Neuroprosthetic Limb Control with Electrocorticography: Approaches and Challenges

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Abstract—**Advanced upper limb prosthetics, such as the Johns Hopkins Applied Physics Lab Modular Prosthetic Limb (MPL), are now available for research and preliminary clinical applications. Research attention has shifted to developing means of controlling these prostheses. Penetrating microelectrode arrays are often used in animal and human models to decode action potentials for cortical control. These arrays may suffer signal loss over the long-term and therefore should not be the only implant type investigated for chronic BMI use. Electrocorticographic (ECoG) signals from electrodes on the cortical surface may provide more stable long-term recordings. Several studies have demonstrated ECoG's potential for decoding cortical activity. As a result, clinical studies are investigating ECoG encoding of limb movement, as well as its use for interfacing with and controlling advanced prosthetic arms. This overview presents the technical state of the art in the use of ECoG in controlling prostheses. Technical limitations of the current approach and future directions are also presented.**

I. INTRODUCTION

PROSTHESIS technology for both upper and lower limbs has advanced rapidly in recent years. Development of upper limb prosthetics in particular received a considerable boost from the Defense Advanced Research Project Agency (DARPA) in the first "Revolutionary Prosthesis" program. Subsequent investments, such as the Grand Challenge program by the National Institutes of Health, have continued to support this research, including the development of brain-machine interfaces (BMI) for prosthetic control. The DARPA program funded the development of the Johns Hopkins Applied Physics Lab (JHU/APL) Modular Prosthetic Limb (MPL) [1] as well as the "Luke" arm developed by DEKA, which has recently been FDA approved for electromyographic (EMG) control by amputees [2]. Commercial prosthetic development has also ramped up. A number of companies, including Touch Bionics and RSL Steeper, have created affordable prosthetic hands. Other companies, such as Hanger Orthopedics, Advanced Arm, and Infinite Biomedical Technologies, have begun equipping amputees with custom-fit prostheses. The most significant advance of this wave of prostheses has been a focus on more anthropomorphic designs, including multi-fingered hands and even wrist, elbow, and shoulder components. These impressive designs have created the challenge of achieving intuitive control of several degrees of freedom (DOF). The JHU/APL MPL, as an example, is capable of being actuated with 17 DOF.

Upper limb prostheses have traditionally either been body-powered—transferring motion from intact musculature to the prosthesis via a cable—or controlled using decoded myoelectric signals from the residual limb. These approaches are less invasive and less expensive than BMI solutions. However, these approaches are not suitable for quadriplegic patients whose residual motor functions cannot be leveraged for prosthetic control signals. With the help of extensive research into neural interfaces, the prospect of direct neural control has gained traction. Technology is now available to record from hundreds of neurons simultaneously using microelectrode arrays, an approach that is invasive yet capable of obtaining highly specific neural signals for prosthetic control. Alternatively, an array of electroencephalographic (EEG) electrodes can be placed on the scalp or an electrocorticographic (ECoG) grid can be placed over the cortex to derive neural control signals.

II. NEURAL PROSTHESIS

A. *Neural Signals: Microelectrodes and Spikes*

Neuroscience research has greatly benefited from advances in the development of microelectrode arrays and neurophysiological recording systems. Research-grade systems can record electrical activity from hundreds of neurons, capturing neural spike trains that code for various cortical functions. For decoding motor intention, microelectrode arrays are usually placed in the primary motor (M1) and/or premotor (PMd/PMv) areas, so that task-related spike trains can be recorded and analyzed. Surprisingly, BMI systems have achieved significant success using simple linear decoding models predicting movement kinematics from neural activity [3]. Research is also being carried out using more sophisticated techniques, such as point process models, Kalman filters, and maximum likelihood estimates of the expected movements (for example [4], [5]).

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BMI control of motor prosthetics using spike trains has been demonstrated in nonhuman primates in addition to human subjects. Earlier studies demonstrated decoding of center-out reach [6], and later studies have also demonstrated decoding of grasps [7] and finger movements [8]. These principles were even leveraged for impressive online demonstrations of cortically controlled prosthetic limbs [9], [10], [3]. While nonhuman primate studies have driven basic research into the neurophysiological correlates of dexterous motor control, subsequent human studies with paralyzed patients have proven that these principles can be applied to neural control of prosthetics to restore lost upper limb functionality [11]–[13]. These pioneering reports have laid the groundwork for providing neuroprosthetics to paralyzed individuals.

While transitioning from nonhuman primates to humans has been rapid, there are impediments to translating this work to more routine clinical use. These barriers pose economic, technical, and clinical challenges to the field. From an economic perspective, hindrances to widespread adoption include the high costs of the implantation surgery and the implants themselves, in addition to an unclear reimbursement strategy for the procedures. From a technical perspective, developing computationally tractable decoding models capable of controlling many DOF remains the goal. The structure of these models will also likely continue to evolve in parallel with our understanding of the neural encoding of complex finger, wrist, and arm movements. From a clinical perspective, the safety and reliability of the implantation procedure are paramount. In addition to honing the surgical technique to minimize trauma from the initial implantation, further research is needed to determine the effects of micromotion and gliosis around penetrating microelectrodes on long-term signal stability and tissue health. While the long-term safety and efficacy of microelectrode technology are being investigated, the need for alternative approaches is also clear.

B. Neural Signals: EEG and ECoG

EEG signals represent the summed dendritic potentials of a large number of neurons. The signals are readily analyzed by conventional methods such as power spectral analysis, which decomposes EEG into various clinically-used and interpreted bands (namely theta, delta, alpha, and beta bands). Alpha-range activity in movement-related electrodes, branded the mu band, has been commonly used to estimate motor intent for EEG BMI applications. There are several problems, however, associated with using EEG to control prosthetic limbs. A fundamental issue is that scalp-based recordings have limited spatial resolution and bandwidth relative to more invasive recording modalities. Current electrodes are also prone to noise and artifact, so are likely not suitable for long-term recording without daily re-application. The application of EEG to chronic neural control of prostheses is therefore limited by these factors.

ECoG signals provide a viable alternative to both EEG and microelectrode arrays. ECoG signals are recorded by placing electrodes on the surface of the cortex. Electrodes may be placed above or below the dura mater, called epidural or subdural, respectively. Greater proximity to the cortex conveys greater spatial specificity than EEG. These recordings also provide much greater sensitivity and signal quality for high frequency activity, including the high gamma band (70+ Hz), which has been found to be generalized index of cortical processing [14] and to correlate well with population firing rates [15].

Though benefiting from comparatively less history than single unit and multiunit studies, ECoG signals have rapidly been established as a useful command signal for upper limb motor BMIs. ECoG signals from humans have been used to decode two-dimensional joystick movements [16], three dimensional arm trajectories [17], slow grasping [18], individual finger movements [19], grasp timing [20], grasp types [21], and hand postures [22]. Online studies with human subjects have demonstrated continuous control over computer cursors [23], [24] and reaching and grasping of prosthetic limbs [25]–[27]. A recent study by Wang et al. even demonstrated that a quadriplegic individual could use ECoG features to control a cursor in three dimensions and obtain rudimentary prosthetic arm movement [27].

Currently, ECoG electrodes are surgically implanted in preparation for epilepsy surgery. While this procedure is invasive, the electrodes do not penetrate the brain tissue and record population activity instead of single units. Micromotion and gliosis are therefore not as likely to interfere with signal fidelity in long-term recordings. In addition, the wide area coverage used for localization of epileptic networks provides greater sampling of sensorimotor networks relative to multiunit recordings. For these reasons, ECoG-based signals may offer unique information that could be particularly useful for chronic BMI control. Since ECoG electrodes are also used clinically for electrocortical stimulation mapping (ESM) of function during surgical planning, they are also suitable for stimulating sensory areas to elicit sensory percepts.

III. ECOG NEUROPROSTHESIS: FUTURE DIRECTIONS

A. Problems and Challenges

A central challenge to translating ECoG-based neuroprosthesis to paralyzed patients is the need for clinical approval and access to patients for ECoG implants. Most present studies are carried out with patients who are admitted for epilepsy surgery, so investigations can only be done acutely under severe constraints. While patients are recovering from one surgery, waiting for the next one, and having seizures for diagnostic purposes, a limited time window is available to train patients and optimize algorithms. The only direct benefit from participation by these patients is more detailed mapping of motor cortex, and patient motivation can vary considerably. For both the technological development of neuroprosthetics and their translation to the target patient population, it is necessary for ECoG research to include work with paralyzed patients.

Prior to any implant, of course, safe and ethical procedures must be put into place, and investigational device exemptions (IDE) must be obtained from the Food and Drug Administration (FDA).

B. Future Directions

The field of ECoG-based neuroprosthetics will also need to undergo significant technical advancements on many fronts. ECoG electrodes and recording systems in current use are predominantly designed for acute or short-term (i.e., < 4 weeks) clinical studies in an inpatient epilepsy monitoring unit and are narrowly approved by the FDA for this purpose. Electrodes made of silicone and platinum are connected by extensive cabling to large clinical-grade external amplifiers and racks of data-acquisition, signal processing and display systems. Future research and development will be needed to move towards fully implanted neural implant systems on par with other implantable technologies. For example, implanted pacemakers and deep brain stimulators have been shown to be safe and effective for up to a decade, but these systems record and/or stimulate through far fewer electrodes and require far less computing power than neural interfaces. Amplifiers, signal processing hardware, and wireless power and data transfer will need to be significantly miniaturized using high density, very large scale integrated (VLSI) circuits. Ideally, these components will be packaged in a biocompatible, hermetically sealed container, and ECoG BMI technology will need to be chronically tested.

There are many challenges whose solutions have the potential to substantially improve BMI systems. For example, decoding models have not yet fully leveraged the wide area coverage of ECoG. Beyond low-level control of individual joints by neurons in primary motor cortex, larger-scale cortical motor networks are likely recruited during complex and coordinated actions. To decode this network activity it may be necessary to estimate correlations and causal interactions between ECoG signals spanning widespread cortical regions. Network theoretic approaches characterizing overall network states may provide additional information over simple spectral analyses of ECoG signals and their pairwise relationships. An important advance on the horizon is high-resolution ECoG arrays, with electrodes spaced at a much finer resolution than the conventional 4-10 mm spacing [28]. This increased spatial resolution will provide finer-grained sampling of neural populations for decoding purposes, but will strain algorithms designed to utilize far fewer channels.

Day-to-day control of limbs will not just require motor commands but also sensory feedback such as proprioception or touch. ECoG-based BMIs do not currently relay sensory information to the user. This feedback may be accomplished by providing direct stimulation to the brain [29] or through visual or auditory channels. The quality of feedback that brain stimulation can provide is unknown: for example, can stimulation provide sensory percepts of touch and/or proprioception, and how graded would this information be? Furthermore, can a patterned stimulation across multiple sites improve the naturalness of the sensory feedback, and what stimulus parameters would be most effective? Investigating these questions may pose more safety concerns than passive recordings from the same electrodes, but may be necessary to truly replace lost limb functionality.

IV. CONCLUSION

The neuroprosthetics field has received a considerable boost in recent years. Following decades of fundamental neuroscience research in nonhuman primates, high-profile studies of human neuroprosthetic control through BMIs hold promise for an underserved quadriplegic population. These BMI systems tend to employ penetrating microelectrode arrays and as yet do not involve fully implanted circuitry and long term packaging; they have also not undergone large long-term safety and efficacy studies. ECoG BMIs may provide a complementary approach to neuroprosthetic control that is more reliable for long-term use. The ideal realization of a fully implanted ECoG system would include high density electrode arrays with amplifier circuitry and signal processing in a hermetically sealed implant, as well as on-board decoding algorithms. Interestingly, such a system could also find important uses in the management of patients with intractable epilepsy, potentially providing outpatient phase II monitoring, particularly useful in patients with infrequent seizures, as well as a more robust and flexible platform for responsive neural stimulation. Providing sensory feedback and operating the neuroprosthesis in a closed loop, perhaps via cortical stimulation, could also improve prosthetic limb performance and enhance its use in activities of daily living by paralyzed subjects.

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