NEUROPROSTHETICS

Engineering and surgical advancements enable more cognitively integrated bionic arms

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Integrating tactile and kinesthetic feedback in a bionic arm results in performance closer to able-bodied individuals.

The amputation of extremities poses serious challenges to an individual's daily life. Manipulation of objects and interpersonal communication are seriously affected by the loss of an arm and even further when losing both. Robotics can now closely replicate the looks and movements of biological arms, however with a major caveat: These artificial limbs are difficult to integrate into the human body to the extent that they can be controlled and perceived as part of it. Electromechanical human-machine integration remains challenging and is currently the major bottleneck in artificial limb replacement. From the patient's standpoint, there is not much use of a sophisticated robotic arm that does not respond reliably and intuitively to the wearer's commands. Moreover, motor control alone is seldom enough; sensory awareness of intended movements (kinesthesia) and external input from the environment (i.e., touch) is a hallmark of human dexterity. Writing in *Science Robotics*, Marasco *et al.* present a combination of surgical and engineering technologies to allow people with above-elbow amputations to control a robotic arm and perceive kinesthetic and tactile sensations (*1*).

Whereas prosthetic systems using closed-loop control schemes have been demonstrated in research environments and only recently used independently in daily life (*2*), the contributions of different control and sensory modalities had been hard to disentangle. Marasco and colleagues introduced a series of functional metrics that can now be used to evaluate the progression of an artificial arm toward human-like function. A way to approximate an objective evaluation of a subjective experience is to use psychophysics—the study of the perceptual effects of physical stimuli. Using psychophysical methods with clinical relevance, Marasco and colleagues introduce a way to quantify sensory-motor features related to arm and hand function—such as visual attention, cognitive workload, motor dexterity, and ownership (the sense of something belonging to our body)—in a way that enables an estimation of their contribution to function, which is arguably the most important objective of prosthetics.

Two above-elbow amputees were enlisted to test the prosthetic system. Both achieved intuitive motor control through a surgical reconstruction by which the hand-severed nerves were transferred to muscles remanent from the amputation and which have no biomechanical function (they no longer have a joint to actuate). This approach, known as targeted muscle reinnervation (TMR), uses dispensable muscles as biological amplifiers of neural signals directed to the missing limb (*3*), so when the patient aims to close the missing hand, the now-reinnervated muscle contracts (Fig. 1A). Similarly, transferring sensory nerve fibers to a portion of skin at the stump allows for tactile sensations to be perceived as arising from the missing limb (*4*), despite that the reinnervated skin patch is physically located at the stump (targeted sensory reinnervation or TSR, Fig. 1B). For instance, touching the reinnervated skin creates the sensory experience of touch in the missing hand. Other surgical techniques—such as regenerative peripheral nerve interfaces (RPNIs) (*5*), vascularized denervated muscle targets (VDMTs) (*6*), or cutaneous mechanoneural interfaces (CMIs) (*7*)—struggle to become clinically implemented because of necessary implanted electrodes that, in turn, require a transcutaneous interface to communicate with the prosthesis. Conversely, TMR uses large muscles that, when contracted, produce electrical activity large enough to be recorded from the surface of the skin, making it suitable for noninvasive human-machine interfacing.

Once motor and sensory access to the missing limb was brought out from the severed nerves buried within the stump to the surface of the body using TMR and TSR, the researchers used electrodes on the surface of the skin to extract motor volition to intuitively activate the prosthetic elbow, wrist, and hand (Fig. 1C). Tactors over the reinnervated skin were used to elicit tactile sensations perceived as arising from the prosthetic hand where artificial touch sensors were located. The kinesthetic sensation of closing the hand was induced, taking advantage of the illusory effect of movement that results when vibrating the tendon of a muscle at specific frequencies (e.g., 90 Hz), despite no actual joint movement occurring (*8*). In addition to motor fibers reinnervating the new host muscle by TMR, proprioceptive neurons also follow along into the muscle, and therefore, the same kinesthetic illusion can be exploited to elicit phantom movements. The researchers managed to place all the processing, sensing, and stimulation hardware within a prosthetic arm that, although bulky, allowed the participants to freely move within the laboratory environment to perform a wide variety of evaluations that show behaviors and functional performance closer to an unimpaired limb than to those observed with conventional prosthetics. Although one could expect that the integration of tactile and proprioceptive feedback with intuitive control would outperform the absence of any of those features, it was not until the introduction of the researchers' new evaluation tools that we have the ability to measure their independent contributions.

A caveat with TMR is that it produced a rather limited number of independent motor signals. This is because the entirety of a nerve that used to control several fingers is used all together to derive a single control signal (e.g., hand close). RPNIs or VDMTs

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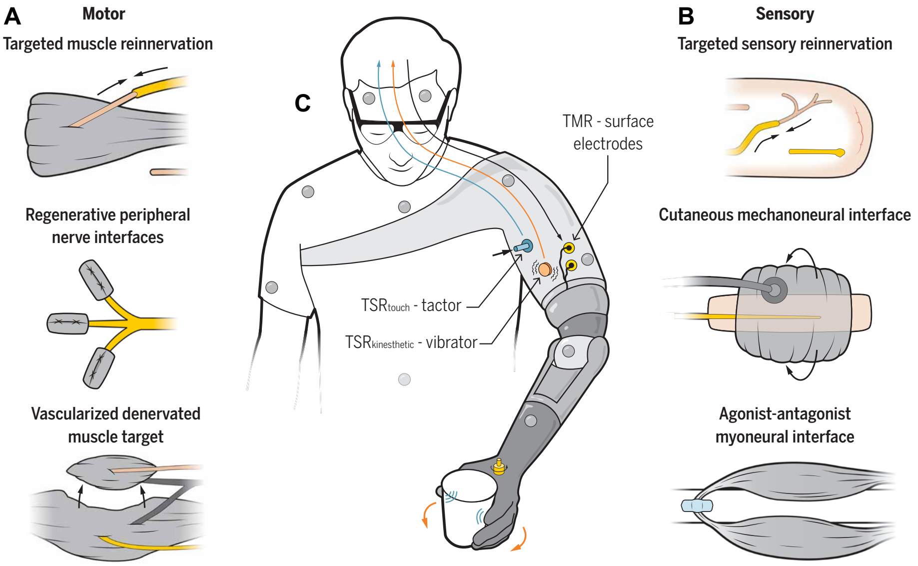

Fig. 1. Neuroroboticlimbs enabled by surgical reconstruction. (**A**) Surgical approaches to access motor neural signals to the missing limb using muscles as biological amplifiers. The nerves severed by the amputation can be transferred to denervated muscles [targeted muscle reinnervation (TMR)] (*3*), to vascularized muscle grafts detached from nearby muscles [vascularized denervated muscle target (VDMT)] (*6*), or be further transected for its individual fascicles to innervate free muscle grafts [regenerative peripheral nerve interface (RPNI)] (*5*). (**B**) Surgical approaches to enable sensory perception from missing limbs by transferring the severed sensory nerves to denervated skin patches in the stump [targeted sensory reinnervation (TSR)], by implanting the reinnervated skin patch and wrapping it with a muscle graft that when electrically stimulated by an electrode contracts over the skin [cutaneous mechanoneural interfaces (CMI)] (*7*), or by coapting antagonistic pairs of muscles [agonist-antagonist myoneural interface (AMI)] (*10*). At present, only TMR has been clinically implemented in prosthetic systems. (**C**) Prosthetic implementation in which surface electrodes extract signals from TMR muscles to control the prosthetic motors (red); pressure sensors in the fingers of the prosthesis (green) drive tactors placed over the TSR sites to provide tactile sensations during grasping; and proprioceptive feedback elicited by vibrators (blue) on TMR/TSR sites that create the illusory effect of hand closing. Marasco and colleagues created this neurorobotic system to validate new metrics that evaluate the integration of sensory feedback modalities and intuitive control algorithms at a resolution not previously achieved (*1*).

provide more control information, but they must be extracted from within the body, which brings its own complications. TSR for its part results in a natural experience of touch, which is hardly achievable using direct neural stimulation with implanted electrodes at present (*9*). On the other hand, TSR produces disorganized and often incomplete reinnervation maps. Regarding kinesthetic feedback, surgically coapting antagonistic pairs of muscles has been reported to result in intuitive proprioception (*10*); however, whether this approach is clinically feasible using reinnervated muscles and in more and complex joints is an open question. Marasco and co-workers successfully elicited proprioceptive illusions using compact superficial tactors exploiting the "side effects" of TMR, yet practicalities for real-world and daily life utilization still need to be resolved (e.g., comfort, longevity, and reliability). Clearly, trade-offs exist between the different surgical and engineering approaches to extract motor control and provide sensory feedback, but because clinical translation remains limited, those that manage the requirements of independent daily use will be likely adopted despite their downsides. Thanks to the work by Marasco and colleagues, we can now better quantify the contribution of different control strategies and sensory modalities to optimally design more functional human-machine interfaces, hopefully reducing their downsides. In addition, individuals with state-of-the-art prostheses are known to perform highly in conventional tests because these were not designed for artificial arms approaching biological ones. The new evaluation tools by Marasco and colleagues overcome these ceiling effects and therefore will be instrumental for the development of future bionic limbs.

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