known as intersex (DSDI). In simple terms, some of the biological characteristics of women with DSDI would be classified as female and others as male. This challenges common ideas about sex, but it is widely recognized in medicine, law, and the social sciences that when people are born with mixed markers of sex (e.g., chromosomes, genitals, gonads), the medical standard is that gender identity is the definitive marker of sex—there is no better criterion (*18*).

What, then, is the logic that classifies women with DSDI as confounders? The Daegu report consistently pairs clinical language, such as "diagnosis" and "disorder," with hyperandrogenism for the women with DSDI, and in their rebuttal to the GH-2000 paper, IAAF-IOC policy-makers use the phrase "hyperandrogenic disorders of sex development" (*12*). This signals their judgment that women with DSDI are not healthy and, therefore, should be excluded from reference ranges. But DSDI women are not necessarily unhealthy. High T can be associated with health issues but is not, in and of itself, a health problem for women (*4*).

> ***"What looks like a [scientific] controversy ... is ultimately a social and ethical one concerning how we understand and frame human diversity."***

An a priori understanding of women with DSDI as unhealthy and, thus, outside normal variation creates a rationale for their exclusion both in reference ranges and the policies. But it is also circular: Because women with DSDI are a priori excluded when the reference ranges are created, the findings from the Daegu study—that women athletes have T levels no different from nonathlete women—reinforce their values as outsiders and justify the policy.

There is a strong scientific argument for including DSDI women in the sample. These studies aim to establish T reference ranges for elite athletes: i.e., the focus is on physiological ranges not clinical ranges. This calls for descriptive statistics, and in this case, there is no valid basis for discarding some values as outliers. In both studies, if the full range of values for women's endogenous T is included, there is an overlap in T.

CALCULATING FAIRNESS. What looks like a controversy rooted firmly in science is ultimately a social and ethical one concerning how we understand and frame human diversity. These assessments are not trivial: They shape not only the research methods and findings but also how we understand what is at stake in this policy. And this has very real consequences for people's lives.

Policy-makers, among others, claim that the problem is that women with naturally high T have unfair advantage, despite having acknowledged in their Daegu study that "there is no clear scientific evidence proving that a high level of T is a significant determinant of performance in female sports" (*11*). Others see a very different problem: Women who have lived and competed as women their whole lives suddenly find themselves having to undergo medical interventions in order to remain eligible to compete in a category to which everyone agrees they belong.

Calculating what counts as a fair and level playing field for women must take all women athletes into account, including those with naturally high T and/or DSDI. We could return to a consensus reached decades ago, where policy-makers faced these same concerns and concluded that women "who were raised as girls and classify themselves as female should not be excluded from competition as women" (*19*). In other words, ensuring that women with high endogenous T and/or DSDI "have the same rights to participation in athletics as all women" (*20*) would be a good place to start. ■

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NEUROSCIENCE

Reading the mind to move the body

Decoding neural signals of intention and movement should guide the development of neural prosthetics

By **J. Andrew Pruszynski**[1] *and* **Jörn Diedrichsen**[2]

Imagine a world in which your smartphone can read your mind. Just at the moment that you decide to move your finger to delete a message, it is already gone. This sounds like science fiction, but for one human in California, this fantasy is becoming reality. On page 906 of this issue, Aflalo *et al.* (*1*) report the case of a tetraplegic individual (called "EGS") who volunteered to have his brain implanted with two small silicon chips that allow researchers to read his intentions directly from his brain activity. The chips—initially developed at the University of Utah (*2*) and now commercially available and approved for human use by the U.S. Food and Drug Administration—consist of a matrix of 96 microscopic electrodes that can record the activity of about 100 nerve cells at the same time.

The main goal of the implantation procedure was to restore EGS's ability to act in his environment. Paralyzed from the neck down, he currently relies on the help of others to perform almost all the daily actions that the vast majority of us take for granted. Using the signals from his brain and bypassing his damaged spinal cord, researchers hope to help him do these things again by allowing him to steer a robotic arm so that he can, for example, reach out, grasp a glass, and take a drink. Alternatively, the acquired signals can be used to control a cursor on a screen so that he can efficiently interact with a computer.

Previously, researchers have implanted chips into regions of the human brain that are closely related to the production of movements, such as the primary motor cortex (*3*, *4*), with the aim of reanimating a limb or controlling a prosthetic. Aflalo *et al.* have taken a different approach. They have

implanted neural recording devices in two locations of the posterior parietal cortex. From many years of basic research in monkeys, it is well established that the activity (firing patterns) of nerve cells in these areas contain a great deal of information not only about planned movements, but also more abstract concepts such as goals and intentions. For example, researchers can robustly "read out" a monkey's decision-making process as it deliberates between alternative actions—that is, look at firing patterns of neuronal activity and decode the decision that the monkey is going to make (*5*). Functional imaging of brain activity and brain lesion studies indicate that similar types of information processing occur in the human posterior parietal cortex (*6*).

Even though EGS was paralyzed more than 10 years ago, Aflalo *et al.* report that nerve cells in his posterior parietal cortex respond when he imagines making a particular movement. Indeed, the researchers were able to reliably read out where EGS intended to move by analyzing the firing patterns of about 100 nerve cells. This information was then used to steer a computer cursor or to direct a robotic arm situated beside EGS to the intended location. Aflalo *et al.* could also read out the velocity of the desired movement, and therefore determine when and how fast EGS wanted to move. The neural signals even provided information about whether EGS wanted to use his left or right hand to move to that location, lending hope to the idea that a single neural implant in the posterior parietal cortex could reanimate two limbs.

In a separate experiment, Aflalo *et al.* showed EGS the activity of a single nerve cell on a computer monitor and he was able to reliably and voluntarily modulate the activity of that nerve cell. These results extend classical work showing that monkeys could be operantly conditioned to regulate the firing rate of specific nerve cells when given similar feedback (*7*). However, Aflalo *et al.* could go further than the previous studies because they could explicitly ask their participant to tell them how he achieved these changes. EGS reported that he was often able to change the activity of these nerve cells by imagining particular motor actions. Such intentional modulation could be remarkably specific. One nerve cell, for example, would increase its activity when he imagined rotating his shoulder, and decrease its activity when he imagined touching his nose. Another nerve cell was activated when EGS imagined moving his hand to his mouth but not when he imagined touching his ear or chin.

The results of Aflalo *et al.* represent one more step toward making brain control of a robotic limb or computing device a reality. Despite the impressive series of steps taken over the past 15 years, however, these neural prosthetic devices still have a substantial way to go before becoming practical therapeutic interventions (*8*). Indeed, work is needed on many fronts, such as improving the durability of the implants, refining the isolation of single nerve cells, optimizing computational algorithms for interpreting the signals, and developing stimulation protocols to "write in" sensory signals from the prosthetic device into the brain. Of particular note is the fact that current systems run wires from within the brain to the outside world—a route for potential infection. In the long term, such systems need to become wireless and contained within the body, like modern pacemakers and cochlear implants. The results of Aflalo *et al.* do promise to deliver one of the missing pieces. The ability to decode signals that are related not only to the details of the movement but also to the patient's overall intention could improve brain control of a robot or cursor tremendously (see the figure). Ultimately, patients could have recording chips implanted in both the posterior parietal cortex and motor cortex, with the former being used to constrain the overall goal of the desired action and the latter providing fine control of the kinematic and dynamic details of the movement.

Beyond the important practical implications of these findings, the ability to record from many nerve cells in the human posterior parietal cortex opens up fascinating new avenues for basic research. For the first time, the activity of nerve cells in this area can be directly measured while simultaneously getting a verbal report about the conscious experience of the person from whom this neural activity is being gathered. This unique capacity allows Aflalo *et al.* to relate the patterns of neural activity associated with intention to the conscious experience of forming them. Such experiments should provide new insights into whether a person's future decisions can be decoded from his or her neural activity before the individual is aware of having formed them (*9*), fundamentally challenging our understanding of intentionality and free will. ■

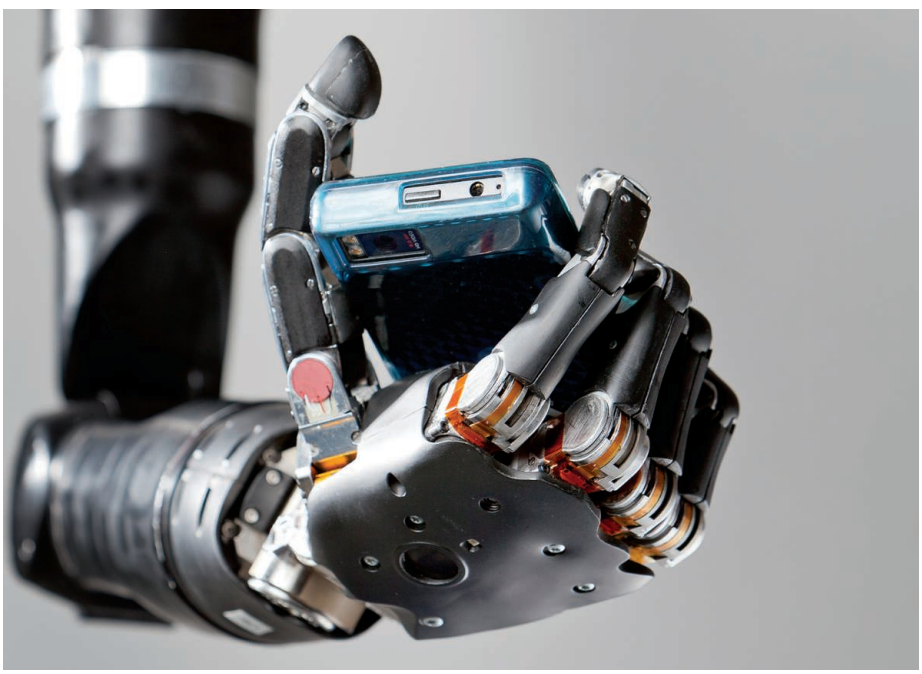

PHOTO: DARPA/JOHNS HOPKINS APPLIED PHYSICS LABORATORY

Imagine that. The ability to decode signals from neural activity in the brain related to details of movement, as well as signals related to the goals of the movement, should improve the design and operation of neural prosthetics. Patients may one day have chips of electrodes implanted in both the posterior parietal cortex and motor cortex to record neuronal activities that would then be decoded and used to control prosthetic limbs.

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