking looked near normal and was fully adaptable to the surface over which the animal was stepping. This was extremely exciting and highly novel. All experimental work in the past focused on either producing in-place stepping or walking on even, unhampered terrain. The preliminary work with the CPG chip allowed for walking to take place on an unpredictable terrain, which is an essential step for producing functional walking systems that can be utilized in everyday life outside the lab environment."

The next step
Mushahwar, much of whose work is devoted to neuroprostheses, is excited about the potential of the new work. "The wonderful feature of the CPG chip is that it can be used with any functional electrical stimulation system for walking. In other words, it can be used with systems employing surface electrodes or implanted wires to activate groups of flexor and extensor muscles. Because of the flexibility in how its neurons are connected, the sensory input they receive and the capacity of these neurons to 'learn,' the chip can be used for restoring locomotion in people with complete spinal cord injury or augment the locomotor capacity in people with incomplete injury.

"Our future goal," she said, "is to combine the CPG chip with microelectronic implants in the spinal cord itself, instead of stimulating muscles directly through surface or implanted wires placed throughout the legs. The spinal implants, which would be distributed in a region of the spinal cord spanning less than 5 cm, would allow the activation of intact populations of neuronal networks within the cord that are responsible for the generation of flexor and extensor alternations in the legs. The combination of the CPG chip with microelectronic implants in the spinal cord would significantly reduce the size of the electrical stimulation system by eliminating the need to implant wires directly in the muscles of the legs. It will also produce even more natural, fatigue-resistant walking than what we were able to achieve to date."

Vogelstein believes that the electronic approach is the only one likely to bear fruit. "In the long term, the CPG chip allows us to pursue an implantable solution, whereas the current [digital] technology has no easy path to implantation. The CPG chip is much smaller than a whole computer, it requires much less power and--because silicon neurons function similarly to biological neurons--it has the potential to communicate directly with the spinal cord and nervous system in its own language. A disadvantage of the CPG chip over a PC-based solution is that it is not as flexible as a computer, but as long as it does its job, it doesn't need flexibility. You'll never need your prosthetic CPG chip to run Windows."

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