EECoG may finally allow enduring control of a prosthetic or a paralyzed arm by thought alone

February 18 2011

Daniel Moran has dedicated his career to developing the best brain-computer interface, or BCI, he possibly can. His motivation is simple but compelling. "My sophomore year in high school," Moran says, "a good friend and I were on the varsity baseball team. I broke my arm and was out for the season. I was feeling sorry for myself when he slide into home plate head first and broke his neck.

"So I knew what I wanted to do when I was 15 years old, and all my career is just based on that."

Moran, PhD, associate professor of biomedical engineering and neurobiology in the School of Engineering & Applied Science at Washington University in St. Louis, is young enough that his career has coincided with the rapid development of the field of brain interfaces. When he began, scientists struggled to achieve lasting control over the movement of a cursor in two dimensions. These days, his aspirational goal is mind control of the nerves and muscles in a paralyzed arm.

A typical primate arm uses 38 independent muscles to control the positions of the shoulder and elbow joints, the forearm and the wrist. To fully control the arm, a BCI system would need 38 independent control channels.

The latest from Moran's lab

There are four types of brain-computer interfaces: EEGs, where the electrodes are outside the skull; microelectrodes, where the electrodes are inserted in the brain; ECoGs, grids of disk-like electrodes that lie directly on the brain, and, Moran's choice, EECoGs, grids of disk-like electrodes that lie inside the skull but outside the dura mater, a membrane that covers and protects the brain.

Moran has just completed a set of experiments with MD/PhD student Adam Rouse to define the minimum spacing between the EECoG electrodes that preserves the independence of control channels. Together with Justin Williams at the University of Wisconsin, he has built a 32-channel EECoG grid small enough to fit within the boundaries of the sensorimotor cortex of the brain.

His next step is to slip the thin, flexible grid under a macaque's skull and to train the monkey to control — strictly by thinking about it — a computational model of a macaque arm that he published in the Journal of Neural Engineering in 2006.

This might sound like science fiction, but in 2006, Moran and his long-time collaborator Eric Leuthardt, MD, a Washington University neurosurgeon at Barnes-Jewish Hospital, had demonstrated that a young patient, in the hospital for surgery to treat intractable epilepsy, could play the video game Space Invaders just by thinking about it.

Of course the virtual arm is a much more ambitious project. Only two degrees of freedom (two independent control channels) are required to move the Space Invaders' cursor in a two-dimensional plane.

The arm, on the other hand, will have seven degrees of freedom, including rotation about the shoulder joint, flexion and extension of the elbow, pronation and supination of the lower forelimb, and flexion, extension, abduction and adduction of the wrist.

(The monkey will not be harmed in this experiment, but instead will be persuaded by a virtual reality simulator into treating the virtual arm as though it were its own.)

Using the virtual arm, Moran showed that the classic task that has been used to study motor control for 20 years, called center-out reaching, does not adequately separate out the control signals that add up to an arm motion, making it difficult to determine which part of the brain is controlling which element of the motion.

So the monkey will instead be asked to trace with its virtual hand three circles that intersect in space at 45 degrees to one another, like interlocked embroidery hoops. Because this task better separates degrees of freedom, it will make it easier for the scientists to map cortical activity to details of movement, such as joint angular velocity or hand velocity.

Should this experiment be successful, and Moran fully expects it will be, he would like eventually connect his EECoG BCI to a new peripheral nerve-stimulating electrode he is developing together with MD/PhD student Matthew R. MacEwan. By connecting these two devices they will create a neuroprosthetic arm: that is, a paralyzed arm that can move again because the mind is sending signals to peripheral nerves that stimulate muscles to expand or contract.

Neuroprosthestics like the one Moran and colleagues are designing may one day help people suffering from spinal cord injury, brainstem stroke or amyotrophic lateral sclerosis, which paralyzes the body while leaving the mind intact.

The background

BCI has been slow to develop in part because early scientists worked with two "platforms" that have turned out to have serious limitations: EEG systems that measure brain signals through the skull and arrays of microelectrodes inserted directly into the brain.

EEG systems have a series of drawbacks related to the distance between the electrodes and the scene of the action. They have poor spatial resolution, the signals do not contain detailed information, and the signals are weak.

"Here's the deal," says Moran. "The brain is about an inch below the surface of your scalp, which in recording terms is a long, long way away. When you're on the surface of the scalp, it's kind of like being five blocks from Busch Stadium. You can't hear anything unless someone hits a home run and all 60,000 fans scream simultaneously.

"For an EEG, you need the neurons in a chunk of cortex about the size of a quarter screaming at the same time in order to record anything. And the primary motor cortex, the thin strip of the brain that controls the skeletal muscles, is so small you're only going to get a few control channels up there."

There are other drawbacks to EEG as well. For example, it takes many training sessions (roughly 20 to 50 half-hour sessions) to learn to control an EEG BCI.

Still, Moran and colleagues write in a review article in Neurosurgical Focus, EEG BCIs perform better than is sometimes supposed. They allow accurate control of a computer cursor in two or three dimensions and so far they are the only systems that have achieved clinical use (in patients with amyotrophic lateral sclerosis and spinal cord injury).

Microelectrode arrays

The traditional alternative to an EEG platform has been an array of microelectrodes whose tiny tips are implanted a few millimeters into the motor cortex.

Microelectrodes were implanted in both monkeys (in the 1970s) and in humans (in 1998), and were very successful -- but only for a short time.

They suffer from what is probably a fatal drawback: The insertion of the electrodes initiates a reactive cell response that promotes the formation of a sheath around the electrode that electrically isolates it from the surrounding neural tissue.

Some labs are investigating biomaterial coatings for electrodes or drug delivery systems that would prevent this foreign body response, but these efforts are still preliminary.

No needles

In working with penetrating microelectrodes scientists made several discoveries that had interesting implications.

The first systems recorded the action potentials in single neurons, but in the 1980s, scientists discovered that populations of neurons in the motor cortex could be used to control the direction and speed of movements in three-dimensional space.

These small assembles of cortical cells synchronize their activity to produce high-frequency local field potentials, called gamma waves, that resemble signals from nearby single-unit microelectrodes.

In short, the gamma waves from neuronal populations can substitute for the action potentials from individual neurons. This meant it wasn't necessary to poke anything into the brain to get a useful signal. Instead, a sheet of disc like electrodes could be laid on the surface of the brain.

Moran was able to piggyback his first ECoG experiments on human epilepsy monitoring taking place at Barnes-Jewish Hospital.

"Our first ECoG experiments in 2004 were done with people," he says. "Patients with focal (localized) seizures that cannot be controlled with medication are regularly implanted with ECoG grids so that surgeons can pinpoint damaged portions of the brain for removal without disturbing healthy tissue. "

In 2006, Moran and Leuthardt attached an ECoG grid that had been implanted in a 15-year-old boy to monitor seizures to a computer running the game Space Invaders.

In order to move the cannon right, the subject thought about wiggling his fingers and to make it move left he thought about wiggling his tongue. "He could duck and dive and had pretty elegant control of the video game," Moran says, "and he made it to level three on the first day."

In the video the subject can be seen wiggling his fingers, but this behavior soon drops away, Moran says. The brain adapts and instead of imagining "wiggle fingers" the boy imagines "cursor right."

Intuitively you would think that signals from the motor cortex would provide the best control for tasks involving movement. But even this turned out not to be true. In 2007, scientists at the University of Wisconsin-Madison reported that patients were able to teach themselves to modulate gamma band activity either by imagining hand, foot or tongue movements, or by imagining a phone ring tone, a song or the voice of a relative. In other words, they were able to train neurons in the auditory as well as the motor cortex to control movement.

A thin sheet slipped under the skull

All of this was very exciting. What if, Moran wondered, the brain was completely plastic and populations of neurons could arbitrarily be reassigned to control movement in different directions in space?

If neuronal populations could be reassigned, maybe more electrodes could be crowded into a grid without losing independent control of movement along different axes in space.

If the electrodes were shrunk as well as moved closer together, he wondered, how far could you go? How many degrees of freedom could you bring under the brain's control?

And why not make the implants safer as well? Instead of laying the electrode grids on the brain's surface, why not lay them on the dura mater, the outermost of the three membranes surrounding and protecting the brain and spinal cord.

In 2009, Moran published the first studies of epidural electrocortiocography (EECoG -- not to be confused with ECoG). Recording sites over the motor cortex of monkeys were arbitrarily assigned to control a cursor's motion in the horizontal and vertical directions as the monkey traced circles on a computer screen.

In the latest set of experiments, Moran sought to define the minimal separation between electrodes that preserved independence of control. Once a monkey gained control of the cursor, the initial electrodes were abandoned and control was given to two electrodes that were closer together. The next week, the control electrodes were closer still.

Moran found that the electrodes, which were initially a centimeter apart, maintained their independence until they were only a few millimeters apart. "So now that we know how many electrodes we can pack into an area, we have some idea how many degrees of freedom we'll be able to control," he says.

Together with Williams, he designed a 32-channel EECoG supported on a sheet of plastic thinner than Saran Wrap that sucks down to the dura and sticks like glue. He can hardly wait to test it with the virtual arm.

"I like doing basic research and I want to continue to do basic research," Moran says, "but I also really want to solve the problem and help people. Someone's got to get the technology translated to the marketplace, so we're trying to do that as well.

"Eventually," he says, "we'll have a little piece of Saran Wrap with telemetry. We'll drill a small hole in the skull, pop the bone out, drop the device in, replace the bone, sew up the scalp and you'll have what amounts to Bluetooth in your head that translates your thoughts into actions.

"My passion is for paralyzed individuals," he says, "but you can see down the road that a lot of people will want one of these devices."

Provided by Washington University in St. Louis