EDITORIAL COMMENTARY

Novel rehabilitation paradigm for restoration of hand functions after tetraplegia

The letter by Bouton et al. (2016) "Restoring cortical control of functional movement in a human with quadriplegia" presents a case report of a 24 year old male with tetraplegia (C_{5-6}). The goal of the work was to bypass the spinal cord injury (SCI) lesion to stimulate the right forearm muscles to perform six movements and daily functional tasks. The work was achieved by implementing three steps: 1) implanting micro-recording electrode arrays in the motor cortex to capture electrical signals when receiving visual or verbal cues; 2) processing the electrical signals captured from the recording electrodes through decoding, coding, filtering, averaging and Kernels approach; and 3) sending the processed electrical signals to a neuromuscular stimulator sleeve to achieve six desired movements. The researchers demonstrated through using neuromuscular electrical stimulation that the participant was able to perform six hand movements, daily functional tasks and demonstrated improvement in motor impairment from C_{5-6} to C_7–T_1. This was accomplished following training 3 times weekly for 15 months 4 years after SCI (Bouton et al., 2016).

Overall, the work has addressed a very important research question on how to bypass the disconnection between the motor cortex and the stimulated muscle groups in a person with tetraplegia (Aflalo et al., 2015). The work represents decades of ongoing research with non-human primates to resolve the dilemma of restoring motor functions following SCI (Moritz et al., 2008; Ethier et al., 2012). Restoring hand functions is a key rehabilitation goal following SCI. Recently, 96 microelectrode arrays were implanted in the posterior parietal cortex to control a 17 degree robotic arm in a person with tetraplegia (Aflalo et al., 2015). Previous research efforts involved direct surface or implanted electrodes to the stimulated muscles, the use of EMG-closed-loop stimulation and the use of neuroprosthetic stimulators that were custom-built to assist in daily hand functions similar to grasp and release (Alon and McBride, 2003; Rupp et al., 2007). More recently, investigators attempted to install micrositimulation chips to activate the cord below the level of SCI and target specific muscle groups to restore walking after SCI (Troyk et al., 2012).

It is clear from this letter that the use of the neural bypass system allows not only single unidirectional movement, but provides the opportunity for multi-planar movements of the wrist joint and thumb. This approach allows the patient to carry out specific tasks similar to holding a bottle, pouring, and stirring, which are challenging for persons with tetraplegia and limit their independence. The neural bypass system may provide an opportunity for persons with tetraplegia by not only restoring functional tasks but also promoting neuro-plasticity by strengthening the spared axons at the level of the injury.

However, the current letter raises various questions that are important to be considered. One may wonder whether we can use highly sophisticated external EEG micro-electrode arrays rather than performing invasive brain surgery to place the intracranial recording electrodes. While EEG signals can be accompanied by artifacts and may not be accurate sources for decoding and therefore are inappropriate signals for electrical stimulation, this safer and less expensive approach should be further explored. Additionally, this trial seems to be patient specific, including identifying the area of the hand in the left motor cortex area by using functional magnetic resonance imaging, and thus may have limited general applicability. For example, the algorithms applied to filter the electrical signals, to decode them to the surface and to train the participant to initiate the movement were all done on the patient's specific trial-and-error observation. Additionally, the use of high resolution surface NMES with 130 electrodes for 3–4 hours per visit may limit the general application of the current trial. Clinically available stimulators may provide only up to 16 electrodes and common application in clinical settings does not go beyond 1 hour. This raises an important question of whether the current rehabilitation paradigm is limited in the duration of each session. It is unclear how the authors decided to choose 3–4 hours per visit.

Another important issue is the overlap between the implanted recording micro-electrode arrays and the region in the motor cortex is believed to stimulate the arm movement; however, developing some sort of retractable electrodes that can spread inside the brain after being deployed may provide a higher region of overlapping with the motor cortex and cover additional regions that may help to refine functional movements (Butson et al., 2006; Butson and Mclntyre, 2006). This may also enhance the decoded signals sent to the stimulating sleeve. Finally, the participant has to receive visual or verbal cues to enhance the cortical activity to produce the desired movements. It is unclear whether as a natural progression the subject will be able to think about the desired hand and finger movements without wiring *via* a PC to process the signals. A portable unit with wireless transition capabilities might be needed for real life aplications.

A very important finding of the report was that during the 8 months after implantation the patient was still experiencing the general motor/sensory characteristics of a person with $C_{5–6}$ SCI; after month 8, his motor skills improved and presented as C_8T_1 SCI. This may provide credence to the need for long-term rehabilitation. Currently, rehabilitation focused on restoring motor functions is limited by short duration, with persons being discharged from therapy 3–4 months after inpatient rehabilitation. At least in this case report, it is clear that improvement in motor functions occurred after 8 months of fairly intensive (3 times per week of focusing on special intervention) services with the neural bypass system on.

Recently, increase in wrist extensor cross-sectional area in persons with SCI following 6 weeks of surface NMES accompanied with blood flow restriction exercise has been shown to improve hand functions as measured by the grasp and release assessment (Gorgey et al., 2016). It is possible in the case of the individual presented that 15 months of training resulted in an increase in skeletal muscle size and led to improvement in hand functions. Other possible mechanisms need to be explored.

In summary, the current findings represent a shift in the area of rehabilitation towards establishing a long-term interdisciplinary approach to restoring motor function following chronic SCI. This application of neural bypass stimulator system may be considered a successful approach; however, the trial is specific to one patient and more general methodological approaches need to be refined prior to considering its applicability to the general SCI population.

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