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Reply to comment

The re-embodiment of bodies, tools, and worlds after spinal cord injury: An intricate picture
Reply to comments on "The embodiment of assistive devices—From wheelchair to exoskeleton"

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We thank the commentators for their invaluable interdisciplinary contributions and perspectives and thought-provoking comments. Their suggestions have raised questions and provided insights that will guide future enquiries. Herein, we consider important theoretical ideas proposed by Cole [1]; Ferrara, Tempesta, and De Gennaro [2]; Kannape and Lenggenhager [3]; Longo, Sadibolova, and Tame [4]; Papadimitriou [5]; and Serino [6], alongside additional, potentially conflicting lines of discussion.

Individuals with spinal cord injuries (SCI) assign to regaining the ability to walk and stand the same priority as recovering bowel, bladder, and sexual functions [7–9]. Individuals with SCIs feel that recovery of locomotive functions (standing, walking, stair climbing) has deep, positive impacts on their physical, mental, and social health [10]. An exoskeleton can achieve this goal, but those with SCIs have not expressed satisfaction with such devices [11]. Based on research on wheelchair experiences, we recognize the benefit of an embodied approach to enriching patients' perceptions of the use of assistive devices [12]. Papadimitriou [5] alerts medical professionals to the risks and sociocultural implications arising, more or less directly, from ongoing developments that have blurred the boundaries between the body and prosthetic technology. We agree with Papadimitriou [5], Kannape and Lenggenhager [3] assertion that this "robotic era" offers the potential for technological transcendence over physical and biological limitations. The embodiment of technology does not deny individuals' corporeality, have a purely physical reparative purpose, or minimize the obligation of social institutions and structures. In the SCI population, rearrangements and renewals of the body model have already occurred in response to new bodily experiences following injury [13]. Unfortunately, as Cole [1] indicates, the experience of SCI brings the often-painful, broken body into focus. The result is a diminished

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experience of both the self and the world. Rehabilitative treatment attempts to reinsert the body self into the flow of experience in order to allow the patient's world to unfold once again [14]. Patients suffer not only bodily injuries but also psychological discomfort from the loss of identity and disconnection from the activities that previously gave their lives meaning [15]. Completion of the renewal process is facilitated by the use of tools, such as exoskeletons, wheelchairs, and robotic legs, which extend the body's functionality and improve access to a world still unprepared to accept immobility.

Clearly, we are aware of the important ethical implications arising from the use of assistive devices and would add to those suggested by Papadimitriou [5] other relevant risks of this specific technology, albeit in the opposite direction. Exoskeletons are still discriminatory; a wide range of people cannot use them. Currently, a major drawback is their high price. Similarly, height, weight, and age requirements limit use of this technology to a specific range of people. Moreover, following Cole [1], other concerns should be considered, such as the concentration, effort, and high cognitive resources needed to plan and control bodily actions performed with such tools.

As discussed in the target paper and comments, however, we identify embodiment as a factor that appears to support optimal neuroprosthetic control in patients exhibiting brain–body disconnection and is employed to decide the use of such tools. As rightly suggested by Cole [1] and emphasized in our paper [16], we should rethink the embodiment of tools and the rubber hand illusion (RHI) by considering bodies with sensorimotor disconnection, instead of embodiment as developed in individuals with intact bodies. By shifting focus from normal signals in healthy individuals to the residual body signals in SCI patients, we gain a new critical outcome from the RHI. In SCI patients, the multisensory manipulation of the RHI not only provides information related to achieving embodiment of an external object, as in healthy, sentient subjects, but also transiently and rapidly awakens tactile sensations from the insentient body [17]. Serino [6] discusses the implications of the multisensory integration mechanism underlying embodiment and its implementation in assistive devices. We know that, in individuals with SCIs, the illusory ownership evoked during the RHI does not occur when stimulation is applied to numb body parts [18,19]; only through residual sensations does synchronous stimulation of the sentient dermatomes provoke body ownership of external objects [17,18,20]. From the clinical perspective, the important point is that i) a complete lack of sensorial information might not support the embodiment process ii) became relevant in SCI patients to identifying a body part with sensation and using it to induce body ownership. Body parts with normal tactile sensations appear to be an interesting alternative for remapping input in affected body parts and restoring physical contact with external tools. Indeed, recent studies on patients with tetraplegia have suggested that the experience of ownership through the multisensory integration mechanism is triggered by the stimulation of body parts with normal sensitivity, such as the face and hand orderly mapped in the somatotopic brain (hand/face [20]; D3/D1 finger [17,18]). As Longo et al. [4] correctly suggest, other signals in addition to tactile signals could serve as mediators. Interoceptive signaling in the RHI could be an additional means of increasing the sense of embodiment. In a recent case using RHI multisensory manipulation, patients experienced normalization of bodily pain and somatic sensations after re-establishing an inner sensation, even if painful [18]. With appropriate caution, it seems possible to argue that the perceptual embodiment of a rubber hand in RHI served as a kind of sensory bypass, allowing individuals to resume contact with their bodies' internal model and external objects.

However rarely, sensorial perception can complete the union between body image and the representation of the object to be embodied. Longo et al. [4] correctly focus primarily on problematic data regarding the flexibility and variations in embodiment during the RHI and on the use of a tool developed using participants with intact bodies. The subjective experiences of using a tool in a healthy body and a prosthetic device in an injured body are quite dissimilar.

Independently from tools specific complexity (e.g., number of components, freedom of movement, resources needed for use), their function and differences depend on the functional skill of the user and the sensing of the body. For example, a tool, such as a bicycle, extends and amplifies skills the user already has; it is only an alternative tool of locomotion. In contrast, a wheelchair or exoskeleton is used to replace the body's missing ability to perform the essential activities of walking and moving and serves as the user's only means to interact with the world.

In addition to this absolute necessity in the functions of everyday life, assistive devices are in direct contact with extensive insentient body surfaces, making the boundaries between the body and the tool less evident [21].

Many other factors, such as transparency in use, duration of experience, and frequency of tool use, although not yet discussed, have become essential. Unlike tools used by people with healthy bodies, assistive devices must be evaluated for their impact on such factors as changes in the posture, movement, and visual perspectives of those who have used them for many years [22]. Data on wheelchair users, for example, indicate even a flexible adaptation of the body to a metric form of the tool [23–25].