The Rise of Neuroprosthetics: The Perception-Action Closed Loop

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Abstract

Future neuroprosthetics will be tightly coupled with the user in such a way that the resulting system can replace and restore impaired upper limb functions because controlled by the same neural signals than their natural counterparts. However, robust and natural interaction of subjects with sophisticated prostheses over long periods of time remains a major challenge. To tackle this challenge we can get inspiration from natural motor control, where goal-directed behavior is dynamically modulated by perceptual feedback resulting from executed actions.

Current brain-machine interfaces (BMI) partly emulate human motor control as they decode cortical correlates of movement parameters —from onset of a movement to directions to instantaneous velocity— in order to generate the sequence of movements for the neuroprosthesis. A closer look, though, shows that motor control results from the combined activity of the cerebral cortex, subcortical areas and spinal cord. This hierarchical organization supports the hypothesis that complex behaviours can be controlled using the low-dimensional output of a BMI in conjunction with intelligent devices in charge to perform low-level commands; akin to the role of subcortical and spinal cord levels in human motor control. Our brain-controlled wheelchair illustrates the future of intelligent neuroprostheses that, as our spinal cord and musculoskeletal system, work in tandem with motor commands decoded from the user's brain cortex. Users can drive it reliably and safely over long periods of time thanks to the incorporation of shared control (or context awareness) techniques. This relieves users from the need to deliver continuously all the necessary low-level control parameters and, so, reduces their cognitive workload.

A further component that will facilitate intuitive and natural control of motor neuroprosthetics is the incorporation of rich multimodal feedback and neural correlates of perceptual processes resulting from this feedback. Realistic sensory feedback must convey artificial tactile and proprioceptive information —i.e. the awareness of the position and movement— of the neuroprosthesis. This type of sensory information has potential to significantly improve the control of the prosthesis by allowing the user to feel the environment in cases in which natural sensory afferents are compromised —either through other senses or by stimulating the body to recover the lost sensation. Furthermore, rich multimodal feedback is essential to promote user's agency and owernship of the prosthesis. Finally, we can decode and integrate in the prosthetic control loop information about perceptual cognitive processes of the user that are crucial for volitional interaction, such as awareness to errors made by the device, anticipation of critical decision points, and lapses of attention. As in natural motor control, this information can dynamically modulate interaction.