Neural Engineering

Neural Engineering:

A recent surge in technologies that interface with the nervous system has led to devices that greatly improve quality of life for people with neurological disorders. Neural engineers are instrumental players in the continued advancement and clinical translation of these emerging neuro-technologies. Toward this goal, research-and-development minded individuals from fields within basic and applied sciences and medicine come together to understand and modulate neural systems.

Neural engineering as a discipline can be broadly defined as the application of neuroscientific and engineering approaches to understand, repair, replace, enhance, or exploit the properties of neural systems, as well as to design solutions to problems associated with neurological limitations and dysfunction.

Often accompanied by scientific research directed at the interface between living neural systems and non-living components, this field brings together teams of engineers, neuroscientists, biologists, chemists, therapists, and physicians. Neural engineers value the heterogeneity of their colleagues and seek out multiple perspectives to inform the development of their technology. The sub-specialties illustrated in figure 1 demonstrate the vast range of professionals involved in neural engineering advancements.

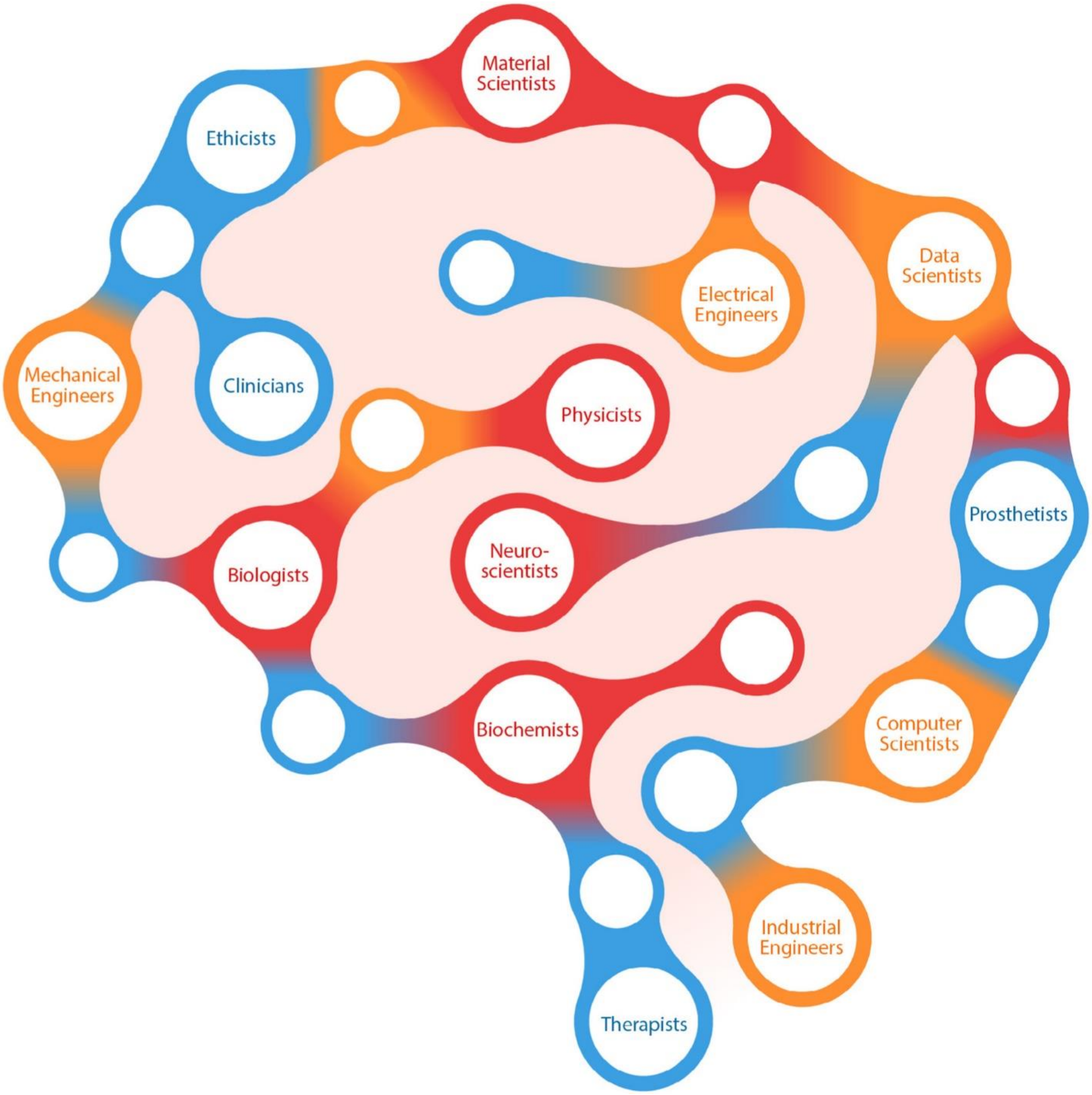
Material Scientists
Ethicists
Data Scientists
Electrical Engineers
Mechanical Engineers
Clinicians
Physicists
Prosthetists
Biologists
Neuro-scientists
Biochemists
Computer Scientists
Industrial Engineers
Therapists

Figure 1

Neural Signal Processing:

Analytical methods are crucial to advance the field of brain sciences, and efficient and effective methods of data analysis are required. Early from the last century, the neural signals have been used in the engineering sphere to discover mechanisms by which neural activity is generated and corresponding behavior is produced. The function of the neural system was detected and studied using engineering methodologies, and meanwhile, the engineering methodologies helped to understand, repair, replace, enhance, or otherwise use the properties and functions of neural systems. The neural signals are recorded by advanced neural recording technologies, and the information is extracted to be used for the understanding of neural representations of behavior. The external devices are designed to assist signal acquisition, signal processing, or provide neural feedback to humans.

Since movement is an essential activity of daily life, some of the major applications of neural engineering in the field of motor control typically involve motor function compensation, movement restoration, rehabilitation, disorder detection, etc. A movement process is integrated and translated from the higher levels of the control system, and it involves a series of transmissions to multi-structure musculoskeletal coordination. The central nervous system (CNS) works as a computational controller structure in motor behavior characterization and reorganization . Multiple structures in the brain contribute to motor control by connecting, integrating, and coordinating the motor-related information. Each structure is utilized in formulating a motor command when a particular action is performed, and the CNS switches the command between multiple motor-related structures . The mechanism of coordination and cooperation of these structures in the brain could be determined as “black box” models, providing the neural representations of relationships between motor command input and predicted behavior output. These models may represent multiple brain structures, especially the regions with synaptic plasticity that can receive and send out information.

Neural recording and stimulation:

Populations of neurons exhibit time-varying fluctuations in their aggregate activity. Currently, various invasive or noninvasive recordings exist that can record large amounts of spatial and temporal information from the human and nonhuman brain. In order to investigate how the motor-related information is generated, and what kind of patterns could be found in certain areas during a specific action, many engineering methodologies are applied.

In the human brain, neurons communicate with each other through connections known as synapses. Synapses can be electrical or chemical, and the excitatory or inhibitory nature of synapses contributes to information transmission—the influx and outflux of sodium and potassium causing the membrane potential to rise and fall rapidly. The rapid changes of membrane potentials are called spikes, which can be recorded by intercellular or extracellular recordings. Valuable information can be discovered from the rate of spikes, namely, the firing rate. The deep brain implanted electrodes allow the recording from individual neurons and can present significant results in awake animals but not in humans. Multielectrode arrays can record the voltage oscillations from multiple neurons. Simultaneously recording from a large population of local neurons increases spatial resolution benefits to the extraction of complex information in contrast with single-unit recordings. The aforementioned invasive recording technologies provide considerably less vulnerability to artifacts and relevantly higher resolution and larger amplitudes (voltages), and thereby the performance relies much more on the technologies of electrodes. However, there are several limitations of these invasive recording technologies including restricted to clinical environments and the risks of surgery and implantations.

As an alternative to the constrained invasive technologies, several noninvasive recording technologies such as electroencephalography and magnetoencephalography have been used in human studies. Advanced computational algorithms promise to promote signal processing and signal filtering; thus, more and more noninvasive recording technologies are being considered in human studies. Some techniques record neuronal potentials from the scalp, and such recordings capture the population activity of thousands of neurons depending on the level of recording. Multiple layers restrict information transmission from the cerebral cortex to the scalp leading to lower amplitudes of the signal and lower spatial resolution. Additionally, the electrodes are sensitive to the surrounding interferences like eye movements, facial movements, chewing, swallowing, etc. Therefore, it is necessary to apply robust and efficient signal processing technologies to amplify the neural activity and filter out the ambient and transducer noise, thus improving the signal-to-noise ratio.

Under noninvasive technologies, there are imaging methods that focus on the metabolic activity in the brain rather than the activity of neurons or the population of neurons. When performing a specific task, the activation of the brain neurons is enhanced and thereby more oxygen is required and absorbed from surrounded blood vessels. An increased inflow and higher oxygenated level can be detected. This hemodynamic response is comparatively slow that it reaches the peak in a few seconds and takes a longer time to fall back to the original level. Therefore, this kind of recording technology provides good spatial resolution but very poor temporal resolution.

In addition to neural recording technologies, there are also neural stimulation technologies that are used in clinical treatments (cochlear implants and deep brain stimulators) and emerging neuroprosthetics. This involves giving electrical or magnetic stimulation to a particular region of the brain to mimic sensorimotor feedback. Most recording electrodes can also be used for stimulations. Brain stimulations have proven effective in clinical treatments. These methodologies also involve the use of signal processing methodologies in determining ideal stimulation patterns. Table 1 summarizes neural recording and stimulation technologies.

Electrical recordings	Single-unit recordings (spikes)	Microelectrodes insert into neurons or placed between adjacent neurons
	Local field potential (LFP) recordings	Multielectrode arrays placed inside the brain
	Electrocorticography (ECoG)	Implanted electrodes placed on the upper layers of cerebral cortex
	Electroencephalography (EEG)	Electrodes placed on the surface of the scalp
Magnetic recordings	Magnetoencephalography (MEG)	Measures the magnetic field produced by electrical activity in the brain
Neuroimaging recordings	Functional near-infrared recordings (fNIR)	Detects near-infrared light absorbance of hemoglobin in the blood with/without oxygen
	Functional magnetic resonance imaging (fMRI)	Measures the changes in oxygenated and deoxygenated hemoglobin concentrations in the blood
	Positron emission tomography (PET)	Detects the radioactive compound as a result of metabolic activity caused by brain activity
Brain stimulations	Transcranial magnetic stimulation (TMS)	Current-passed coil of wire paced next to the skull to produce a rapidly change magnetic field
	Transcranial direct current stimulation (tDCS)	Stimulates specific parts of the brain using low-intensity direct electrical currents
	Deep brain stimulation (DBS)	Electrodes are implanted in target regions of the brain

Table 1. Neural recording and stimulation technologies.