NEUROSCIENCE

A brain-computer interface that evokes tactile sensations improves robotic arm control

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Prosthetic arms controlled by a brain-computer interface can enable people with tetraplegia to perform functional movements. However, vision provides limited feedback because information about grasping objects is best relayed through tactile feedback. We supplemented vision with tactile percepts evoked using a bidirectional brain-computer interface that records neural activity from the motor cortex and generates tactile sensations through intracortical microstimulation of the somatosensory cortex. This enabled a person with tetraplegia to substantially improve performance with a robotic limb; trial times on a clinical upper-limb assessment were reduced by half, from a median time of 20.9 to 10.2 seconds. Faster times were primarily due to less time spent attempting to grasp objects, revealing that mimicking known biological control principles results in task performance that is closer to able-bodied human abilities.

There are about 169,000 people in the United States living with tetraplegia due to spinal cord injury (SCI) (*1*). Of those with cervical SCI, nearly half desire improved arm and hand function over all other rehabilitation priorities (*2*, *3*). Brain-computer interfaces (BCIs) that measure movement-related neural activity with implanted electrodes can restore some of this lost arm and hand function (*4*–*6*) because the cortex remains capable of generating neural activity that controls arm and hand motion. BCIs can therefore bypass the injured spinal cord to control prosthetic limbs (*4*–*6*), functional electrical stimulation systems (*7*, *8*), or other devices (*9*, *10*).

We previously developed a BCI-controlled robotic arm that enables reaching and grasping movements (*6*) in up to 10 continuously and simultaneously controlled dimensions (*5*). This high-dimensional continuous control has enabled participants to complete clinical assessments of upper-limb function such as the Action Research Arm Test (ARAT) (*11*). However, this BCI control relied on vision alone and lacks a critical sensory dimension. When able-bodied people interact with the environment, tactile feedback from the skin is essential to effectively explore and manipulate objects; without tactile somatosensory feedback, even simple manipulation tasks become clumsy and slow (*12*, *13*).

Neural prosthetics that restore some somatosensation for amputees are becoming more common (*14*–*17*). However, these peripheral stimulation approaches cannot translate to individuals with tetraplegia; stimulation below the level of the lesion is unable to relay information to the somatosensory cortex for processing and perception. Although stimulation in the somatosensory cortex has long been known to evoke detectable sensations (*18*), it is only in recent studies of humans with chronically implanted microelectrode arrays that the perceptual characteristics of microstimulation have been elucidated (*19*, *20*). The potential benefits of a bidirectional BCI—a system in which tactile sensations are evoked through cortical stimulation while neural recordings during attempted movement are decoded to control a robotic prosthesis—have remained unexplored in humans.

Here, we show that a bidirectional BCI (Fig. 1, A and B) that evokes tactile percepts substantially improves performance on functional tasks. These artificial tactile percepts were driven in real time by sensors in a robotic hand that responded to object contact and grasp force (Fig. 1, C and D; and figs. S1 and S2), were evoked through intracortical microstimulation (ICMS) of area 1 of the somatosensory cortex, and were experienced as originating from the participant's own palm and fingers (fig. S1). This result demonstrates that a neural interface that mimics principles of sensorimotor control can be intuitively used by a person with extensive motor impairments.

The male participant in this study was 28 years old at the time of device implant and had tetraplegia due to a C5 motor/C6 sensory ASIA B spinal cord injury sustained 10 years before providing informed consent (*19*). This study was conducted under an investigational device exemption from the U.S. Food and Drug Administration and is registered at clinicaltrials.gov (NCT01894802). Two microelectrode arrays with 88 wired electrodes were implanted in the hand and arm region of the motor cortex (Fig. 1B) to decode movement intent (Fig. 1E and supplementary materials). Two additional microelectrode arrays with 32 wired electrodes were implanted in area 1 (Fig. 1B), which is a cutaneous region of the somatosensory cortex (*21*). Stimulation evoked sensations in the palm and fingers of the participant's right hand, which he described as having cutaneous qualities (Fig. 1, C and D; and fig. S1) (*19*). We used an observation-based paradigm (*6*) to train a new 5 degrees-of-freedom velocity decoder each day (3 degrees-of-freedom hand endpoint, wrist rotation, and hand grasp). Stimulation was never delivered during calibration (fig. S3), and the participant had an unobstructed view of the robotic hand for all trials. Before these experiments, the participant had practiced the tasks for about 2 years.

We compared performance with and without ICMS on a modified version of the ARAT (*11*, *22*) (Fig. 1F and movies S1 to S3). The ARAT variant that we used involved picking up one of eight objects and placing each one on a platform as quickly as possible. We also included a ninth task from the ARAT set: picking up a cup of water, pouring its contents into another cup, and setting the cup back down, upright, on the table. Each object was attempted three times in each session. The trials were timed and scored from 0 to 3 (see supplementary materials), and the highest scores for each object were summed together to produce the ARAT score; the maximum score was 27. In the first four sessions with ICMS-induced sensations driven by robotic touch, the participant achieved a median ARAT score of 21. This was significantly higher than the median score of 17 achieved during the next four sessions without ICMS-evoked tactile sensations ($p = 0.029$, Wilcoxon rank sum test; Table 1 and Fig. 2A) as well as 23 sessions conducted during the 23 months before these experiments ($p = 0.005$, Wilcoxon rank sum test; Table 1 and Fig. 2A). The scores in the four experimental sessions without ICMS were no different than the prior 23 sessions ($p = 0.65$, Wilcoxon rank sum test). Previous ARAT sessions included four exploratory trials with ICMS-driven tactile feedback (Fig. 2A); however, stimulation parameters were variable, and trials with and without ICMS were intermixed, rather than occurring in a blocked design (fig. S3), making the feedback unreliable.

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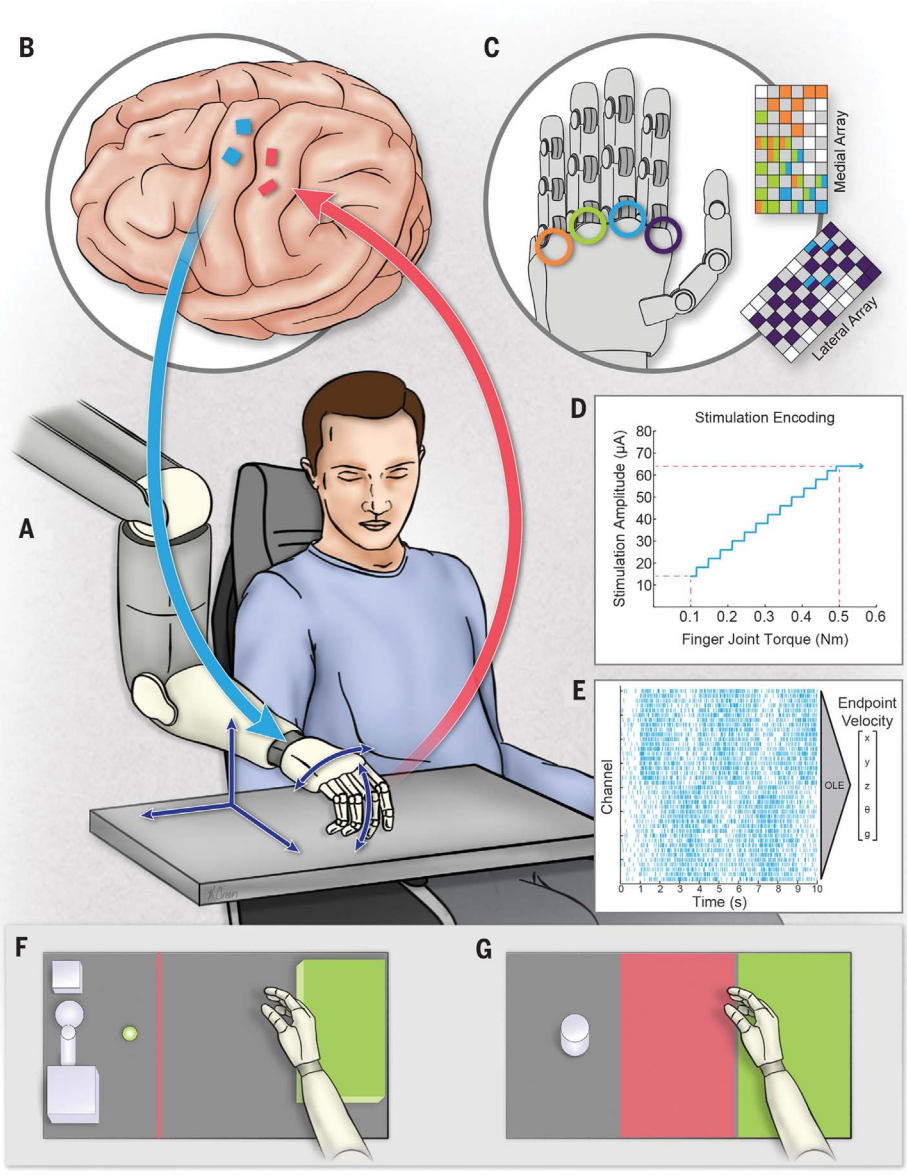

Fig. 1. Overview of the bidirectional BCI system. (**A**) The participant used the intracortical BCI to control a robotic prosthesis in real time, controlling all five dimensions (dark blue arrows) continuously from the start to the end of the trial. (**B**) Four microelectrode arrays were implanted in the left hemisphere. Arrays in the motor cortex (blue) recorded neural activity to control the prosthesis. Arrays in the somatosensory cortex (red) delivered stimulation pulses, evoking sensory percepts referred to the hand. (**C**) Torque measurements from the robotic hand controlled the stimulation of individual electrodes. Colored grids [adapted from (*19*)] represent electrodes and locations on the hand where stimulation evoked a percept. Index finger torque was used to drive stimulation of the index finger sensation, and middle finger torque was used to drive stimulation of electrodes associated with the middle, ring, and pinky finger. (**D**) Stimulation current amplitude was modulated by torque using a linear transformation. (**E**) Example raster plot of neural data recorded from the motor cortex and decoded into endpoint velocities using an optimal linear estimator (OLE). (**F**) Overhead view of the ARAT. Different objects (not all shown) were positioned at the presentation location (green dot), grasped, and then placed on the platform (green box) as quickly as possible. (**G**) Overhead view of the object-transfer task, showing the object (gray), transit (red), and target (green) zones. [Image credit: K. Green]

ARAT scores improved because individual trials were completed much faster when ICMS feedback was delivered (Fig. 2, B and C; and movie S2). In the ARAT scoring system, successfully transferring an object in less than 5 s (a score of 3) is considered able-bodied performance (*22*). Without tactile sensations, this score was achieved only once during all 108 trials. When tactile sensations were provided, a score of 3 was achieved 15 times. Further, 14% of the trials with tactile feedback were completed more quickly than the fastest trial without ICMS (Fig. 2C). Times for successfully completed trials decreased by 51.2%, from a median of 20.9 to 10.2 s, when tactile feedback was provided ($p < 0.0001$, Wilcoxon rank sum test; Table 1; Fig. 2, B and C; and movie S3). These faster completion times were the cause of the 3.5-point improvement in the ARAT score that occurred when ICMS was provided and can be interpreted to mean that ICMS-induced tactile sensations allowed 3.5 more objects, out of nine possible objects, to be transported to the platform in a normal time (<5 s). Although the performance gains were not the same for every object, completion times improved significantly for more than half of the ARAT objects, and the median completion times were lower in all cases (fig. S4 and table S1). The objects with the largest improvements were rated by the participant as being the easiest to manipulate within the constraints of the robotic hand. Some of the smaller objects were difficult to pick up, given the grasping kinematics of the fingers; the tips of the fingers often made contact with the object rather than the pads of the distal phalanx, making grasp less stable. Further, the participant only had control over one grasp dimension that opened and closed all of the fingers as a group. There was no change in the total number of successfully completed trials with or without ICMS ($p = 0.83$, Wilcoxon rank sum test; Table 1).

The median time spent attempting to grasp an object—defined as the period of time between object contact and object liftoff—decreased by 66% from 13.3 s without ICMS to 4.6 s with ICMS ($p < 0.0001$, Wilcoxon rank sum test; Fig. 2D and table S2) and accounted for 88% of the total improvement. The median time spent in the reaching and transport phases (see supplementary materials) both decreased by 25% with ICMS. Once the participant had successfully grasped an object, he rarely dropped it. This occurred just four times with ICMS and five times without. All the

drops resulted from an unstable grasp rather than the participant opening the hand.

We also tested the effect of providing ICMS-induced tactile feedback on functional performance using an object-transfer task (Fig. 1G and movie S4). In this task, the participant was asked to pick up an object from the left side of the workspace (object zone), carry it across the table (transit zone), and drop it on the right side (target zone) as many times as possible in 2 min. Four sessions without ICMS and four sessions with ICMS were conducted (fig. S3), and this task was repeated five times per session. The time spent in the object zone (Fig. 1G) decreased by 30.3%, from 3.3 ± 1.2 s

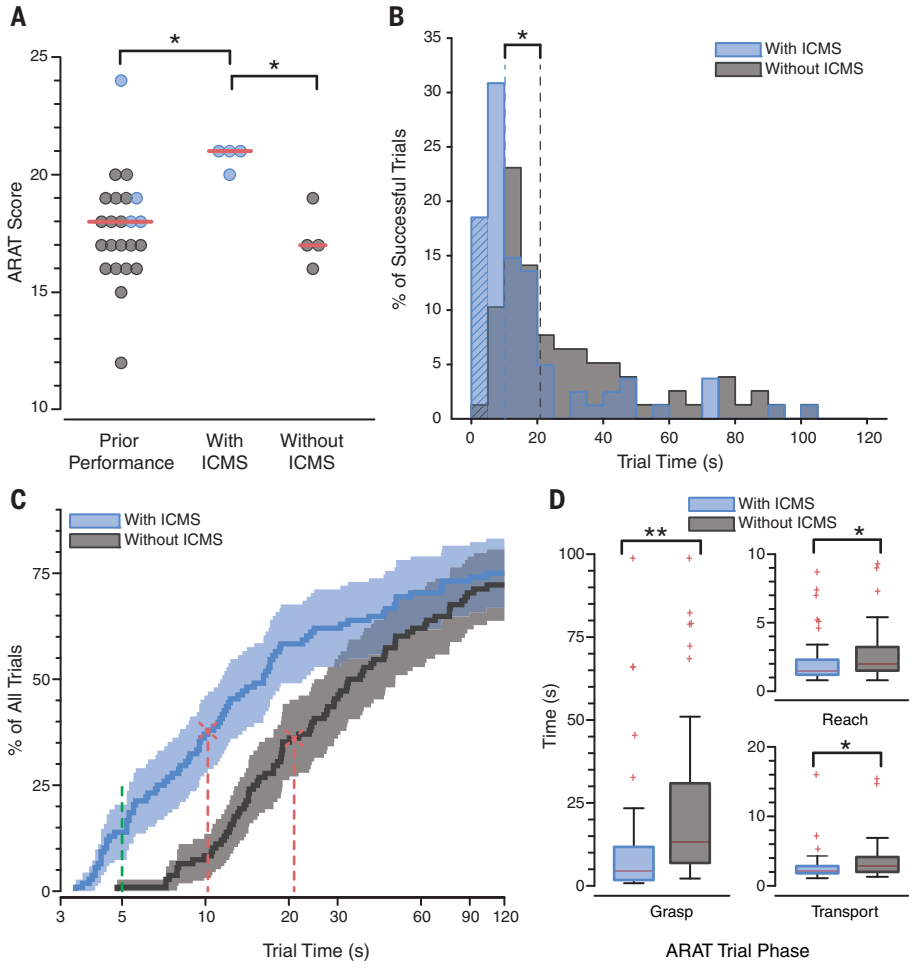

Fig. 2. Effect of ICMS on ARAT performance. (**A**) ARAT scores when ICMS feedback was provided were significantly better than prior ARAT scores (*p = 0.005), which occasionally used ICMS feedback (blue dots), and data from the current experiment without ICMS feedback (*p = 0.029). Red lines indicate median scores. (**B**) Histogram of successful trial times completed with (blue) and without (gray) ICMS tactile feedback. Median trial times (dashed lines) were significantly faster with ICMS (*p < 0.0001). Hatched bars represent trials completed in less than 5 s. (**C**) Empirical cumulative distribution of individual trial times, including failed trials, shown on a log-normalized axis. Vertical red dashed lines indicate when 50% of successful trials were completed. Data to the left of the vertical green dashed line represent trials completed in less than 5 s. Shading indicates the 95% confidence bounds, calculated with Greenwood's formula. (**D**) Amount of time spent in each phase of the ARAT task. Red lines are medians, box outlines are interquartile ranges, and whiskers are the range of the data excluding outliers (red plus signs). All task phases were faster when ICMS feedback was provided (*p < 0.001 and **p < 0.0001; table S2). For (A) to (D), significance was assessed with a Wilcoxon rank sum test.

Table 1. Performance metrics for each task per experiment day. ARAT scores were computed as the sum of the best score per object, with a maximum score of 27. Each of the nine objects was attempted three times, so that the maximum number of trials attempted per session was 27. The median and interquartile (IQR) trial times for successful ARAT trials are shown for each session. The median and IQR trials times for all successful trials were calculated by pooling trial times across all four sessions per feedback condition and calculating the median and IQR from the aggregate distribution. The total number of object transfers is the sum of all five 2-min trials per day.

Feedback condition	Session	ARAT score (out of 27)	ARAT trials completed (out of 27)	Median and IQR trial times for successful ARAT trials (s)	Object transfer (transfers per day)
With ICMS feedback	1	21	19	11.9 (6.6–27.7)	97
	2	21	22	12.0 (5.6–38.9)	74
	3	21	21	8.8 (6.0–17.2)	93
	4	20	19	8.1 (4.6–11.9)	88
	Summary	Median: 21	Median: 20	Median of all trials: 10.2 (5.5–18.1)	Total: 352
Without ICMS feedback	1	19	23	14.0 (11.1–30.9)	88
	2	16	19	27.6 (18.8–37.2)	55
	3	17	23	18.7 (12.3–41.7)	74
	4	17	13	40.5 (15.5–48.4)	98
	Summary	Median: 17	Median: 21	Median of all trials: 20.9 (13.1–40.5)	Total: 315

per transfer without ICMS to 2.3 ± 0.4 s per transfer with ICMS (p = 0.002, Student's t test; Fig. 3A). With ICMS, the participant moved the prosthetic hand significantly less in the object zone (32.4 ± 5.9 cm per transfer with ICMS, 44.2 ± 13.1 cm per transfer without ICMS, p = 0.0007, Student's t test; Fig. 3B) and spent less time in the immediate vicinity of the object (Fig. 3C). The time spent in the target zone also decreased, whereas the time spent in the transit zone was unaffected (Fig. 3A and table S3). Overall, 352 transfers were completed with ICMS and 315 transfers were completed without ICMS (Table 1), and the number of transfers increased from 15.8 ± 3.8 transfers per 2-min trial to 17.8 ± 2.4 transfers per trial with ICMS, though this difference was not statistically significant (p = 0.050, Student's t test).

Because differences in neural decoder performance could lead to differences in the ability to control the arm, it is possible that the improvements on days with artificial tactile feedback were simply due to the decoder. We therefore used a random target sequence task (*6*) each day to measure how well the participant could independently control each degree of freedom. This task was always performed without ICMS (fig. S3). On days when functional tasks were completed with ICMS, fewer target sequence trials were successfully completed (table S4). The median endpoint translation velocity of the robot during the sequence task was also slightly slower (table S4), suggesting that the decoder performance itself—and thus the participant's ability to control the robotic arm—was not biased toward better performance on days with ICMS.

Creating artificial tactile feedback using a bidirectional BCI substantially improved functional performance during reaching and grasping tasks compared with a motor-only BCI with visual feedback. In contrast to many studies where the effects of artificial sensations on task performance are measured without visual or auditory feedback (*14*, *15*, *23*–*27*), our aim was to determine whether a bidirectional BCI would improve performance on tasks that were already possible with existing sensory modalities, namely vision. This bidirectional BCI taps into cortical sensorimotor systems that remain intact after injury, allowing a person with chronic tetraplegia to, in some cases, perform functional tasks at able-bodied speeds.

This better performance was driven primarily by reducing the time spent attempting to grasp objects. Indeed, in the ARAT task, the grasp time decreased by more than half with ICMS, accounting for 88% of the overall time reduction. Without tactile sensations, the participant spent more time placing the hand in a position that would ensure a stable grasp. Small performance gains also occurred during the reaching phase when ICMS was not delivered. This improvement suggests that the participant approached the task with increased confidence and speed when he knew that ICMS-evoked tactile sensations would signal object contact. Similar effects were observed during the object-transfer task; shorter path lengths near the object indicate fewer corrective movements and increased confidence.

As with any single-subject study, it is not guaranteed that these findings will generalize to future experiments and participants. However, there are several reasons to believe that these results indicate the potential of restoring somatosensory percepts using ICMS in a bidirectional BCI. First, using the same fundamental neural decoding and control methods, two participants have achieved similar scores on functional tasks with vision alone (*5*, *6*, *28*). With the current participant, these scores were only exceeded when ICMS-evoked tactile feedback was provided (Fig. 2A), suggesting that without artificial tactile feedback, control is impaired, much as it is when tactile sensations are absent in people with otherwise normal motor control capabilities (*13*, *29*). Second, performance improvements were driven primarily by reductions in the time taken to successfully grasp an object (Figs. 2D and 3A). State transitions, such as object contact (*30*) during grasping, are explicitly encoded by tactile feedback in the intact nervous system. That the percepts signaled these state transitions with high temporal accuracy and enabled the participant to grasp objects more quickly suggests that ICMS delivered to area 1 of the somatosensory cortex improves task performance in a way that is congruent to the way natural cutaneous feedback improves grasp performance. In a similar way, behaviorally relevant state transitions also occur during object release (*30*), potentially explaining the slightly improved times during the transport phase in the ARAT task and the time spent in

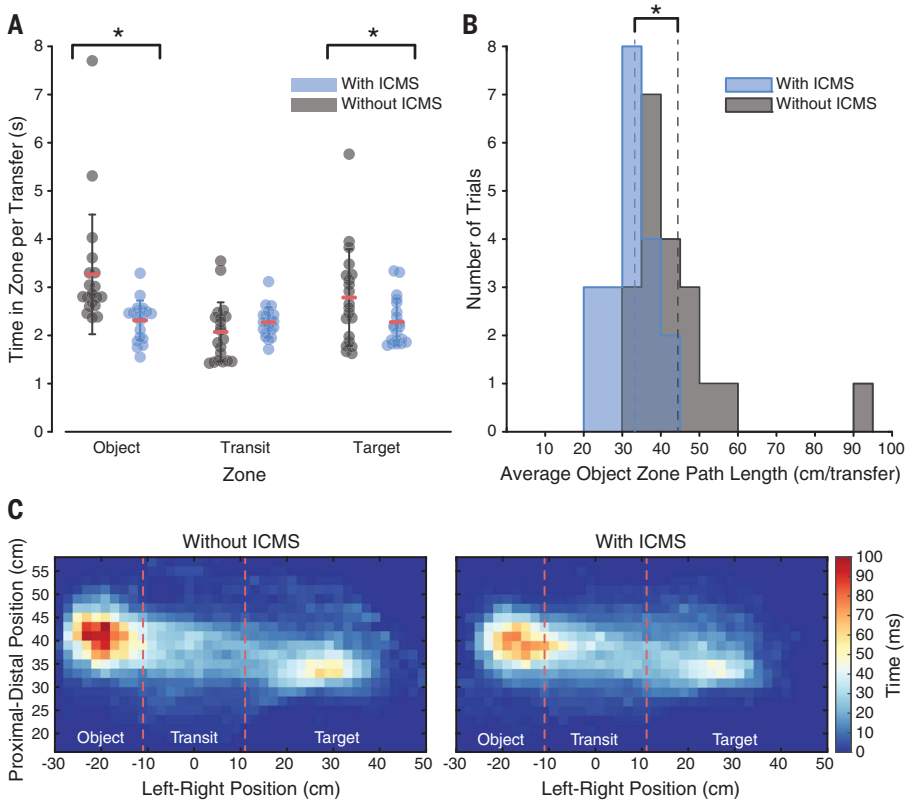

Fig. 3. Effect of ICMS on object-transfer performance. (**A**) Amount of time spent in each task zone, per transfer, by feedback condition (n = 20 trials per feedback condition). Data for all trials are shown, with the mean value indicated by the red lines and the whiskers indicating one standard deviation. The amount of time spent in the object and target zones decreased significantly with ICMS feedback (*p = 0.002 and 0.048, respectively; Student's t test). (**B**) Distribution of average path lengths in the object zone per trial for the two feedback conditions, computed as the total path length divided by the number of transfers. Mean path length decreased with ICMS feedback (*p = 0.0007, Student's t test). (**C**) Spatial map of the average amount of time spent in each location in the workspace per transfer. Each individual square represents a 2-cm–by–2-cm region of the workspace. The color indicates the average amount of time spent in each location per transfer. Without stimulation, more time was spent near the object in the object zone, as shown by the darker red colors in the object zone. Red dashed lines indicate zone boundaries.

the target zone in the object-transfer task. Finally, when ICMS-induced percepts were provided after 2 years of consistent ARAT scores, performance improved significantly, and when they were removed, performance returned to pre-ICMS levels (Fig. 2A). These observations suggest that the improvements were primarily due to the addition of reliable sensory information, rather than the result of additional practice. This immediate performance improvement also demonstrates that ICMS in the somatosensory cortex was not akin to sensory substitution cues that could have been provided by electrical or mechanical stimulation of intact skin or audio or visual cues, because the relationship between these cues and behavior must be learned (*31*). This learning requirement and other factors related to attentional load have limited the impact of sensory substitution in real-world scenarios (*32*). The immediate improvements that we observed with ICMS in area 1 also demonstrate the benefits of providing intuitive feedback. By contrast, ICMS feedback in a relevant area of the cortex, but in an unintuitive way, requires considerable learning time (thousands of trials) to use effectively (*33*).

In this study, we chose one sensory encoding scheme that leveraged two capabilities of ICMS—variable intensity and multiple focal percepts (*19*)—to provide proportional feedback that evoked sensations localized to individual fingers (figs. S1 and S2). Future work should examine how the stimulation encoding design (e.g., proportional versus on-off) may affect performance across a wide range of tasks. For example, the participant rarely dropped any of the objects once they were successfully grasped. However, many of the objects were rigid, and there was no penalty for grasping the objects too firmly. Tasks that involve fragile objects or more precise control of hand posture and grasp force could be more dependent on specific sensory encoding schemes.

Ultimately, ICMS-induced tactile percepts improved task performance to levels never previously observed, decreased the time spent reaching and grasping in ways that were analogous to the role of natural tactile sensations during grasp state transitions, and do not appear to be the result of practice. That artificial tactile sensations substantially improved performance demonstrates that engineered approaches that mimic known sensorimotor circuits—albeit imperfectly at present—will have a major impact on the future performance of BCIs. This is particularly important for individuals with conditions such as SCI where the peripheral nervous system is no longer intact.

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SUPPLEMENTARY MATERIALS

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Materials and Methods
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A boost for brain–computer interfaces

The finely controlled movement of our limbs requires two-way neuronal communication between the brain and the body periphery. This includes afferent information from muscles, joints, and skin, as well as visual feedback to plan, initiate, and execute motor output. In tetraplegia, this neural communication is interrupted in both directions at the level of the spinal cord. Brain–computer interfaces have been developed to produce voluntary motor output controlled by directly recording from brain activity. Flesher *et al.* added an afferent channel to the brain–computer interface to mimic sensory input from the skin of a hand (see the Perspective by Faisal). The improvements achieved by adding the afferent input were substantial in a battery of motor tasks tested in a human subject.

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