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Editorial

Restoration of somatosensory perception via electrical stimulation of peripheral nerves

See Article, pages 851–862

Sensory impairment hinders a person's ability to interact with their environment, and thus reduces their quality of life. In the case of impaired somatosensory perception, visual input can only provide indirect information at a non-negligible cognitive cost. Therefore, restoration of natural somatosensory perception via artificial means has led to the exploration of different biological targets (Weber et al., 2012). Stimulation of the somatosensory cortex (Bensmaia, 2015), dorsal root ganglia (Weber et al., 2011), and peripheral nerves (Pasluosta et al., 2018) can produce intuitive and near-natural tactile and proprioceptive sensations, although proprioception has been studied to a lesser extent than touch (Weber et al., 2012).

Restoration of somatosensory feedback has been long sought in prosthetic limb development (Clippinger et al., 1974), with most published approaches using non-invasive devices delivering sensory substitution (Antfolk et al., 2013). This is arguably because implantable devices require larger budgets and face higher regulatory requirements. Sensory substitution forces subjects to learn new associations between the physical causes of a sensation, and the sensation itself. For example, vibrotactile stimulation over the forearm to convey the grasping force applied by the prosthetic hand. The mismatch between sensory location (forearm instead of fingers) and modality (vibration instead of pressure) is caused by the limitations of eliciting physiologically appropriate percepts transcutaneously, unless a phantom map is present (*i.e.*, incidental, uncontrolled, and disorganized sensory reinnervation causing that stimulation on the stump, results in distally referred sensations perceived as arising from the missing limb). Unfortunately, phantom maps are uncommon and often incomplete (Grüsser et al., 2001). In contrast, most amputees retain afferent neural pathways to convey intuitive and natural sensations, which remain viable for decades (Stein et al., 1980). The caveat lays on the need of permanently implanting electrodes, along with a human-prosthesis interface that allows for long-term stable communication between the said electrodes and the prosthesis (Ortiz-Catalan, 2017). Therefore, a trade-off exists between the intuitive and natural quality of perceived sensations, and the complexity and costs of the devices required to elicit them.

In this issue of *Clinical Neurophysiology*, Pasluosta and colleagues review current paradigms of electrical nerve stimulation, focusing particularly on the restoration of somatosensory perception after amputation (Pasluosta et al., 2018). Physiologically appropriate percepts can be elicited by directly stimulating the brain in patients with spinal cord injuries (Flesher et al., 2016). In the case of amputees, however, peripheral nerves provide a naturally filtered, easier to access, and safer biological channel for which long-term stable, electrical neural interfaces are readily available (Ortiz-Catalan et al., 2012). Electrical stimulation has been the preferred means to elicit biological action potentials, but inherent spatial limitations hinder selectivity. Other technologies such as infrared neural stimulation (Richter et al., 2011) and optogenetics (Deisseroth, 2011) can provide higher selectivity, but are not yet clinically ready. Pasluosta and colleagues present the latest advances in electrical nerve stimulation as currently the most clinically viable solution for close-loop control of prosthetic limbs. They summarize the relevant human physiology including sensory encoding, and provide a thorough review of electrical stimulation parameters (pulse shape, duration, amplitude, and frequency), along with their associated outcomes derived from clinical experimentation conducted to date.

Artificially induced natural sensations are the ultimate aim of somatosensory restoration in bionic limbs. Electrical stimulation of the central or peripheral nervous systems have been shown to elicit sensations that are physiologically appropriate with regards to modality and origin, and thus natural in this respect. However, these sensations are experienced as qualitatively artificial with "electric/tingling" traits, as repeatedly observed since the first experiments on microstimulation of single afferent fibers (Vallbo et al., 1984). Recently, patterned stimulation was proposed as a solution to transform artificial into "as natural as can be" sensations (Tan et al., 2014). However, replication of these results has not yet been achieved (Ortiz-Catalan et al., in preparation). Whereas it is currently possible to elicit long-term stable, intuitive percepts (Graczyk et al., 2016; Ortiz-Catalan et al., 2014; Tan et al., 2014), the challenge of providing a completely natural sensory experience persists. In addition, the ultimate natural somatosensory feedback would require tactile and proprioceptive integration (Rincon-Gonzalez et al., 2011), for which current neural interfaces lack target selectivity.

Sensory feedback has been found critical to learning how to modulate neural activity when faced with new tasks (Koralek et al., 2012). In prosthetic control, tactile feedback has been shown to improve performance under uncertainty (Saunders and Vijayakumar, 2011), but irrelevant under repetitive tasks (Schiefer et al., 2016). Nevertheless, the need for sensory feedback is intuitive to scientists, engineers, and medical professionals, who

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remain fascinated by the challenge and potential benefits to patients. Yet on the practical side, hard evidence is still required to demonstrate substantial functional benefits, as functional restoration is the key driver for reimbursement of assistive technologies. Obtaining this evidence will ensure that patients can ultimately benefit from the research and developing efforts conducted in the field of neuroprosthetics.

Conflict of interest

MO-C is partially employed by Integrum AB, a company producing implants for bone-anchored limb prostheses via osseointegration.

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Max Ortiz-Catalan
Chalmers University of Technology,
Department of Electrical Engineering,
Biomechatronics and Neurorehabilitation Laboratory,
Hörsalsvägen 11, SE-41296 Gothenburg, Sweden

Integrum AB, Krokslätts Fabriker 50, SE-43137 Mölndal, Sweden
E-mail address: maxo@chalmers.se

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