https://doi.org/10.1038/s41551-023-01036-y

Towards handy neural prostheses

Bionic hands exemplify the challenges of developing neuroprostheses that can be embodied.

The anatomy of a hand enables its functional versatility. Yet hand dexterity also relies on a sophisticated neural system that manages the fingers and the application of finely graded forces to fit specific tasks. It is therefore unsurprising that replicating a hand in bionic form involves myriad challenges in control, feedback, integration with the body and usability. These considerations apply generally to bionic limbs, exoskeletons and brain–machine interfaces, as highlighted in this focus issue of *Nature Biomedical Engineering* dedicated to neurotechnologies for the treatment of conditions of the central and peripheral nervous systems, with emphasis on neural interfaces and on motor and visual neural prostheses.

Naturally, controlling an externally powered prosthetic device requires accurate and reliable detection of the user's intended movements via a suitable interface. Depending on the severity and type of amputation and on the type of prosthetic device, this is usually achieved by using surface sensors or subcutaneously implanted sensors for electromyography to detect electrical signals from the user's residual muscles, or by using implanted electrodes and electrode arrays that record electrical activity directly from cortical neurons or from peripheral nerves. Also, nerves that have lost their natural target muscles can be redirected to other muscle tissue (this is known as 'targeted muscle reinnervation') to amplify their activity. Regardless of whether the neuromuscular interfaces are invasive or non-invasive, and whether recordings are from neurons, nerves or muscle, the signals have to be decoded and mapped into commands for the control of the prosthesis. And, expectedly, a host of challenges can derail the reliable and robust decoding of neural signals.

Artificial sensory feedback can improve the control of a prosthesis. Yet such feedback is particularly difficult to implement, in part because it is far from obvious how to replicate the natural patterns of neuronal activation that lead to specific somatosensory signals providing information about the position and movement of the prosthesis, and about its mechanical and thermal interactions with any object. Commercially available bionic hands and limbs rely heavily on visual feedback for control; yet, to the user, this feels unnatural and limiting. Tactile feedback and proprioceptive feedback can be restored by mechanically or electrically stimulating the skin, or via implanted interfaces with the nervous system (the latter is perceived as more natural by the user). This requires sensors to be embedded in the prosthesis to measure joint positions, tactile pressure and grasping forces. Still, sensory feedback does not always translate into functional advantages; in fact, the technology has so far had limited clinical impact. As Sliman Bensmaia, Dustin Tyler and Silvestro Micera discussed in a Review included in this issue, bionic hands that provide sensory information face substantial clinical challenges, partly stemming from difficulties in showing the benefits of sensory feedback in daily living activities and in diverse user populations with different needs. In fact, few commercial hand prostheses can provide sensory information, and they do so via vibrotactile feedback on grasping forces. Further technology development is therefore clearly needed. As Guoying Gu, Xiangyang Zhu, Xuanhe Zhao and colleagues showed in an Article that we published in 2021 and include in this issue, tactile feedback from a neuroprosthetic hand controlled myoelectrically can also be provided via electrical stimulation on the skin of residual forearm muscles. The newer prosthetic (Fig. 1) is pneumatically actuated and is made of soft materials, and hence is much lighter and should be cheaper. In future, sensorized artificial skin may mimic the signals elicited by native mechanoreceptors. Although natural mimicry does not guarantee enhanced usability, it is likely to improve the functionality of a bionic limb as well as its embodiment — that is, the perception of it being part of the body.

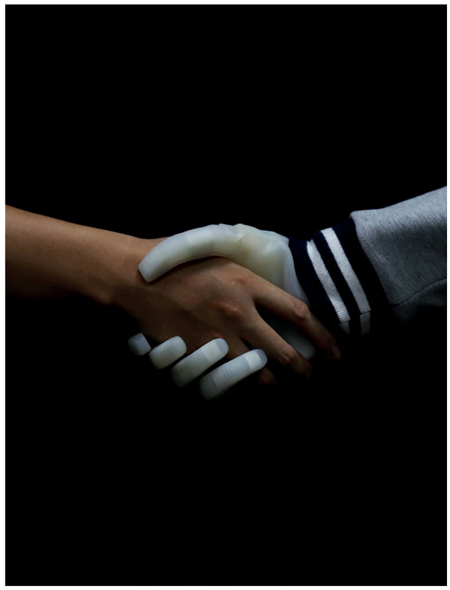

Fig. 1 | A softer handshake. The design, fabrication and performance of the pneumatically actuated neuroprosthetic hand providing simultaneous myoelectric control and tactile feedback is now reported in *Nature Biomedical Engineering*.

Regardless of the type of bionic device and neural interface for the restoration of natural motor function (or for motor augmentation), neurocognitive constraints need to be considered, as Tamar Makin, Silvestro Micera and Lee Miller discussed in a Comment piece. The constraints are different for replacement limbs and augmentation limbs, yet a common main challenge is to allow the user to attain control of the device fluidly and intuitively without restraining the natural functions of other body parts. This may require simplifying the cognitive and motor demands for controlling the device, probably through embedded artificial intelligence that facilitates semi-autonomous control.

Overall, for a bionic hand to be truly useful, the user has to perceive it as a natural extension of their body (hence, weight, size, appearance and other such factors also contribute to such perception). This requires seamless integration of the bionic device mechanically and also with the user's body schema — that is, the internal representation of the body's physical characteristics and of the spatial relationships between body parts. Biomechanical integration has typically made use of sockets, which are generally unsatisfactory, especially for users who have damaged soft tissue (as a result of heterotopic ossification, for instance). A direct connection to residual skeletal muscle via osseointegration (that is, connecting the prosthesis to a skeletal structure through a metal inserted into it) can be more stable, and may allow for osseoperception. Moreover, a bionic hand ought to be durable, reliable and versatile so that it can be used for as many tasks as a natural hand and in virtually any common environment. The hand should also be fit for purpose, and therefore meet the user's level of amputation, needs and preferences.

As highlighted by Dario Farina and co-authors in a Perspective also included in the focus issue, bionic limbs will increasingly enhance their utility and usability by making use of targeted muscle reinnervation, osseointegration, implanted wireless myoelectric sensors and control electrodes, advanced decoding and control algorithms, and sensory feedback, so that the prosthetic limb can be more easily controlled and feels natural. Let's shake hands to that.

Published online: 20 April 2023