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Brain–muscle interface: The next-generation BMI

Spinal cord injuries result in loss of movements below the site of injury because connections between the brain and the muscles are cut. Treatment strategies have focused on restoring connectivity by the application of drugs, or cell or tissue transplants. Brain–machine interface (BMI) devices, on the other hand, aim to improve the quality of life of the patients by using technology to record neural signals directly from the brain and using these signals to control robotic devices, which substitute for the paralysed body part by performing functions such as locomotion and feeding (Jain 2010).

BMI devices, which have been successfully demonstrated in rats, monkeys and humans (Chapin *et al.* 1999; Wessberg *et al.* 2000; Hochberg *et al.* 2006), are based on a discovery made nearly three decades ago by Georgopoulos and colleagues. They found that in the primary motor cortex direction of movements is coded in the activity of neurons (Georgopoulos *et al.* 1983). The firing rate of a neuron coding for the direction of the arm movement is maximum for movement in a particular direction, and decreases as the movement direction shifts away. Neurons in the premotor cortex show a similar directional tuning, except that they discharge before the actual movement takes place, during the movement planning phase. BMI devices record activity of ensembles of neurons, analyse it using mathematical algorithms to predict the intended movement and use the output to generate command signals that control the robotic devices (figure 1A).

BMI technology has recently added two new tools to its arsenal, which have the potential to overcome certain technical challenges and make it easier to implement.

The first advancement is the use of an individual's ability to modulate neural activity at will. Practitioners of Indian meditative yoga can control their brain rhythms (Khare and Nigam 2000). Interestingly, control can be achieved at the level of a single neuron. Fetz (1969) showed that monkeys could learn to modulate the firing rate of individual neurons in the motor cortex to obtain rewards, an ability that the Fetz group recently used in a BMI device (Moritz *et al.* 2008). Previous BMI devices have generally relied on recordings from neurons that actually participate in generating specific movements. In these devices the neuronal activity recorded when the animal is physically doing the task is used to optimize a mathematical algorithm, which is subsequently used to control the robot for mimicking the arm movement. This sequence of optimization is not possible in patients with paralysis, because the devices will be introduced post-injury; no pre-injury recordings of the neuronal activity will obviously be available. Voluntary control over the activity of neurons makes it unnecessary to know *a priori* the exact contribution of a neuron in the movement generation in order to get a signal suitable for controlling a robotic device.

The intra-cortical electrodes can provide stable recordings for many years (Jain *et al.* 2001; Rajan and Jain, unpublished observations), but cannot be moved easily once placed. Moreover, electrodes often lose the ability to record from the same sets of neurons. This, combined with widespread reorganization of the brain following spinal cord injuries (Jain *et al.* 1997; Tandon *et al.* 2009; Kambi *et al.* 2011), can be especially problematic if recordings from specific neurons were essential for BMI devices. The ability to modulate neuronal activity also provides greater flexibility to the scientists in choosing a site for placement of intra-cortical microelectrodes. Finally, the patients can possibly generate multiple patterns of activities, allowing use of recordings from the same groups of neurons to control different movements, such as feeding and walking, which are normally controlled by different neurons in the brain.

The second important technological advancement made by Fetz and colleagues (Moritz *et al.* 2008) gets rid of the robot as the effector device. Instead of using the brain activity to control a robotic arm, they converted the brain signals into electrical signals, which were used to stimulate the muscles of the

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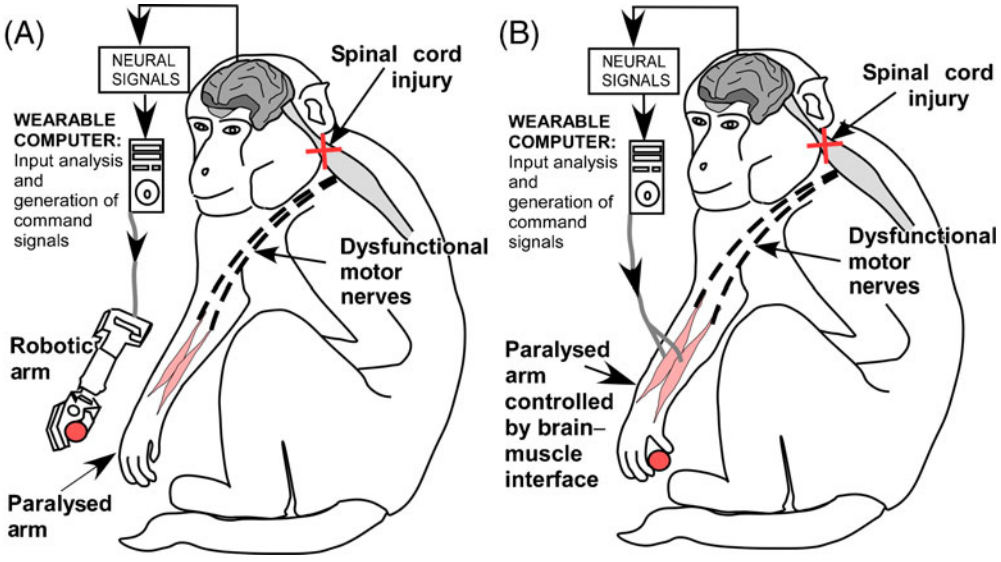

Figure 1. (**A**) Schematic of a brain–machine interface device showing neural signals being recorded from the brain of a spinal-cord-injured monkey. The signals were analysed and used to control a robotic arm, which is used to pick up the food item. (**B**) In the brain–muscle interface device (Moritz *et al.* 2008), the neural signals were recorded from the brain, analysed and converted into electrical impulses, which are transmitted to the paralysed arm to restore movement.

paralysed arm. In their study, they first trained monkeys to make rotational movements of the wrist to control a cursor and move it towards a target that appeared on a computer screen, and recorded neural activity from neurons in the motor cortex that controlled the flexor and the extensor muscles of the wrist. In the second step of the training, the position of the cursor was represented as a function of the firing rates of the neurons, which were also available to the monkeys as a visual feedback. The monkeys rapidly learnt to maintain the neuronal activity at a particular level to control the cursor. Post training, muscles of the wrist were reversibly paralysed by injecting a local anesthetic into the peripheral nerves innervating the arm, thus blocking neuronal activity from reaching the arm. In the final testing step, the neuronal activities were converted into proportional electrical currents and used to directly stimulate the paralysed muscles of the arm. Monkeys learnt to precisely control the cursor by increasing or decreasing the neuronal activity, which changed the amount of electrical current delivered to the muscles, and generated the appropriate levels of wrist torque. Moreover, monkeys could independently control the activity of a pair of neurons to specifically stimulate antagonistic pairs of muscles, thus effectively restoring movement of the paralysed arm (figure 1B). Although one could assume that activity of neurons associated with the wrist movement would be more accurate at generating wrist torques, the monkeys were able to control wrist torques by controlling activity of neurons irrespective of their association with the wrist movements.

As compared with a BMI device controlling a robotic arm, restoring control of movement in the paralysed arm will reduce the hardware that the patients need to carry around. Use of the natural arm will also make the device less obtrusive and aesthetically more acceptable. In their study, Moritz *et al.* (2008) were able to produce large ballistic movements by muscle stimulation. It is not clear if a similar device can achieve fine control of complex finger movements as this would require rapid, simultaneous or sequential control of multiple neurons. A detailed understanding of the neural control of individual muscles and the role of sensory feedback in muscle control is necessary.

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