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Prosthetic embodiment or what makes a limb part of your body

Prosthetic embodiment, or the incorporation of a prosthesis into one's sensory and functional body schema, may be achieved by engineering bionic limbs that leverage a closed-loop mechanoneural–machine interface. However, the subjective experience of embodiment remains difficult to define and assess.

Embodiment refers to the ability to process information through external objects at the sensory, motor and/or affective levels in the same way as the properties of one's own body parts[1]. This concept of embodiment has become a central theme in bionic prosthetics research, particularly when evaluating psychosocial outcomes of use and user experience. However, to pursue the concept of prosthetic embodiment, we may first want to consider what actually makes a limb part of the body.

This question can be addressed in phenomenological terms: the boundaries of embodiment may be determined by how we experience our bodies as sites of agency and ownership[2,3]; here, agency refers to 'volition', that is, the sensation of control over our actions, whereas ownership refers to a sense of 'belonging', that is, being able to explain the reasons for and justify one's actions.

For example, we have a particularly direct agential relation to our hands[2]. If we want to do or feel something with our hands, we do not need to consciously position our arms and wrists and direct the movements of the relevant muscles; instead, we do this intuitively — but with full control and expecting a certain outcome. This sense of agency is thought to rely mainly upon the comparison of predictions regarding the sensory outcomes of one's actions and the actual sensory outcomes. If a discrepancy is introduced between an action and the sensory feedback, the sense of agency is reduced[4].

Translating this phenomenological framework to prosthetic embodiment, it is clear that both the sense of agency and ownership of a user need to be considered in the design of an artificial limb, going beyond 'simple' functionality. In this sense, prosthetic embodiment has the ambitious aim to achieve the complete conscious and subconscious assimilation of an artificial limb, or, in other words, incorporate a prosthesis into a person's sensory and functional body schema — similarly to how a non-prosthetic limb would be perceived.

Prosthetic embodiment would thus require closing of the sensorimotor feedback loop between human and machine (a closed-loop mechanoneural–machine interface) to restore the sensorimotor bandwidth and enable bidirectional signalling. Such proprioceptive sensory feedback is physiologically enabled through agonist–antagonist muscle relationships, which, therefore, provide the crucial interface that prosthetic devices need to align with. Techniques such as targeted muscle and sensory reinnervation have shown promise in this context.

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Such a bionic approach to rehabilitation is discussed in this issue by Hugh Herr and colleagues, who explore how soft tissue constructs, such as nerves and muscles, can enable sensorimotor function of bionic limbs. The authors explore how surgically generated soft tissue constructs can be combined with artificial devices capable of sensing and/or stimulating to form so called mechanoneural interfaces that leverage mechanoreceptors in muscle and cutaneous tissue to provide the user with somatosensory information. This strategy enhances efferent neural signals conveying motor commands outward from the peripheral nervous system and afferent signals conveying sensory information back from the external prosthesis to the central nervous system. Hence, such interfaces allow the user to control and sense their artificial limbs by thought alone, essentially enabling a sense of agency and reducing cognitive burden.

However, the subjective experience of users, including agency, ownership and prosthesis adaptation[5], and how restored physiological function may affect a sense of embodiment, remains challenging to assess. Accordingly, a bionic information theory unifying measures of the effect of closed-loop mechanoneural–machine interfaces towards embodiment remains to be developed; however, such a 'phenomenological framework of bionic embodiment' may ultimately be needed to fully evaluate the 'success' of bionic prosthetics.

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