Interfacing with the Neural System

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There is a variety of systems that have been developed for interfacing with the nervous system. The applications range from deep brain stimulation and various invasive and non-invasive BCI solutions, over retinal and cochlear implants to spinal cord stimulation and muscular interfacing (EMG). These systems interface at all levels of the nervous system from the highest level (brain) to the very distal one (muscles). Due to the invasiveness of these techniques, they have not made significant impact in treatment of diseases and rehabilitation. This particular talk focused on the ways of interfacing the peripheral nervous system directly at the nerves, and the information that was available at this level.

Nerves consist of a loose outer layer, *Epinerium*, containing numerous small bundles of nerve fibers each contained within a mechanically tough layer *Perineum*. Comprised of thousands of axons, reconnecting or structural regeneration of nerves presents itself as the biggest challenge in the area of interfacing with the nervous system. Within the subset of peripheral nervous interfaces there are a number of designs that use varying techniques to address the underlying structure of the nerve.

The least invasive approach is the cuff electrode which wraps its sensing plates around the nerve. On the other hand, the Michigan Sieve electrode operates on the principle of severing the nerve and attempting to force the individual nerve fibers to regrow through many small holes. The success of this design has been limited due to the invasiveness of the device and difficulty in promoting regrowth through the sieves. Utah array pierces the *Perineum* and places a large number of electrodes amongst the fibers.

Flat Interface Nerve Electrode (FINE) is a system developed by prof. Durand's group and it makes use of the least nerve damaging cuff electrode design and exploits the plastic nature of the nerve to deform its profile into a flat shape which increases the electrode contact area and ability to spatially discriminate signals. This flat cuff electrode design has been applied to both fascicular stimulation and decoding. First application is intended for providing sensory feedback and the later one for analysis of voluntary control of movement. Regardless of the application, the question that is intended to be addressed is how well can one target stimulation or localize the special orientation of recordings.

To study the question of selective fascicular stimulation for muscular control the early work focused on simulation of the nerve reconstruction based on Finite Element Analysis (FEA). Model was varied by placing the electrodes in different points in order to selectively stimulate nerves. 22 electrode cuff was used and the models indicated that the roughly 70% selectivity could be achieved. Follow up experiments on the *Sciatic* nerve stimulation in a cat were aligned with the modeled selectivity and demonstrated long term stability.

Control of activity in peripheral nerves based on a feedforward control algorithm for FES using FINE can be designed in two ways; first approach is - a model based control, which involves building a mathematical model of the controller and tune it in such a way so that it fits the real-world system. The second approach is a "black box" approach, which doesn't require a model but only input and output data as long as the overall redundancy is achieved. This redundancy in nature is achieved by having a larger number of muscles controlling a few DoFs of the targeted joint through their various activation patterns. In a control theory based approaches this can be achieved by implementing a cost-function driven optimal feedback control (originally proposed by Kawato in 1993). Muscular output can be controlled using a feedforward controller in addition to an inverse steady state controller (ISSC). The strategy relies on separating the steady state inverse properties from dynamic inverse, and finding the steady state inverse without using a mathematical model. The ISSC uses a trial and error approach relying on linear interpolation to fill in untested conditions to model the current to each electrode required to appropriately stimulate each muscle to achieve a desired output. Experiments with rabbits, which have 1 DOF at the ankle, showed that the stimulation induced dorsiflexion/plantarflexion matches the desired motion well and could do so with submaximal stimulation.

Fascicular stimulation can also be used to restore sensation back to the impaired patients by using pressure sensors on the fingers of a prosthetic hand. It was found that each contact provided sensation to a unique part of the hand and that the results were stable over the course of 2+ years. Successful implantation showed to reduce the phantom limb pain in amputees. It required modulation of the electrode signal amplitudes to achieve natural feeling sensation (square wave pulses produced painful stimulation). The effects of the signal frequency modulation are currently studied.

To study the question of recording and decoding the special origin of signals in nerves a modified cuff electrode was developed adding differential contacts at either end of the cuff. Aim of these was to reject common mode signals, such as EMG, which are usually orders of magnitude larger than the targeted signals. FEA models were developed using 10 fascicular sources and beamforming techniques were applied to the outputs modeled at the cuff electrodes (which include noise) to localize the source. Two sources could be discriminated with roughly 90% correlation between the modeled source locations and modeled electrode measurements, as long as distance between them is bigger than 1mm. Simulations allowed for up to five sources to be localized. These results were validated experimentally in rabbits and free moving dogs. Additionally, it was demonstrated that results seem to be fairly stable over the course of nine months after implantation in freely moving dogs.