# Mini-Symposia Title:

Augmented Neural Prostheses

**Mini-Symposia Organizer Name & Affiliation:**

James Weiland, University of Michigan, Tim Denison, Oxford

**Mini-Symposia Speaker Name & Affiliation 1:**

Cynthia Chestek, University of Michigan

**Mini-Symposia Speaker Name & Affiliation 2:**

Dustin Tyler, Case University

**Mini-Symposia Speaker Name & Affiliation 3:**

James Weiland, University of Michigan

**Mini-Symposia Speaker Name & Affiliation 4:**

Jennifer Collinger, University of Pittsburgh

**S Mini-Symposia Speaker Name & Affiliation 5:**

Robert Gregg, University of Michigan

**Mini-Symposia Speaker Name & Affiliation 6:**

Huiling Tan, University of Oxford

# Theme:

- [ ] 01. Biomedical Signal Processing
- [ ] 02. Biomedical Imaging and Image Processing
- [ ] 03. Micro/ Nano-bioengineering; Cellular/ Tissue Engineering &
- [ ] 04. Computational Systems & Synthetic Biology; Multiscale modeling
- [ ] 05. Cardiovascular and Respiratory Systems Engineering
- [x] 06. Neural and Rehabilitation Engineering
- [ ] 07. Biomedical Sensors and Wearable Systems
- [ ] 08. Biorobotics and Biomechanics
- [ ] 09. Therapeutic & Diagnostic Systems and Technologies
- [ ] 10. Biomedical & Health Informatics
- [ ] 11. Biomedical Engineering Education and Society
- [ ] 12. Translational Engineering for Healthcare Innovation and Commercialization

**Mini-Symposia Synopsis— Max 2000 Characters**

Neural prosthesis and neural modulation systems can benefit from adding capability that integrates information from wearable sensors and/ or enables closed loop operation. Coordinated and complementary distribution of function between implanted and external systems will become increasingly important to the success of such systems. Neural implants have been created to treat blindness, parlysis, movement disorders, deamess, and othe neurological disorders. But the level of functional recovery possible with these devices is limited. Wearable sensing and computing technology, as well as sophisticated robotic limbs, offers increasing levels of complextity and capability, and a possible means to augment neural prostheses and increase the level of functional recovery. Provision of feedback to control neural stimualation will result in fewer side-effects and more naturalistic control. In this mini-symposium, we will present neural prostheses for vision restoration, control of paralyzed or robotic arms, and mitigation of movement disorders, and discuss how these devices are and will be augmented through the deployment of wearable sensring/ computing/ actuation and the use of closed loop control as well as neuromodulation.

# Augmenting neuroprosthetic control for individuated finger movements

Cynthia Chestek, Associate Professor of Biomedical Engineering
University of Michigan, Ann Arbor

*Abstract*— **Motor neuroprosthetics have the potential to one-day restore fine movement of the hand and fingers to people with upper limb amputations or paralysis. There have been promising proof of concept demonstrations, but performance has so far been far below able-bodied hand movement. In our group we have explored controlling individuated finger movements with muscle-amplified nerve signals from amputated nerves in humans, as well as with neural activity from primary motor cortex in nonhuman primates. Most motor decoders in the literature would naturally improve with the quality and quantity of neural signals recorded, but these types of hardware improvements translate very slowly to human use. Fortunately, machine learning has provided a range of methods for augmenting a simple underlying linear model linking neural activity to movement. These include Kalman filter trajectory models, enforced smoothing, mode selection schemes, and recurrent neural networks. In the future, neural networks have the potential to further embed intelligence about what movements should look like directly into our decoding algorithms.**

Within the past decade, there have been numerous demonstration of cortical brain-machine interfaces (BMIs) controlling upper limb movement in people with spinal cord injuries. [1], [3], [4], [6]. While this is promising preliminary work, performance is not yet sufficient for a disabled patient to be without a caregiver for long periods of time. Increased independence would likely be a prerequisite for wide-scale clinical BMI deployment. There is strong interest in the spinal cord injury (SCI) community to have cortical neuroprostheses, particularly to regain control of their native arm [2]. However, BMI performance must be high enough to produce meaningful life improvements, for example through increased autonomy or restoration of the ability to work.

Intracortical BMI performance has increased dramatically since the early 2000s. Interestingly, the underlying map between neural firing rates has remained basically the same since early work. Most human and monkey brain machine interface experiments today still use linear regression often augmented by regularization (e.g. [4]. This is simple to use and generalizes well to movements not specifically in the training dataset. Nonetheless, the linear prediction itself is actually very poor, requiring heavy "fixing" to produce a smooth movement. Also, the problem becomes harder as we add degrees of freedom or move to the fingers, where movements span the full range of highly coupled joints rather than staying within a local linear approximation in a limited working volume. As a result, the large improvements over the past twenty years have come about by augmenting this basic underlying linear fit with additional information. The Kalman filter, and its many variants add an underlying physical model to neural prediction [5]. Similarly, recurrent neural networks have begun to show promise in brain machine interfaces and have their own underlying dynamics that could theoretically infer missing information from a weak neural signal [7],[8].

While we routinely augment our algorithms with information beyond what we get directly from the neurons, augmentation in terms of going beyond what could be accomplished with able-bodied hands is far more challenging. All of the high performance BMI systems currently require a brain surgery. Also, in terms of end effector, it is still extremely difficult for even a state of the art robotic manipulator to fold a shirt. However, to quote Bill Gates, "we always overestimate the change that will occur in the next two years and underestimate the change that will occur in the next ten." As intracortical high channel count BMIs enter their third decade with promising paths to further improvement, things may progress faster than expected.

1. Ajiboye, A. Bolu, et al. "Restoration of reaching and grasping movements through brain-controlled muscle stimulation in a person with tetraplegia: a proof-of-concept demonstration." *The Lancet* 389.10081 (2017): 1821-1830.
2. Blabe, Christine H., et al. "Assessment of brain–machine interfaces from the perspective of people with paralysis." *Journal of neural engineering* 12.4 (2015): 043002.
3. Bouton, Chad E., et al. "Restoring cortical control of functional movement in a human with quadriplegia." *Nature* 533.7602 (2016): 247.
4. Collinger, Jennifer L., et al. "High-performance neuroprosthetic control by an individual with tetraplegia." *The Lancet* 381.9866 (2013): 557-564.
5. Gilja, Vikash, et al. "Clinical translation of a high-performance neural prosthesis." *Nature medicine* 21.10 (2015): 1142.
6. Hochberg, Leigh R., et al. "Reach and grasp by people with tetraplegia using a neurally controlled robotic arm." *Nature* 485.7398 (2012): 372.
7. Pandarinath, Chethan, et al. "Inferring single-trial neural population dynamics using sequential auto-encoders." *Nature methods* (2018): 1.
8. Sussillo, David, et al. "A recurrent neural network for closed-loop intracortical brain–machine interface decoders." *Journal of neural engineering* 9.2 (2012): 026027.

# Putting the Human in the Loop for Prosthetics following Limb Loss

Dustin J. Tyler, Case Western Reserve University and Cleveland VA Medical Center

*Abstract*— The loss of a hand or foot results in significant loss of function and significant loss of connection to objects and others. When asked, the first response from each of our research subjects it that they most miss the ability to feel the hands of a loved one. They also talk about their prosthesis as a tool at the end of their residual limb. When using the prosthesis, they are heavily dependent on visual feedback for task function. All of this results in a very unnatural and ineffective replacement for the lost limb. To change this paradigm, the prosthesis' interaction with the world must feel like the user's hand interacting with the world and the control of the prosthesis should engage the conscious and pre-conscious human motor-control systems. This requires that we take external information from the prosthesis, convert it to neural code and apply it to the user's nervous system, which we do with peripheral interfaces. This provides the control input to the human motor-control system and human brain to cause muscle activation to continue or correct device action. We record this muscle output by intramuscular electrodes and transmit the signal to an external hub that converts EMG patterns to motor commands for the prosthesis. This system must run continuously and with bidirectional bandwidth for sensing and control. As well, the total transit loop must be less than 50 msec so that the user feels this as a natural connection and extension of their body. We will describe the system to achieve these goals and demonstrate the capabilities of this system for restore a lost limb.

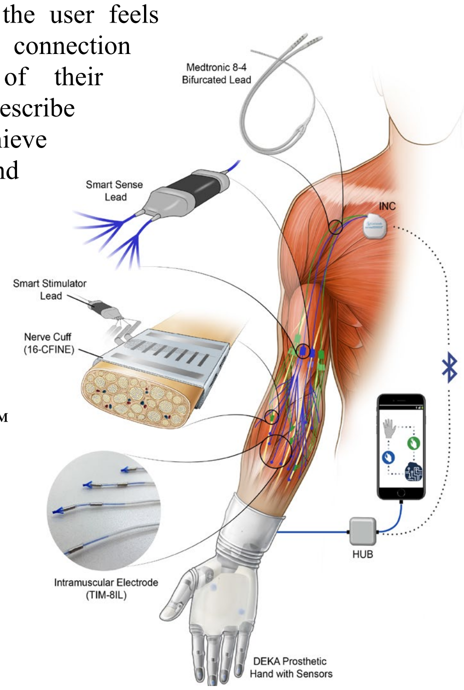


**Figure 1**. Fully implanted, Bluetooth™ connected, human in the loop system for prosthetic devices. Implanted intramuscular electrodes record user intent and neural interfaces provide naturalistic sensory feedback.

## I. Introduction

The goal of a limb loss prosthesis is for user to experience the prosthesis as though it is their limb (Figure 1). This requires agency and visual-tactile synchrony. Agency refers to the user's "effortless" control of the limb where a user thinks about moving the device and it "just moves" as intended. Visual-tactile synchrony refers to the user feeling tactile information that is simultaneous to the visual experience of a tactile interaction and matches the expected location, intensity, and quality based on the visual input. To feel like part of the user, the delay loop from subject initiation of task to perceptual feedback must be less than approximately 50 msec. If a system connects to natural neural systems, it should become more incorporated over long-term use.

## II. Methods

A fully implanted system with Bluetooth™ connection to external devices (Figure 1) records activity of residual muscles. Learning methods discern user intent to control the prosthesis. Tactile and proprioception information from the prosthesis are converted to neural code and applied to the use through nerve electrodes on the median, radial, and ulnar nerves. Psychometric tests examined the perceptual simultaneity and psychometric similarity of characteristics of electrically elicited sensation to normal sensation. Functional tests examined speed and simultaneity of multiple degree-of-freedom control. Long-term use in home environments examined the changes in prosthetic usage, quality of life, and incorporation.

## III. Results

The total system delay from recording EMG activity to control movement or mechanic input to neural stimulation is is 15 msec or less. Tactile and proprioceptive sensation perceived to be the user's own hand with perceived simultaneity and intensity discrimination like the biological hand. High degree of freedom control has speed and accuracy of intact hand. During home use, prosthetic usage increased with sensory feedback. Quality of life, social interaction, and incorporation all improved in home use.

## IV. Conclusion

Connecting directly to the human nervous system for control and direct sensory feedback results in a symbiotic connection with the prosthetic device and incorporation into a sense of self to effectively replace the lost limb.

# Augmenting visual prostheses with computer vision

James Weiland, University of Michigan

***Abstract*— Electronic visual prostheses can provide artificial vision to individuals who have little to no light perception. This vision can be used to detect large objects and distinguish between items in a set (for example letters). Patients also report feeling more socially connected in spite of the modest improvement in measureable vision. While research continues to improve the retina-electrode interface, another approach to improving overall outcomes is to utilize wearable systems running computer vision algorithms, which simplify scenes and provide a layer of understanding. We present an augmented camera system that connects directly to a human retinal prosthesis to guide a user in a complex scene. We also explore the use of multisensory cues to direct the gaze of the headworn camera. We will present preliminary experiments that demonstrate navigation with this system.**

## I. Introduction

Photoreceptor loss can lead to severe blindness, in diseases such as retinitis pigmentosa. The remaining cells of the retina, when electrically stimulated, can create the perception of light. This is the basis for several retinal prostheses that are available for patients with severe blindness. The reports from patients with retinal implants suggest that large objects of high contrast are easily visible, but finer detail and low contrast are difficult to see. Computer vision algorithms that detect and highlight points of interest offer a means to improve navigation.

## II. Methods

We have developed a computer vision-based system that can augment a retinal prosthesis during navigation. The system includes an Intel RealSense Depth Camera D435i, a laptop(GTX 1660 Ti) and three head-mounted vibration motors (left and right temple and center forehead) to provide orientation and mobility cues. The camera records color image, depth information, and IMU data. The camera is attached to a head strap designed to hold point-of-view camera (like a go-pro), thus mimicking how those with sight perceive the world. Using this hardware, we programmed a simple door finding task and tested the system in a large conference room. A VGG-based single shot multibox detector (SSD) was used to detect the target door at 10 frames per second. The depth information gathered from the camera was used to determine the distance between the subject and the door and the location of the door in the FOV. Users were guided in 3 different modes:

1. Argus II user is provided an alternative video signal, which hid any features or objects other than the door and displayed the door as a large white object.
2. Argus II users were provided the alternative video described above, with the addition of vibrational motors, which were activated on one side when the door was in the peripheral view of the camera on that side. This served to guide the user to center the camera on the door. When centered, prosthetic vision was used to locate the door and move towards it.
3. A central vibration motor was used to indicate that the camera was pointed towards the door. In this case, the Argus was disabled.

## III. Results and Discussion

We have tested one Argus II user with this. The Argus II user could not find the door using the camera provided with the Argus II, since there were distracting objects in the room (large TV monitors, Figure 1). When using the alternative video source (door only), door detection and navigation to the door was improved. Adding peripheral cues further improved the user's success rate. Use of motors only was comparable with motors plus prosthesis, which suggest mobility guidance solely through a wearable system may be viable. Although preliminary, this demonstration shows the potential of marrying artificial vision with multisensory cues to guide navigation. Object and environment detection can be extended beyond doors and expanded to more complex routes and a wider array of objects and even people.

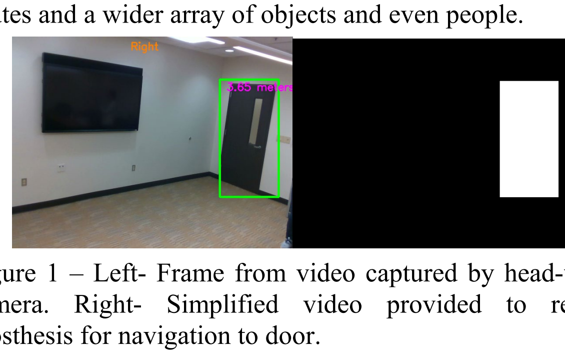


Figure 1 – Left- Frame from video captured by head-worn camera. Right- Simplified video provided to retinal prosthesis for navigation to door.

*Research supported by Research to Prevent Blindness and the University of Michigan

J.D Weiland is with the University of Michigan, Departments of Biomedical Engineering and Ophthalmology & Visual Sciences, Ann Arbor, MI 48019. weiland@med.umich.edu

# Intracortical brain-computer interface control of hand movement

Jennifer L. Collinger, University of Pittsburgh, Pittsburgh VA Healthcare System

***Abstract*— Robotic therapies and brain-computer interfaces (BCIs) have been proposed as methods to drive therapeutic neuroplasticity after injury. Here we combine and evaluate these two technologies with a participant with tetraplegia who has intracortical microelectrode arrays implanted in motor cortex. Grasp velocity was decoded from his neural activity and to control a powered hand exoskeleton. The subject achieved BCI control of grasp position, which enabled him to perform functional tasks with his own hand.**

## I. INTRODUCTION

Restoration of arm and hand function is a top priority for people with tetraplegia due to spinal cord injury. Brain-computer interfaces (BCIs) can bypass the injured spinal cord to translate intention into movement. We have used intracortical BCIs to control high degree-of-freedom movements of a robotic arm [1]. Here we present results demonstrating results using an intracortical BCI to control a hand exoskeleton that allowed a person with tetraplegia to perform function activities with their own arm and hand.

## II. METHODS

This study was conducted as part of an ongoing intracortical BCI clinical trial (NCT01894802) under an Investigational Device Exemption (IDE) granted by the US Food and Drug Administration and with approval from the Institutional Review Boards at the University of Pittsburgh and the Space and Naval Warfare Systems Center Pacific. The study participant was a 31-year-old male with C5/C6 ASIA B spinal cord injury (SCI) that resulted in complete paralysis of his hands with some residual function of the proximal arm and wrist. At age 28, 10-years post-SCI, the participant had two 88-electrode-microarrays (4 mm x4 mm footprint, 1.5mm shank length, Blackrock Microsystems, Salt Lake City, UT, USA) implanted in his left motor cortex.

The goal of this study was to demonstrate BCI control of a powered hand exoskeleton (Gloreha Sinfonia, Idrogenet s.r.l., Lumezzane, Italy). To calibrate a 1-Dimensional (1D) grasp decoder, the subject wore the glove, which moved his fingers and thumb in unison to achieve an open or closed grasp posture driven by the computer. The subject attempted to perform the movements while neural data was recorded. Inverse optimal linear estimation was used to derive a neural decoder that transformed firing rates into grasp velocity commands. The subject then used this decoder to open and close his own hand with the BCI-controlled exoskeleton.

## III. RESULTS

The participant was successful on 90.7% of flexion trials and 88.1% of extension trials. The median completion time for flexion was 1.98 [IQR 1.81-2.61] seconds, and 3.86 [IQR 3.33-4.87] seconds for extension. The participant also used the exoskeleton to perform tasks of his choosing including picking up blocks, holding a marker to draw, and eating a taco. For comparison, the participant was able to use the BCI-control exoskeleton to grasp a tissue from a box in 9 seconds, compared to 52 seconds with his unassisted hand, where he used a different strategy (i.e. wedging tissue inside thumb and wrapping tissue around his fist).

## IV. DISCUSSION & CONCLUSION

We have demonstrated the successful control of a hand exoskeleton using an intracortical BCI. Success rates on a position matching tasks were fairly high (~80%), but more importantly, the subject was also able to use the exoskeleton for functional tasks. An important consideration for combining BCI with wearable technology is the interaction of neural activity generated to control the BCI with that generated to execute residual movements of the native limb. Preliminary data suggests that independent representations of right and left arm movements can be decoded from a single hemisphere, however neural encoding of right and left grasp movements is highly correlated [2]. Future efforts will focus on developing BCI-based interventions for multi-dimensional grasp control as well as the integration of BCI-controlled and natural arm and hand movements.

## ACKNOWLEDGMENT

Thank you to those who collaborated on this work: Michael Boninger, John Downey, Ahmed Jorge, Kristin Quick, Nathaniel Schwed, Elizabeth Tyler-Kabara, George Wittenberg, Jeffrey Weiss

## REFERENCES

[1] J. L. Collinger *et al.*, "High-performance neuroprosthetic control by an individual with tetraplegia," *Lancet*, vol. 381, no. 9866, pp. 557–564, 2013.

[2] J.E. Downey *et al.*, "Primary motor cortex has independent representations for ipsilateral and contralateral arm movements but correlated representations for grasping," *medRxiv*, 19008128 [Preprint]. Oct 2, 2019. https://doi.org/10.1101/19008128.

* This material is based upon work supported by the UPMC Rehabilitation Institute, Aging Institute of UPMC Senior Services, and DARPA and SSC Pacific under Contract No. N66001-16-C-4051. Any opinions and conclusions expressed in this material are those of the authors and do not necessarily reflect the views of DARPA or SSC Pacific.

J.L. Collinger is with the Department of Physical Medicine and Rehabilitation, University of Pittsburgh, Pittsburgh, PA, 15213, USA, (phone: 412-383-1274; e-mail: collinger@pitt.edu).

# Augmenting Voluntary Movement with Backdrivable Powered Leg Orthoses

Robert D. Gregg, University of Michigan

***Abstract*— State-of-art assistive exoskeletons (i.e., powered orthoses) are designed to rigidly track time-based kinematic patterns using highly geared actuators, which prevent users from moving their joints voluntarily or with assistance from a neural prosthesis. In order to augment human-driven movement, orthotic joints must be backdrivable and the control strategy must be invariant to the user's intended motion. This talk will present the design philosophy behind two generations of backdrivable powered orthoses, which utilize torque-dense motors with low-ratio transmissions. These orthoses produce task-invariant assistive torques using a trajectory-free control framework that shapes the kinetic and potential energies of the human body rather than prescribing joint kinematics. Preliminary experiments with able-bodied human subjects demonstrate reduced quadriceps muscle activation when assisted during different activities, including a repetitive lifting and lowering task.**

## I. Introduction

Although several lower-limb exoskeletons have entered the market in recent years, they feature an integrated lower-body frame with very stiff actuators (i.e., motor with highly geared transmission) that are intended to provide the complete support and motion for someone with a spinal cord injury. Because of their rigidity, these devices have not seen success in patient populations with some voluntary control of their limbs, including hybrid applications with functional electric stimulation (FES). These applications require partial, not full, assistance of user-specific muscle groups to achieve their activities of daily living, but current exoskeletons do not allow this flexibility. This talk presents the design philosophy behind two generations of backdrivable exoskeletons (Fig. 1) that control force rather than position to strengthen rather than impede voluntary motion.

## II. Methods

Our novel design philosophy concerns 1) the actuator producing the forces to move, and 2) the control strategy determining how/when/where to move. The actuators utilize torque-dense motors with low-ratio transmissions to minimize the friction and reflected inertia of the joint, allowing it to be freely rotated by the human [1]. In the 2nd-generation design, the transmission is designed into the inner diameter of the motor to achieve a compact, low profile that can be placed over different human joints. The custom electromagnetic design of the motor can then deliver large forces to amplify voluntary motion. Instead of controlling limb position according to a pre-defined trajectory—which prohibits voluntary motion—we have established a trajectory-free control strategy that augments the human body's mechanical energy. The exoskeleton produces forces that reduce the perceived weight and limb inertia of the human user, helping their muscles overcome gravity and accelerate/decelerate their body. Leveraging our backdrivable actuators, this control strategy assists the user in generating their preferred limb motion for any activity.

## III. Results

Benchtop experiments verify the actuators meet design specifications in terms of high output torque and low backdrive torque. Pilot experiments with able-bodied subjects (Fig. 1) show the exoskeletons reduce muscle effort (measured by surface electrodes) during various activities including lifting/lowering [2], sit-to-stand, and stair climbing.

Figure 1. Powered knee-ankle orthosis (left) and powered knee orthosis (right).

## IV. Discussion & Conclusion

These exoskeletons provide backdrivability with torque assistance to augment voluntary movement, such as movement induced by FES. This motivates future hybrid applications of this exoskeleton technology with FES.

## References

[1] G. Lv, H. Zhu, and R. Gregg, "On the design and control of highly backdrivable lower-limb exoskeletons," *IEEE Control Syst. Mag.*, vol. 38, no. 6, pp. 88–113, 2018.

[2] H. Zhu, C. Nesler, N. Divekar, M. Ahmad, and R. D. Gregg, "Design and Validation of a Partial-Assist Knee Orthosis with Compact, Backdrivable Actuation," in *IEEE Int. Conf. Rehab. Robot.*, 2019, pp. 917–924.

*Research supported by NIH Award DP2HD080349 and NSF Award 1637704. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH or the NSF. Robert D. Gregg, IV, Ph.D., holds a Career Award at the Scientific Interface from the Burroughs Wellcome Fund.

R. D. Gregg is with the Department of Electrical Engineering and Computer Science; Robotics Institute, University of Michigan, Ann Arbor, MI, 48109 USA (e-mail: rdgregg@umich.edu).

# Pros and Cons of feedback signals from implanted electrodes vs peripheral sensors for closed-loop DBS for Essential Tremor

Huiling Tan[1] , University of Oxford

*Abstract*— **In Essential Tremor, the symptom of tremor mainly affects voluntary movements and sustained posture. Therefore, decoding the presence of movements and/or tremor to drive the Deep Brain Stimulation (DBS) has been proposed to control tremor while reducing the current delivered to the brain when unnecessary in order to reduce side effects. Different signals, including cortical local field potentials (LFPs) recorded form electrodes implanted over the surface of the motor cortex, subcortical LFPs recorded from electrodes implanted for clinical stimulation, and measurements from EMG or other peripheral sensors, have been used for decoding movements and/or tremor to drive the DBS. Here, we review the pros and cons of the implantable vs peripheral wearable systems in terms of decoding sensitivity, false positive rate, response delay, cost and associated risk factors on the treatment. Peripheral wearable system have the highest decoding sensitivity; on the other hand, invasively implanted systems have the potential to predict the presence of symptoms or movement intentions to trigger the DBS before the breaking out of symptoms or before actual execution of movements can be detected based on peripheral sensors.**

## I. Introduction

Deep brain stimulation (DBS) targeting the ventro-intermedius (VIM) thalamus or Zona Incerta (Zi) is an established therapy for patients with medically refractory Essential Tremor (ET). By continuously stimulating the target structure, VIM DBS can lead to 40% to 80% reduction in tremor severity. However as many as 70% of patients loose the benefit of DBS over time, due to disease progression and habituation to stimulation. Closed-loop DBS (clDBS), in which stimulation parameters are automatically adjusted to stimulate on demand, could be a solution to the drawbacks of the continuous open-loop stimulation currently employed. In particular, since tremor mainly affects periods of voluntary movements and sustained postures in ET, decoding the presence of movements and/or tremor to drive the DBS has the potential to control tremor while reducing the current delivered to the brain when unnecessary. Wearable inertial sensors [1] and/or electromyography (EMG) measurements provide reliable feedback about the pathological state of the tremor, and can drive the stimulator wirelessly. Movement-related signals have also been recorded using an extra strip of electrodes chronically implanted over the surface of the motor cortex in order to detect movement and to activate the DBS [2]. We showed that both movement and postural tremor can be decoded based on thalamic local field potentials recorded from electrodes implanted for stimulation to close the loop for DBS for Essential Tremor [3]. We evaluate the pros and cons of these methods.

*Research supported by Medical Research Council (MR/P012272/1 and MC_UU_12024/1), the Rosetree's Trust. [1]MRC Brain Network Dynamics Unit, Nuffield Department of Clinical Neurosciences, University of Oxford phone: +44-1865-572483; e-mail: huiling.tan@ndcn.ox.ac.uk

## II. Methods

Local field potentials (LFPs) from the motor thalamus together with measurements from accelerometers attached to the hand and EMG were simultaneously recorded from ET patients after the DBS surgery while they performed different voluntary movements. Movements were decoded based on 1) thalamic LFPs using machine learning classifiers and 2) thresholding applied to accelerometer or EMG measurements. The decoding accuracy and the onset times of the decoded movements based on the two methods were compared.

## III. Results

Compared to detection based on measurements from peripheral sensors, which have highest sensitivity and reliability, the decoder based on thalamic LFPs achieved average sensitivity of around 0.8 with a false positive rate of around 0.2 for both offline and real-time decoding. The onset times of cued ballistic movements decoded based on thalamic LFPs were in average 300 ms before those detected based on external sensors. Preliminary data also show that there is a potential to decode movement intention at around 2 s before self-paced voluntary movements can be detected using external sensors. These thalamic LFPs based clDBS have the potential to trigger the DBS before actual execution of movements detectable from peripheral sensors.

## IV. Discussion

Combining measurements from peripheral sensors and implantable systems provide the potential to take the advantages of both systems. It is also worthwhile pointing out that a threshold is required for movement detection based clDBS, no matter what systems are used for the detection. The threshold determines the tradeoff between the sensitivity and false positive rate. The choice of the threshold needs to take into account the risks of missed detection and false positive detection, which are related to the patient's subjective feeling about the emergence of tremor due to miss detection, any short term and long term side effect of over stimulating when unnecessary. Joint decision between the developer, the clinician and the patient would be required for the optimal performance of closed-loop DBS for ET.

## References

[1] M. Malekmohammadi *et al.,* "Kinematic adaptive Deep Brain Stimulation for resting tremor in Parkinson's disease." *Movement Disorders*, Vol. 31, no. 3, pp. 426-428

[2] J. A. Herron et al. "Chronic electrocorticography for sensing movement intention and closed-loop deep brain stimulation with wearable sensors in an essential tremor patient" *Journal of Neurosurgery*, vol. 127, no. 3, pp. 580-587, 2017

[3] H. Tan *et al.*, "Decoding voluntary movements and postural tremor based on thalamic LFPs as a basis for closed-loop stimulation for essential tremor." *Brain stimulation*, vol. 12, no. 4, pp. 858-867, 2019.