# High-Performance Neuroprosthetics: Improvements Within Reach

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Andrew Schwartz, PhD, University of Pittsburgh, Pittsburgh, Pennsylvania, USA, delivered the Paty lecture, discussing the development of high-performance neuroprosthetics. He provided a broad perspective of how the brain functions during volitional movement, and he explained how neuron signals can be recorded and the information used to direct movement of a prosthetic arm.

The motor cortex is located on the surface of the brain, in front of the central sulcus. Small electrical shocks delivered to specific parts of the motor cortex will cause movement in the corresponding parts of the body. When an action potential fires, a pulse of electricity is transmitted in an electric field to the surrounding tissue. Dr Schwartz started his neuroprosthetics project 20 years ago by recording neuron activity while a trained monkey made specific arm movements in a virtual reality environment. Microelectrodes were implanted near motor cortex neurons, and microelectric recording was used to record the action potentials as the monkey moved its arm. A neuron's action potential is specific and repeatable for a particular movement.

The connection between the neuron firing and the movement is related to the direction of the movement. When a monkey moves its arm on a table from a central target to 1 of 8 targets on the face of a clock, the firing rates can be plotted as data points, showing a consistent relationship between the movement and the firing rate.

When fit into a cosine function, the direction of movement is described by the $x$ and $y$ coefficients; if the movement direction is straight up, the $y$ coefficient is 1, and the $x$ coefficient is 0. The M vector describes the movement, and the B vector describes the preferred direction of the neuron firing. The neuron firing rate can be determined from the angle between these vectors. This determination of how the neurons function is referred to as *N-coding*.

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To develop neural prosthetics, Dr Schwartz studied neural activity and predicted the resulting movement, referred to as *decoding*. Billions of neurons fire simultaneously for each movement. The discharge rates of all the neurons in a sample of that neuron population were recorded as a monkey drew with its arm. The preferred direction of each neuron was determined; vectors were laid down for each; the vector lengths were adjusted according to the firing rate at a particular point in time; and all the vectors were added to generate a trajectory of the movement. This population vector algorithm can be used to predict movement and then to generate that movement. In this way, intention in a paralyzed patient can be extracted and used to restore movement.

In the next step, monkeys with implanted electrodes were trained to move a hand toward 2 targets in a 3-dimensional cube. The hand movement was tracked to move a cursor to the targets, starting in the middle and reaching toward the corners. Then the hand sensor was switched off, and the monkey moved the cursor directly from its brain. This expanded the equation, or model, to 3 dimensions. Thus, the neurons' preferred directions were determined, and that information was used to train the monkey to move the cursor using only its neural activity. The monkey's performance improved as it repeated this exercise, learning how the model worked and fitting its brain activity to the model.

Technology has improved since Dr Schwartz began this work. Currently, he is using electrode arrays (4 × 4 mm) developed at the University of Utah, which consist of a block of 100 silicone electrodes with platinum-iridium tips arranged in rows of 10 by 10 that are implanted into the motor cortex. These are used to determine the preferred directions of neurons to create a neuron population vector that represents velocity of movement. This control signal is fed to a robot controller that is instructed to move according to the vector.

Additional hand and wrist movements have been added to increase the dimensions of the equation and the complexity of the movements. Hand movements have about 20 degrees of freedom, but many of these are correlated with each other. Groups of correlated joints have been used to create 4 basic hand shapes, or principal components, and to construct all the other hand shapes from combinations of these, resulting in 10 dimensions of hand and wrist movement.

Dr Schwartz teamed up with the US Department of Defense to develop a high-performance prosthetic arm with many of the same degrees of freedom as a natural arm, including 3 shoulder motions, an elbow, a wrist with 3 degrees of freedom, and a hand with 12 to 15 degrees of freedom and an opposable thumb. The arm weighs about 9.5 pounds, is the size of an adult male's arm, and can lift about 50 pounds.

In 2012, the arm was first used in a 53-year-old woman who had a form of multiple sclerosis and had been paralyzed for 11 years. Two electrode arrays were placed on the surface of her motor cortex during a 6-hour surgical procedure and were wired to computer connections that controlled the prosthetic arm. After 5 months of training, the patient was able to control the robotic arm with nothing but her thoughts. She could move the arm in different directions, shake hands, grasp objects, and feed herself. According to the patient, it was hard work learning to control the arm, but then it became automatic, the same as with her own arm before the paralysis. The movement is natural and efficient. However, the quality of the electrode recordings deteriorated over time due to tissue reactions around the electrodes in her brain, resulting in decreased performance.

Dr Schwartz's team is developing new technology to address the biocompatibility problem of the electrodes. The team is working on a wireless version that will not require implanted electrodes. It is also developing sensory technology that will allow the robot hand to sense pressure and transmit the sensation back to the brain as the sense of touch. Other future developments include telemetry miniaturization, better prosthetic effectors, and reanimation of paralyzed limbs.