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A novel robot-assisted method for implanting intracortical sensorimotor devices for brain-computer interface studies: principles, surgical techniques, and challenges

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Precise anatomical implantation of a microelectrode array is fundamental for successful brain-computer interface (BCI) surgery, ensuring high-quality, robust signal communication between the brain and the computer interface. Robotic neurosurgery can contribute to this goal, but its application in BCI surgery has been underexplored. Here, the authors present a novel robot-assisted surgical technique to implant rigid intracortical microelectrode arrays for the BCI. Using this technique, the authors performed surgery in a 31-year-old male with tetraplegia due to a traumatic C4 spinal cord injury that occurred a decade earlier. Each of the arrays was embedded into the parenchyma with a single insertion without complication. Postoperative imaging verified that the devices were placed as intended. With the motor cortex arrays, the participant successfully accomplished 2D control of a virtual arm and hand, with a success rate of 20 of 20 attempts, and recording quality was maintained at 100 and 200 days postimplantation. Intracortical microstimulation of the somatosensory cortex arrays elicited sensations in the fingers and palm. A robotic neurosurgery technique was successfully translated into BCI device implantation as part of an early feasibility trial with the long-term goal of restoring upper-limb function. The technique was demonstrated to be accurate and subsequently contributed to high-quality signal communication.

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Motor impairment of the upper limbs is a subsequent dysfunction following various neurological disorders. Traumatic spinal cord injury is one of the major causes of the impairment, with 250,000 to 500,000 individuals impacted every year worldwide.[1] Of those injuries, approximately 55% are likely to localize to the cervical spine, with the greatest proportion at the C4 level (15.7%), where the impairment leads to severe motor and sensory limitations.[2] The impairment can reduce independence and quality of life and imposes physical, mental, social, financial, and caregiver burdens.[1]

Brain-computer interfaces (BCIs) are an emerging solution for restoring upper-limb motor function. A fundamental aspect of this approach is the high-quality, robust signal recordings obtained by precise intracortical microelectrode array implantations.[3–7] From the surgical aspect, precise array positioning, proper alignment between electrode shanks and insertion axis, and minimal vascular and cortical tissue damage by insertion have been shown to be essential to achieve the high signal quality, stability, and longevity of device communication after the implantation.[4,8–11] In addition, building on the pioneering success of motor cortex BCIs for upper-limb motor control,[12–15] recent advances in the neuroscience and neuroengineering fields have demonstrated further improvement of motor function by targeting areas other than the motor cortex. For example, one notable development involves targeting distinct digit areas within the somatotopically organized

ABBREVIATIONS BCI = brain-computer interface; fMRI = functional MRI.
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somatosensory cortex, facilitating enhanced motor control performance.[16,17] This development subsequently requires neurosurgeons to perform highly precise and repetitive implantations, while managing time-consuming maneuvers efficiently. Thus, the demand for surgical procedures using the BCI has been rising and is anticipated to grow even more.

Using presurgical imaging, robotics in neurosurgery provides highly accurate positioning with sophisticated computation, semiautomated motion guidance, and rigid holding ability, which in turn reduces exhaustion to repetitive motion, human errors, and operation time.[18,19] Utilization of robotic technology is taking precedence in epilepsy, functional, and spinal surgery among the neurosurgical fields. Robotic techniques can theoretically contribute to precise positioning of the multiple microelectrode arrays and subsequent sufficient signal recordings in the BCI.[20] However, even among the cutting-edge research groups in the field, translation of robotic neurosurgery techniques to the BCI has been largely undocumented.[10,12–14,16,17,21–29]

Here, we present a BCI case in which a robotic neurosurgery technique was utilized for surgical planning and guidance. The participant, who had tetraplegia due to a spinal cord injury, underwent the implantation of four microelectrode arrays (Utah Array, Blackrock Neurotech;[30] which is the most widely used array for the BCI), which enabled successful sensorimotor BCI performance, substantiating the promise of the approach. We further discuss the future challenges of surgical aspects of the BCI via this case demonstration.

Methods

The robotic surgical protocol was developed based on our team's extensive experience with hundreds of cases treating refractory epilepsy and movement disorders.[31,32] This robotic surgery experience was combined with expertise in implanting intracortical microelectrode arrays in humans and animals.[33] The motivation for using a robotic surgery technique lies in its core competencies: high accuracy, time efficiency, reducing human error, and minimizing surgeon burden in repetitive procedures.[18] In the participant in this study, we implanted four microelectrode arrays (Blackrock Neurotech): two in the hand and arm area of the motor cortex (96 wired electrodes, 4 × 4–mm array, 1.5-mm-long electrode, sputtered iridium oxide film) and two in area 1 of the somatosensory cortex (32 wired electrodes, 2.4 × 4–mm array, 1.5-mm-long electrode, sputtered iridium oxide film). The methods and hardware required to conduct neural recording and microstimulation experiments following array implantation have been described elsewhere.[14,16,34] The study was conducted under an investigational device exemption from the US Food and Drug Administration and approved by the institutional review board at the University of Pittsburgh. Informed consent was obtained before the study procedures were performed.

Participant History

At the time of implantation, the participant was a 31-year-old male with a traumatic C4 spinal cord injury (American Spinal Injury Association Impairment Scale grade A) secondary to a fall 10 years prior. The participant is dependent for all mobility and activities of daily living but is able to control a power wheelchair with head controls and his touchscreen computer with a stylus.

Operation

Preoperative Preparation

For the preoperative planning, structural 3T MRI (MPRAGE, 1-mm isotropic voxels with and without contrast, TR 2400 msec, TE 3.09 msec, TI 1000 msec, flip angle 8°, acquisition matrix 256 × 256 × 192, GRAPPA factor 2) and functional MRI (fMRI; acquired with 32 slices centered on the anatomical hand knob using 2-mm isotropic voxels, TR 2000 msec, TE 30 msec, acquisition matrix 94 × 110 × 32, flip angle 90°, GRAPPA factor 3) were performed during sensorimotor tasks and the images were used to determine the array locations as previously described.[14,16,17,34] The cortical surface was created from the structural MR images and overlaid with the fMRI activation map to determine array placement (Fig. 1A). The array location was determined via consensus of the study team based on discussions about the imaging results, and the location plans were proposed independently by multiple study investigators. The structural MR images were uploaded to a robotic stereotactic system (ROSA, Zimmer Biomet). Using ROSA software's planning function, we created the trajectories for array insertion points on the motor cortex for the shoulder and hand, and on the somatosensory cortex for the index finger and thumb (Fig. 1B–D). Using the postcontrast T1-weighted images, we confirmed the trajectories so that they did not interfere with any visible vessels.

Workflow for Microelectrode Array Installation

On the day of surgery, the surgical team and neural engineering team prepared the surgical field and microelectrode array verification, respectively, to minimize the procedure time.

Under general anesthesia, a Mayfield 3-pin clamp was used for head fixation, with the head rotated 60° contralateral to the array insertion side (Fig. 2A). The robotic system was connected to the head clamp, and registration was performed through the laser surface pointing system. The registration was confirmed when the accuracy was satisfactory (< 0.75 mm).[31,35] Then, the operating table was locked and unplugged to prevent accidental imprecision. The sagittal midline of the head was marked to locate the planned percutaneous connector (pedestal) positions. Placement of the horseshoe skin incision and craniotomy was designed such that the trajectories were surrounded using the guidance of the robotic system (Fig. 2B and C). These designs were defined considering that each pedestal incorporates one array for the motor cortex and one for the somatosensory cortex, connected via a 15-cm-long wire bundle. Antibiotics were given and the patient was prepped and draped in the usual craniotomy fashion. The skin incision and a craniotomy were performed using a No. 15 blade knife and a high-speed pneumatic drill (Midas Rex, Medtronic), but the dura mater was not opened until

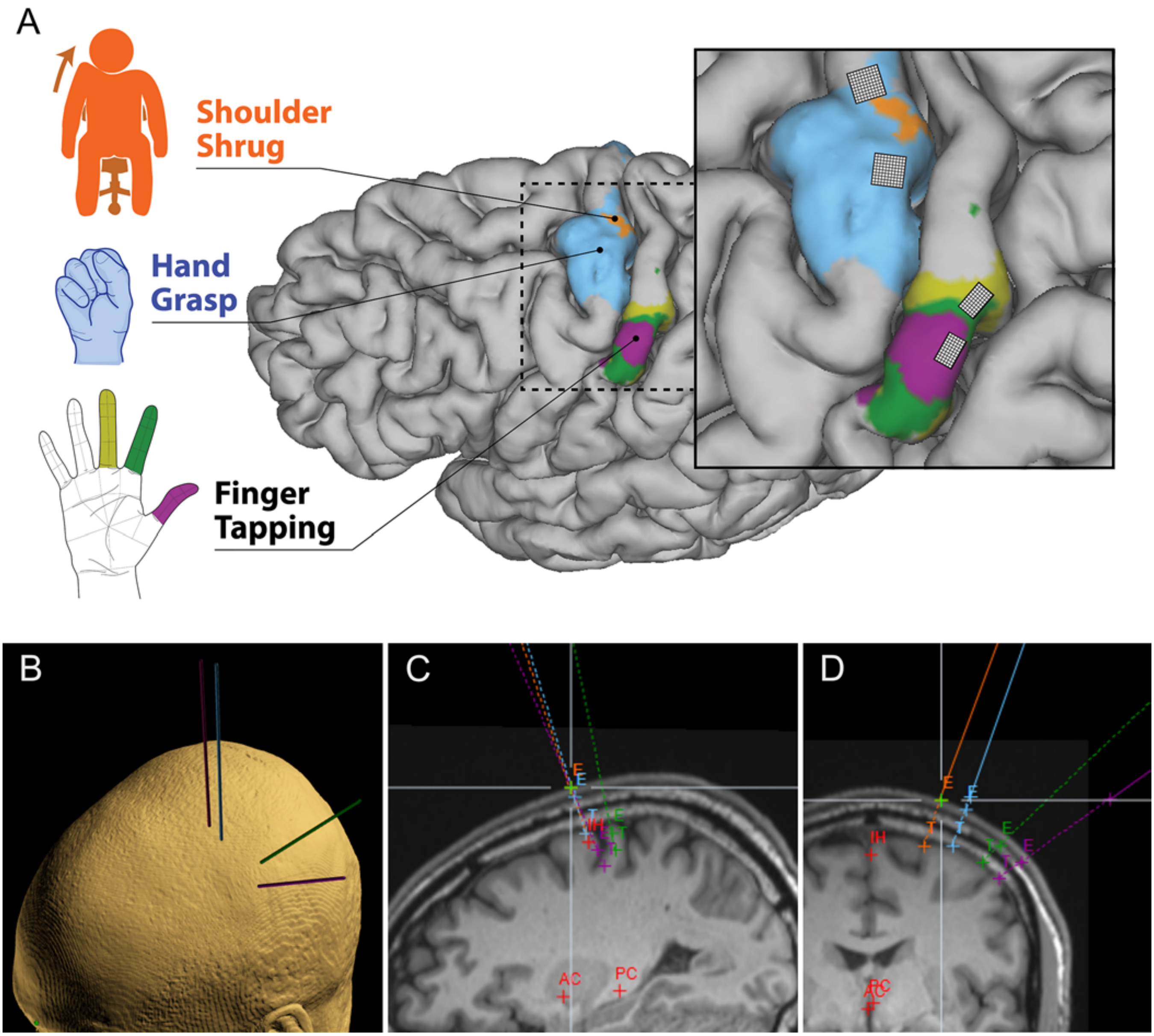

FIG. 1. Preoperative planning. **A:** Coregistered T1-weighted MR image (MPRAGE) and processed fMRI data showing activation for shoulder (*orange*) and hand (*blue*) movements in the motor cortex, and thumb (*purple*), index finger (*green*), and middle finger (*yellow*) representations in the somatosensory cortex. Planned array locations based on team consensus are shown as *rectangular/square grids*. **B:** A general view of trajectories indicating the four insertion points as seen from above the scalp. **C and D:** Four trajectories for shoulder (*red*), hand motor (*blue*), index finger (*green*), and thumb sensory (*purple*) areas on the MR images (sagittal [C] and coronal [D] sections) depicted in the native software of the robotic system. The targets of the trajectories are at the brain surface where the fMR image indicated increases in activity in the motor and somatosensory cortices, and where the ideal array locations were planned (A). AC = anterior commissure; E = entry point; IH = interhemispheric point; PC = posterior commissure; T = target point. Figure is available in color online only.

the other preparations for the arrays were completed (Fig. 2D). When the craniotomy was performed, the neural engineering team simultaneously inspected the Utah Array (Fig. 2E and F). After verification, the devices were carefully carried to the operating table.

Two skin incisions, remote from the craniotomy and along the midline of the head, were made for postoperative access to the pedestals. The array insertion points, as well as the central sulcus and sensorimotor cortex, were again checked with the robotic system before starting the dural incision (Fig. 3A and B). Then, a small dural incision was made just above the insertion point. The insertion point on the brain surface was marked immediately after the dural opening, guided by the robotic system's trajectory (Fig. 3C). In order to minimize deviation from the preoperative plan due to brain shift, mannitol was not used. Following the markings for each of the arrays, the dura mater was opened widely so that the brain surface could be exposed

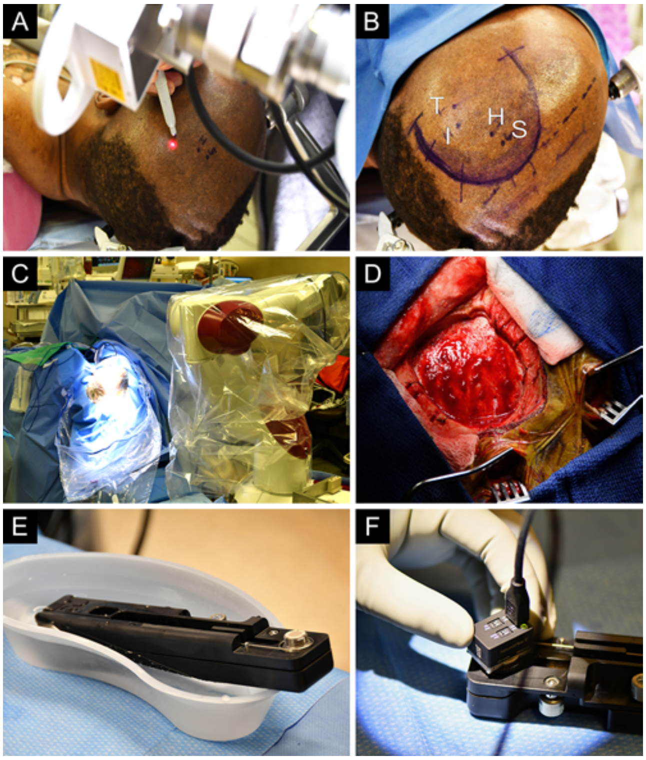

FIG. 2. Operation workflow (before implanting the microelectrode arrays). The surgical team positioned the patient with his head fixed in a 3-pin skull clamp and rotated 60°, and set up the robotic system by connecting it to the head clamp set. **A:** Through use of the laser pointing (*red*) function of the trajectories, insertion points of the microelectrode arrays were marked. **B:** Once all insertion points were marked, a craniotomy and skin incision were designed to encompass them. **C:** A general view of setting after draping. **D:** A postcraniotomy surgical view. Two skin incisions for the device connectors (pedestals) were opened using retractors. **E and F:** The Utah Array is visually inspected by the neural engineering team to ensure the device is undamaged, as a standard procedure. Optionally, the array can be checked by submerging it in a tray of normal saline (E) and connecting a NeuroPlex E headstage (Blackrock Neurotech) (F). H = hand motor; I = index sensory; S = shoulder motor area; T = thumb sensory. Figure is available in color online only.

for visual inspection (Fig. 3D). The pedestals were then guided under the skin toward the incisions. The microelectrode arrays were positioned outside the craniotomy field, stabilizing unexpected movement (Fig. 3E). Congruency between the preoperative plan and brain surface marking was verified by both the surgical and neural engineering teams, and fine-tuning adjustments were implemented for small vessels that were invisible on the preoperative imaging. Then, the devices were laid out over the insertion points while being mindful of the shape memory properties of the wire bundles (Fig. 3F).[36] Once deployed, all arrays were inserted into the parenchyma using a pneumatic insertion device.[37] The insertion trajectories were aligned with those planned in the robotic system such that the impact vector was perpendicular to the brain surface, as it conveys maximum penetration force and avoids reinsertions and oblique insertions (Fig. 3G–I). We observed local subarachnoid hemorrhage after the insertions, but all of them were embedded with a single impact. Magnified images with a high-resolution camera confirmed that all the arrays were fully embedded into the parenchyma (Fig. 3J and K). We further confirmed their placement using a flexible endoscope, allowing real-time visualization of device insertions (Video 1).

VIDEO 1. Video clip demonstrating confirmation of the microelectrode array implantation using an endoscope. © Jorge A. Gonzalez-Martinez, published with permission. Click here to view.

After the verification, dural closure was performed without anchoring the device's lead to the dura (Fig. 3L). The leads were routed subcutaneously through the burr hole toward the pedestals. Skin closures and dressings were placed in the usual fashion, and after the patient emerged from anesthesia he was extubated. The operation time was 4 hours 19 minutes. The volume of blood loss was too small to measure but was estimated to be less than 50 ml.

Results

A fusion image of the preoperative T1-weighted MR image and postoperative CT scan shows that the devices were positioned as intended (Fig. 4A and B). No acute hemorrhagic or other types of complications were observed on the postoperative CT scan (Fig. 4C). The participant developed a local and limited skin infection after surgery, which was treated with focal skin debridement and short-term antibiotics, resulting in complete resolution.

Postoperative experimental protocols were performed by the neural engineering team through the externalized pedestals (Fig. 4D). At 14 days postimplantation, the participant attempted 2D control of a virtual arm and hand using the motor cortex arrays for the first time and was successful on 20 of 20 attempts (Video 2).

VIDEO 2. Video clip demonstrating the participant's first attempted brain-controlled movement of the virtual arm toward the target 2 weeks after implantation. The BCI was calibrated as in a previous report[14] to enable the participant to control 2D endpoint velocity of the hand using neural activity generated by the participant attempting to move the virtual arm. The 2D BCI enabled the participant to move the hand to any location in a vertical plane. For each trial, a transparent target appeared, and when signaled by the audio cue, the participant attempted to reach toward the target within a predefined radius of success. After successfully acquiring the target, the hand was paused by the computer, a new target appeared, and then an audio cue signaled the transition to brain control. © Jennifer L. Collinger, published with permission. Click here to view.

At 14 days 6 months postimplantation, multiple microstimulation surveys were conducted for each electrode of the somatosensory cortex arrays and elicited sensations in the little, ring, and middle fingers, and at the base of the index finger or thumb on the palm. At the time of this writing (approximately 1 year postimplantation), the devices remain functional and the clinical trial and associated experiments are ongoing. Figure 5 illustrates the recording quality from the motor arrays at 14, 100, and approximately 200 days postimplantation, and evoked sensations through intracortical microstimulations on the somatosensory cortex arrays.

Discussion

We described the rationale for and utility of robotics

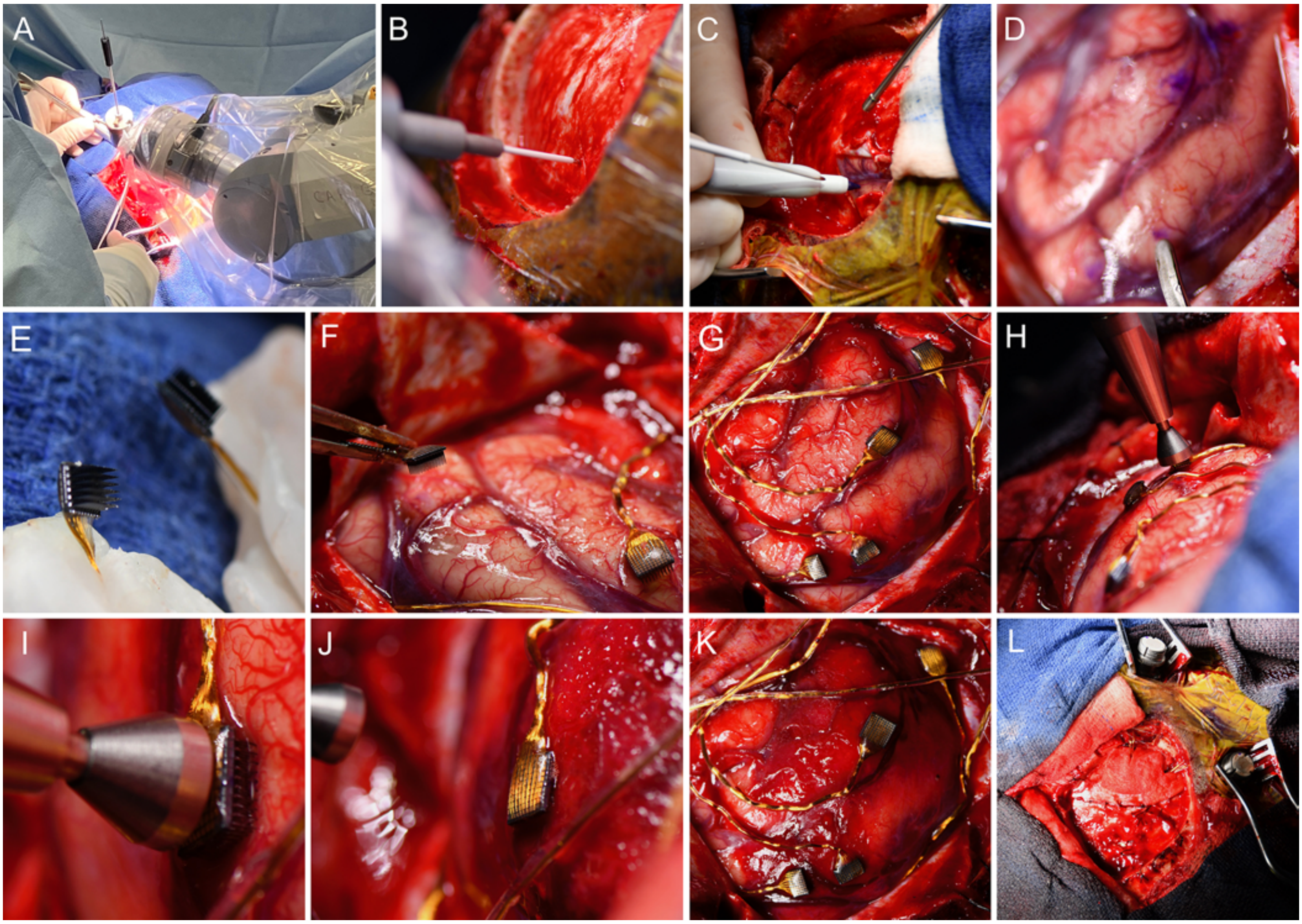

FIG. 3. Operation workflow (microelectrode array insertion). **A:** The robotic system indicated an insertion point on the dura mater. **B:** Magnified view. **C:** The dura mater was opened with a small incision, guided by the robotic system. Immediately after that, the insertion point was marked with a pen at the cerebral surface. **D:** The four insertion points were marked and the dura mater was fully opened. The tip of a micro spatula indicated the somatosensory area for the thumb. **E:** The Utah Arrays were held by bone wax. Note that the electrodes are delicate and fragile, requiring careful handling. **F and G:** The arrays were deployed to the planned points. **H:** The pneumatic insertion device was positioned over the middle of the back of the array, perpendicular to the brain surface. **I:** A magnified image of the pneumatic insertion device head before the impact. The microelectrode was slightly pressing on the brain surface but had not yet been inserted. **J:** Microelectrodes were inserted by the pneumatic device that uses a high-speed plunger on the back of the array. Note that the microelectrode shanks were embedded in the brain and not visible at this point. **K:** All arrays inserted into the brain. Note that the position of the arrays was identical to the planned location (G). **L:** A general view of the device installation after dural closure. Figure is available in color online only.

in BCI surgery and reported a case of robot-assisted BCI implantation in which four intracortical microelectrode arrays were implanted in the sensorimotor cortex of a man with tetraplegia due to a C4 spinal cord injury. Specifically, the robotic stereotactic system was used to plan the array location and insertion trajectories, which then informed the craniotomy location and enabled intraoperative confirmation of expected array placement. Preoperative plans and surgical flow were conceived based on our extensive experience, and those were translated into the implementation of a safe, feasible, and precise robot-assisted surgical approach.[18,34] Consequently, all the arrays were successfully inserted and the signals from the implanted arrays demonstrated the expected motor activity suitable for BCI control and sensory responses suitable for restoration of touch. Robotic neurosurgery is well suited for the BCI, and its use will likely continue to expand in the near future. Future studies may incorporate surgical robots into the surgical procedures themselves, assisting with opening the craniotomy or inserting the arrays directly.

The approach utilized here is a precise targeting technique for the implantation plan of an intracortical sensorimotor BCI, especially rigid microelectrode arrays, such as the Utah Arrays. This technique can be applied to implantation targets beyond the sensorimotor cortex. For example, some studies have targeted the posterior parietal cortex, premotor cortex, or Broca's area.[21,38] From a comparative viewpoint of surgical technique, image-guided surgery has been the conventional standard approach for BCI implantation. This approach is simple and time-efficient, but its accuracy is limited because aligning the

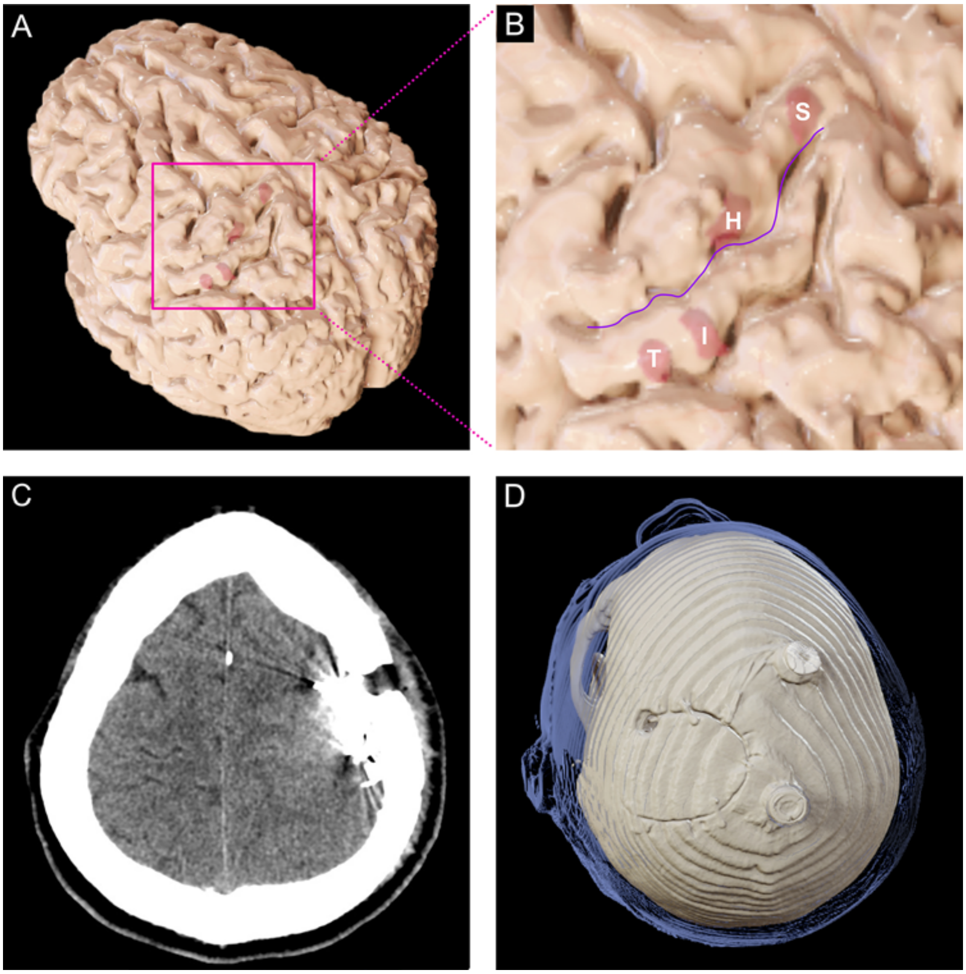

FIG. 4. Postoperative images. **A:** A 3D brain surface image with microelectrode arrays. The array was depicted as the object (*red*). The objects were depicted by localizing the microelectrode arrays on the fusion images of a postoperative CT scan and preoperative T1-weighted MR image (MPRAGE). **B:** A magnified 3D image showing the location of each array around the central sulcus (*purple line*). Note that the positions of the array depicted are consistent with the insertion points as intended (see Fig. 3). **C:** An axial postoperative CT scan showing device artifact without any surgical complications. **D:** A 3D postoperative bone image showing the connectors of the device (pedestals) and the craniotomy field where the arrays were implanted. Figure is available in color online only.

marking with the trajectory relies on targeting through human hands, using a handheld pointer. Another approach is conventional stereotactic frame-based surgery. However, a considerable number of papers have indicated that robotic surgery has a greater time efficiency and may have equivalent or higher accuracy compared with the classic stereotactic approach.[18,31] The advantage of a frame-based approach using a rigid reference frame lies in the ability to simulate the trajectory on a phantom, improving accuracy and precision before the actual procedure. Furthermore, the robotic system accurately projected the array locations to the skin surface using the laser indicator, assisting in planning the skin incisions and craniotomy. Therefore, a robot-guided method, which has the advantage of repetitive, rapid, and precise motion without human errors, substantially assists in overcoming the challenges inherent in BCI implantation with a need for accurately targeting multiple insertion points.

In this case, we implanted four arrays, and they were each inserted with a single impact of a pneumatic device. Because there are no avascular areas in the cerebral cortex, intracortical array insertion poses the unavoidable risks of small-vessel disruption and hemorrhage, which lead to neuronal loss and signal quality degradation.[10] Moreover, each insertion causes mechanical disruption to the cortex that may initiate a foreign body response, which can result in signal instability.[4] Hence, to avoid multiple reinsertion maneuvers that increase the chances for cortical damage, we visually aligned the array and pneumatic device perpendicular to the brain surface. In the future, to improve reliability and increase time efficiency, it would be desirable if the maneuver could be semiautomatically controlled by robotics. The real-time visual feedback via endoscopy that we demonstrated potentially contributes to such a system in the device position control. In this respect, Neuralink's light-based automatic real-time feedback approach is advanced.[20] Furthermore, its almost fully robotic approach has promising time efficiency, yet its impact on

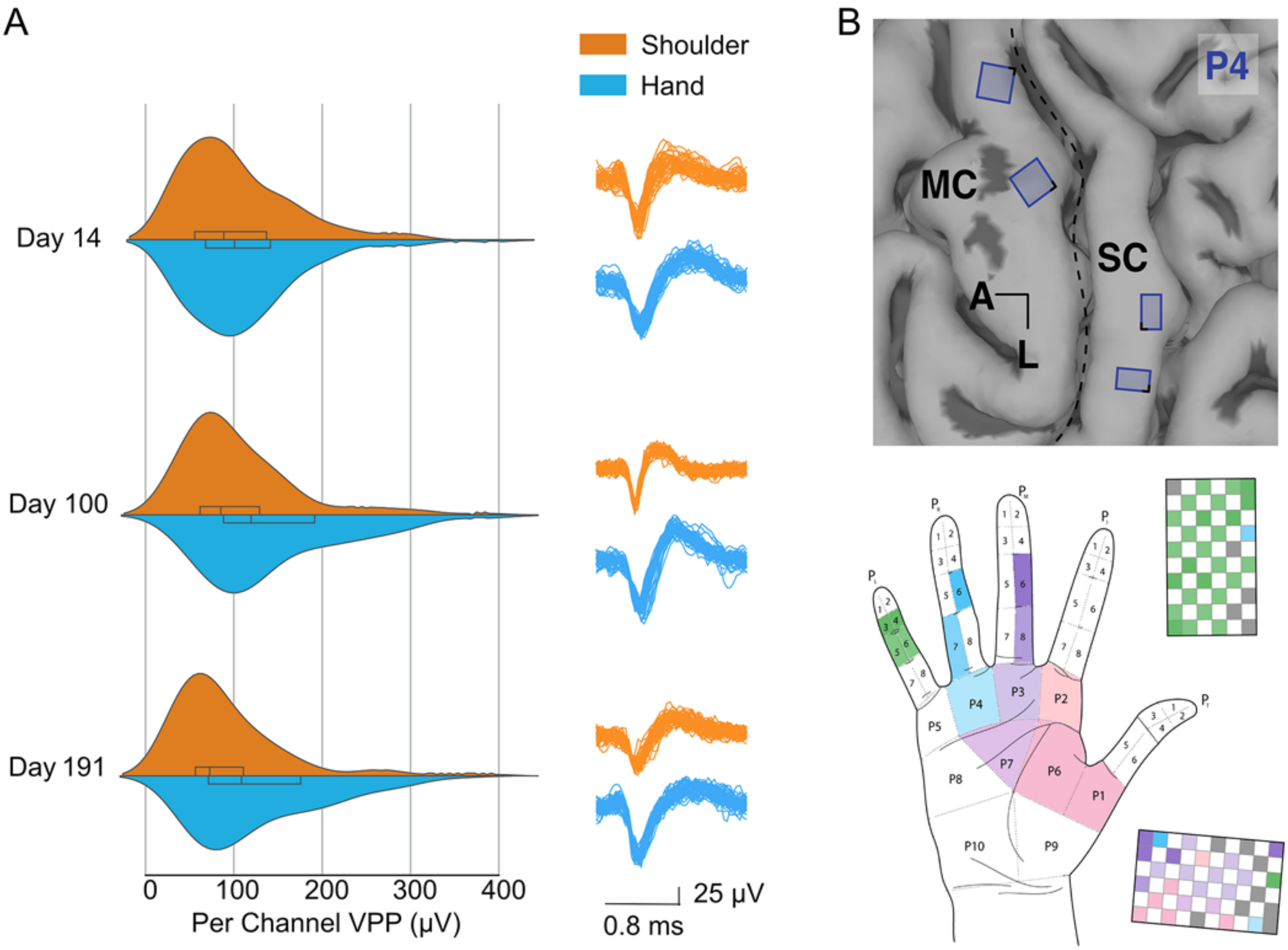

FIG. 5. Neural signal stability. **A:** Distribution of median peak-to-peak voltage amplitudes across all channels of the medial (targeting the shoulder motor area: *orange*) and lateral (targeting the hand motor area: *blue*) motor cortex arrays (*left*), and 50 representative waveforms from a channel with the median peak-to-peak voltage value (VPP) for each array (*right*) across 3 time points postimplantation, showing that high signal quality was maintained. **B:** Array locations and illustrations of hand and magnified arrays colored based on the projected fields elicited by intracortical microstimulations for each electrode. The *blue boxes* in the *upper image* represent the intended locations of the microelectrode arrays. The illustration shows the centroid of the projected field across all survey repetitions of each electrode. The lateral array mainly corresponds to the thumb to middle finger, while the medial array corresponds to the little finger. Further details regarding this result are discussed elsewhere (Downey et al., 2024).[34] MC = motor cortex array; P_I = index finger projection; P_L = little finger projection; P_M = middle finger projection; P_R = ring finger projection; P_T = thumb projection; SC = somatosensory cortex array. Figure is available in color online only.

safety and accuracy, as well as on the outcome of the BCI itself, remains to be evaluated.[39]

A further challenge in this process lies in establishing a standard insertion method that is reliable and less dependent on human involvement for current state-of-the-art intracortical devices that underpin the bulk of the BCI works to date,[40,41] as well as developing and improving surgical techniques that allow new technologies to be applied to interventional devices while advances in neuroscience and neuroengineering continue. Meeting this challenge will likely include the involvement of neurosurgeons in the device development stage. Moreover, while robotic guidance in surgical procedures is undisputed in accuracy, there remains the intraoperative challenge of refining the insertion location to account for microvessels that were invisible during preoperative imaging. Therefore, multidimensional approaches are required to further improve the methodology.

Limitations

We evaluated signal robustness over a relatively short follow-up period of approximately 1 year and in a single participant; thus, a validation study with a larger number of participants with long-term follow-up is required. Despite this limitation, robotic surgery is a well-suited technique for BCI device implantation compared with the conventional approach and is adaptable to future advances in this field.

Conclusions

A robot-assisted neurosurgery technique was successfully translated into BCI device implantation as part of an early feasibility trial with the long-term goal of restoring upper-limb function. The technique was demonstrated to be accurate and time-efficient, and subsequently contributed to high-quality signal communication.

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References

1. Spinal cord injury. World Health Organization. Accessed September 17, 2024. https://www.who.int/news-room/fact-sheets/detail/spinal-cord-injury
2. *The 2022 Annual Statistical Report Complete Public Version for the Spinal Cord Injury Model Systems*. National Spinal Cord Injury Statistical Center; 2022. Accessed September 19, 2024. https://www.nscisc.uab.edu/public/AR2022_public%20version.pdf
3. Collinger JL, Gaunt RA, Schwartz AB. Progress towards restoring upper limb movement and sensation through intracortical brain-computer interfaces. *Curr Opin Biomed Eng*. 2018;8:84-92.
4. Kozai TD, Jaquins-Gerstl AS, Vazquez AL, Michael AC, Cui XT. Brain tissue responses to neural implants impact signal sensitivity and intervention strategies. *ACS Chem Neurosci*. 2015;6(1):48-67.
5. Losanno E, Mender M, Chestek C, Shokur S, Micera S. Neurotechnologies to restore hand functions. *Nat Rev Bioeng*. 2023;1:390-407.
6. Pandarinath C, Bensmaia SJ. The science and engineering behind sensitized brain-controlled bionic hands. *Physiol Rev*. 2022;102(2):551-604.
7. Sponheim C, Papadourakis V, Collinger JL, et al. Longevity and reliability of chronic unit recordings using the Utah, intracortical multi-electrode arrays. *J Neural Eng*. 2021;18(6):10.1088/1741-2552/ac3eaf.
8. Kozai TD, Marzullo TC, Hooi F, et al. Reduction of neurovascular damage resulting from microelectrode insertion into the cerebral cortex using in vivo two-photon mapping. *J Neural Eng*. 2010;7(4):046011.
9. Polikov VS, Tresco PA, Reichert WM. Response of brain tissue to chronically implanted neural electrodes. *J Neurosci Methods*. 2005;148(1):1-18.
10. Szymanski LJ, Kellis S, Liu CY, et al. Neuropathological effects of chronically implanted, intracortical microelectrodes in a tetraplegic patient. *J Neural Eng*. 2021;18(4):0460b9.
11. Salatino JW, Ludwig KA, Kozai TDY, Purcell EK. Glial responses to implanted electrodes in the brain. *Nat Biomed Eng*. 2017;1(11):862-877.
12. Ajiboye AB, Willett FR, Young DR, et al. Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration. *Lancet*. 2017;389(10081):1821-1830.
13. Bouton CE, Shaikhouni A, Annetta NV, et al. Restoring cortical control of functional movement in a human with quadriplegia. *Nature*. 2016;533(7602):247-250.
14. Collinger JL, Wodlinger B, Downey JE, et al. High-performance neuroprosthetic control by an individual with tetraplegia. *Lancet*. 2013;381(9866):557-564.
15. Hochberg LR, Bacher D, Jarosiewicz B, et al. Reach and grasp by people with tetraplegia using a neurally controlled robotic arm. *Nature*. 2012;485(7398):372-375.
16. Flesher SN, Collinger JL, Foldes ST, et al. Intracortical microstimulation of human somatosensory cortex. *Sci Transl Med*. 2016;8(361):361ra141.
17. Flesher SN, Downey JE, Weiss JM, et al. A brain-computer interface that evokes tactile sensations improves robotic arm control. *Science*. 2021;372(6544):831-836.
18. Abou-Al-Shaar H, Mallela AN, Corson D, Sweat J, González Martínez JA. Robotics in epilepsy surgery. In: González Martínez JA, Cardinale F, eds. *Robotics in Neurosurgery: Principles and Practice*. 1st ed. Springer Cham; 2022:105-117.
19. Ball T, González-Martínez J, Zemmar A, et al. Robotic applications in cranial neurosurgery: current and future. *Oper Neurosurg (Hagerstown)*. 2021;21(6):371-379.
20. Musk E. An integrated brain-machine interface platform with thousands of channels. *J Med Internet Res*. 2019;21(10):e16194.
21. Aflalo T, Kellis S, Klaes C, et al. Neurophysiology. Decoding motor imagery from the posterior parietal cortex of a tetraplegic human. *Science*. 2015;348(6237):906-910.
22. Armenta Salas M, Bashford L, Kellis S, et al. Proprioceptive and cutaneous sensations in humans elicited by intracortical microstimulation. *eLife*. 2018;7:e32904.
23. Brandman DM, Hosman T, Saab J, et al. Rapid calibration of an intracortical brain-computer interface for people with tetraplegia. *J Neural Eng*. 2018;15(2):026007.
24. Eichenlaub JB, Jarosiewicz B, Saab J, et al. Replay of learned neural firing sequences during rest in human motor cortex. *Cell Rep*. 2020;31(5):107581.
25. Gilja V, Pandarinath C, Blabe CH, et al. Clinical translation of a high-performance neural prosthesis. *Nat Med*. 2015;21(10):1142-1145.
26. Guan C, Aflalo T, Zhang CY, et al. Stability of motor representations after paralysis. *Elife*. 2022;11:e74478.
27. Hochberg LR, Serruya MD, Friehs GM, et al. Neuronal ensemble control of prosthetic devices by a human with tetraplegia. *Nature*. 2006;442(7099):164-171.
28. Kim SP, Simeral JD, Hochberg LR, Donoghue JP, Black MJ. Neural control of computer cursor velocity by decoding motor cortical spiking activity in humans with tetraplegia. *J Neural Eng*. 2008;5(4):455-476.
29. Simeral JD, Kim SP, Black MJ, Donoghue JP, Hochberg LR. Neural control of cursor trajectory and click by a human with tetraplegia 1000 days after implant of an intracortical microelectrode array. *J Neural Eng*. 2011;8(2):025027.
30. Rousche PJ, Normann RA. Chronic recording capability of the Utah Intracortical Electrode Array in cat sensory cortex. *J Neurosci Methods*. 1998;82(1):1-15.
31. González-Martínez J, Bulacio J, Thompson S, et al. Technique, results, and complications related to robot-assisted stereoelectroencephalography. *Neurosurgery*. 2016;78(2):169-180.
32. Mallela AN, Beiriger J, Gersey ZC, et al. Targeting the future: developing a training curriculum for robotic assisted neurosurgery. *World Neurosurg*. 2022;167:e770-e777.
33. Collinger JL, Kryger MA, Barbara R, et al. Collaborative approach in the development of high-performance brain-computer interfaces for a neuroprosthetic arm: translation from animal models to human control. *Clin Transl Sci*. 2014;7(1):52-59.
34. Downey JE, Schone HR, Foldes ST, et al. A roadmap for implanting microelectrode arrays to evoke tactile sensations through intracortical microstimulation. *medRxiv*. Preprint posted online April 28, 2024. doi: 10.1101/2024.04.26.24306239
35. McGovern RA, Knight EP, Gupta A, et al. Robot-assisted stereoelectroencephalography in children. *J Neurosurg Pediatr*. 2019;23(3):288-296.

36. Waziri A, Schevon CA, Cappell J, Emerson RG, McKhann GM II, Goodman RR. Initial surgical experience with a dense cortical microarray in epileptic patients undergoing craniotomy for subdural electrode implantation. *Neurosurgery*. 2009;64(3):540-545.
37. Rousche PJ, Normann RA. A method for pneumatically inserting an array of penetrating electrodes into cortical tissue. *Ann Biomed Eng*. 1992;20(4):413-422.
38. Willett FR, Kunz EM, Fan C, et al. A high-performance speech neuroprosthesis. *Nature*. 2023;620(7976):1031-1036.
39. Drew L. Neuralink brain chip: advance sparks safety and secrecy concerns. *Nature*. 2024;627(8002):19.
40. Maynard EM, Nordhausen CT, Normann RA. The Utah Intracortical Electrode Array: a recording structure for potential brain-computer interfaces. *Electroencephalogr Clin Neurophysiol*. 1997;102(3):228-239.
41. Sahasrabuddhe K, Khan AA, Singh AP, et al. The Argo: a high channel count recording system for neural recording in vivo. *J Neural Eng*. 2021;18(1):015002.

Disclosures

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Author Contributions

Conception and design: Gonzalez-Martinez, Ikegaya, Hatsopoulos, Downey, Boninger, Gaunt, Collinger. Acquisition of data: Ikegaya, Mallela, Warnke, Kunigk, Liu, Verbaarschot, Downey, Boninger, Gaunt, Collinger. Analysis and interpretation of data: Ikegaya, Mallela, Warnke, Kunigk, Liu, Schone, Verbaarschot, Hatsopoulos, Downey, Boninger, Gaunt, Collinger. Drafting the article: Gonzalez-Martinez, Ikegaya, Warnke, Liu, Verbaarschot. Critically revising the article: Gonzalez-Martinez, Ikegaya, Mallela, Warnke, Kunigk, Liu, Schone, Verbaarschot, Downey, Boninger, Gaunt, Collinger. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Gonzalez-Martinez. Administrative/technical/material support: Gonzalez-Martinez, Hatsopoulos, Boninger. Study supervision: Gonzalez-Martinez, Boninger.

Supplemental Information

Videos

Video 1. https://vimeo.com/1003215028.
Video 2. https://vimeo.com/1003217933.

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