Article

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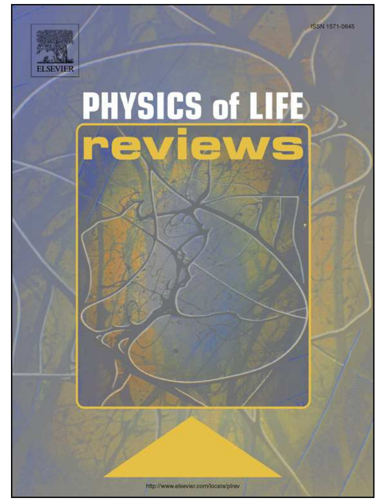
Accepted Manuscript



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PII: S1571-0645(16)00012-9
DOI: http://dx.doi.org/10.1016/j.plrev.2016.01.011
Reference: PLREV 705

To appear in: *Physics of Life Reviews*

Received date: 12 January 2016
Accepted date: 21 January 2016

Please cite this article in press as: Kannape OA, Lenggenhager B. Engineered embodiment. *Phys Life Rev* (2016), http://dx.doi.org/10.1016/j.plrev.2016.01.011

Engineered Embodiment:

Comment on "The embodiment of assistive devices-from wheelchair to exoskeleton" by M. Pazzaglia & M. Molinari

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Character count: 5125 / 5985 (without/with whitespaces)

From brain-computer interfaces to wearable robotics and bionic prostheses – intelligent assistive devices have already become indispensable in the therapy of people living with reduced sensorimotor functioning of their physical body, be it due to spinal cord injury, amputation or brain lesions [1]. Rapid technological advances will continue to fuel this field for years to come. As Pazzaglia and Molinari [2] rightly point out, progress in this domain should not solely be driven by engineering prowess, but utilize the increasing psychological and neuroscientific understanding of cortical body-representations and their plasticity [3]. We argue that a core concept for such an integrated embodiment framework was introduced with the formalization of the forward model for sensorimotor control [4]. The application of engineering concepts to human movement control paved the way for rigorous computational and neuroscientific analysis. The forward model has successfully been adapted to investigate principles underlying aspects of bodily awareness such as the sense of agency in the comparator framework [5]. At the example of recent advances in lower limb prostheses, we propose a cross-disciplinary, integrated embodiment framework to investigate the sense of agency and the related sense of body ownership for such devices. The main onus now is on the engineers and cognitive scientists to embed such an approach into the design of assistive technology and its evaluation battery.

The initial challenge for assistive devices aiding bipedal locomotion is to ensure balance and reliability; unlike for the majority of upper limb movements, a single misstep may have severe consequences. Locomotion is largely reflex-driven and reliant on spinal cord pattern generators; often, only aspects such as initiation and termination are considered truly volitional. In part for these reasons and in part due to technological limitations, commercially available prostheses are to this day largely restricted to passive devices that rely on spring or damping mechanisms offering little adaptability and increasing the amputees' energy expenditure [6]. Only recently have active, powered lower limb prostheses become commercially available [7,8]. While the most common control strategy for these prostheses are finite state machines based on abstracted gait cycles, the availability of microcontrollers has already brought forth biomimetic control strategies incorporating neuromuscular models [9]. These have been shown to normalize walking and improve speed adaptability [10] but more intriguingly lead to an important conceptual consideration – to what extent can we embody (cognition on) the prosthesis?

Besides improved control algorithms, active prostheses have opened up the possibility of hybrid and fully volitional controllers through neural interfaces. Amputees, at least in the laboratory, are now able to use their residual muscles to control ankle push-off [11,12], stiffness over the gait-cycle [13], and even the movement of a biarticulate prosthesis [14]. But, do such sophisticated interfaces increase the sense of agency over the prostheses? Is this reflected in an increased sense of ownership and a more complete feeling of embodiment? There is a clear need to systematically address these points and evaluate prosthesis performance over and above the calculation of transition work and joint-mechanics. The implications extend to general health themes as an increased embodiment of the prosthesis may lead to an improved own body image, a more active life style, and decreased social isolation [15].

Apart from the psychological effect on the amputee, an integrated embodiment framework may teach us about the consequences of an altered sensorimotor system and its effects on locomotor control, motor learning, and body-awareness. This in turn provides a unique possibility for a comparison with psychiatric or neurological conditions of altered sensorimotor processes and embodiment [16]. Evaluating prosthetic devices using this integrated framework may further bring to light compensatory strategies related to multisensory integration and a potential reweighting of efferent and re-afferent information – both of great importance to refine neuroscientific models and develop therapies for neurologically-caused disorders of embodiment. To address all these issues, it is our strong opinion that research is not limited to patient populations. Analogue to using virtual reality to introduce visuotactile and visuomotor conflicts in ownership [17,18] and agency research [19–21], assistive devices such as orthoses and exoskeletons should be employed to investigate the effect of altered sensorimotor feedback in healthy participants. The autonomous exoskeleton developed by Mooney et al. [22] would for example allow for systematically varying the external power input during ankle plantar-flexion and methodically documenting adaptive sensorimotor control and accompanying changes in body-awareness.

It is quite likely that the human brain is capable of developing distinct forward models [23] – adapted to the type of assistive device, the control strategy employed, and ultimately the reafferent sensory information available to the user (especially with the addition of bidirectional neural interfaces). Being able to systematically modulate the inputs and reafferent signals to those models will not only allow us to further improve assistive technology and investigate principles of sensorimotor control but to potentially tease out a set of rules underlying embodiment, independent of the end-effector. Interestingly, current ethical debates largely focus on whether or not assistive devices should be used to not only replace lost functionality but augment it, transcending the limitations of the healthy human body [24,25]. An antecedent concern, at least from a neurobiological perspective, may be to determine *what*, not who, defines a healthy human body.

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