Consciousness and Cognition 45 (2016) 75–88

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Embodied prosthetic arm stabilizes body posture, while unembodied one perturbs it

Shu Imaizumi [a,b,c,*], Tomohisa Asai [b], Shinichi Koyama [a]

[a] Graduate School of Engineering, Chiba University, 1-33 Yayoi, Inage, Chiba 263-8522, Japan
[b] NTT Communication Science Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan
[c] Japan Society for the Promotion of Science, 5-3-1 Kojimachi, Chiyoda, Tokyo 102-0083, Japan

ARTICLE INFO

Article history:
Received 29 March 2016
Revised 1 July 2016
Accepted 22 August 2016

Keywords:
Self
Agency
Embodiment
Amputation
Upper-limb prosthesis
Postural control

ABSTRACT

Senses of ownership (this arm belongs to me) and agency (I am controlling this arm) originate from sensorimotor system. External objects can be integrated into the sensorimotor system following long-term use, and recognized as one's own body. We examined how an (un)embodied prosthetic arm modulates whole-body control, and assessed the components of prosthetic embodiment. Nine unilateral upper-limb amputees participated. Four frequently used their prosthetic arm, while the others rarely did. Their postural sway was measured during quiet standing with or without their prosthesis. The frequent users showed greater sway when they removed the prosthesis, while the rare users showed greater sway when they fitted the prosthesis. Frequent users reported greater everyday feelings of postural stabilization by prosthesis and a larger sense of agency over the prosthesis. We suggest that a prosthetic arm maintains or perturbs postural control, depending on the prosthetic embodiment, which involves sense of agency rather than ownership.

1. Introduction

1.1. Embodied sense of self and embodiment of external objects

Several recent psychological and neuroscientific studies suggest that the human sense of self is represented within the body and sensorimotor system (Blanke, Slater, & Serino, 2015; Haggard, 2005; Tsakiris, 2010). Such an *embodied* sense of self (Gallagher, 2000) consists of a sense of one's own body (i.e., sense of body ownership: "this hand belongs to my body") and a sense of one's own action (i.e., sense of agency: "I am causing this action and controlling my body"). These two senses are conceptually (Gallagher, 2000), behaviorally (Tsakiris, Prabhu, & Haggard, 2006), psychometrically (Longo, Schuur, Kammers, Tsakiris, & Haggard, 2008), and neurally (Tsakiris, Longo, & Haggard, 2010) distinctive (but also interactive, see below). In theory, the sense of body ownership is based on multisensory afferent inputs (e.g., visuo-tactile), which are spatially and temporally congruent (Botvinick & Cohen, 1998; Kilteni, Maselli, Kording, & Slater, 2015). The sense of agency stems from congruence between a motor prediction based on an internal forward model for motor control and its predicted sensory feedback (Blakemore, Wolpert, & Frith, 2002; Wolpert, Ghahramani, & Jordan, 1995). This non-conceptual "comparator" model has been used to elucidate the mechanism of sense of agency (Blakemore et al., 2002; Tsakiris & Haggard, 2005a);

* Corresponding author at: Graduate School of Arts and Sciences, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan.
E-mail address: shuimaizumi@gmail.com (S. Imaizumi).

http://dx.doi.org/10.1016/j.concog.2016.08.019
1053-8100/

it must be noted, however, that there are other conceptual models as well (Chambon, Sidarus, & Haggard, 2014; Synofzik, Vosgerau, & Newen, 2008).

External objects (e.g., tools and fake body parts) can be incorporated into human body representation and recognized as one's own body parts (i.e., embodied) when two main sensorimotor requirements are met. First, continuous multisensory afferent inputs from an external object can elicit a sense of body-ownership toward it (i.e., ownership-driven embodiment). An example of this is the rubber hand illusion (RHI), in which observers watch a rubber hand being stroked while their own unseen hand is synchronously stroked, and start to feel as if the rubber hand belongs to their own body (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005b). Second, motor learning and internal model updates can occur due to short- and long-term use of an external proxy of one's effector (e.g., tools) with one's voluntary action (Imamizu, Kuroda, Miyauchi, Yoshioka, & Kawato, 2003; Imamizu et al., 2000). This can be referred to as agency-driven embodiment and is exemplified by an active version of the RHI, wherein synchronously acting visual feedback of one's own voluntary action, such as a fake hand (Caspar, Cleeremans, & Haggard, 2015; Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2012, 2014a, 2014b) or a hand video (Asai, 2016; Imaizumi & Asai, 2015; Tsakiris et al., 2006) can lead to embodiment. Importantly, passive movement (Haggard, Clark, & Kalogeras, 2002) or incongruent visual feedback (Franck et al., 2001) can eliminate or attenuate the sense of agency, and therefore are unlikely to lead to embodiment of the proxy (Asai, 2016; Kalckert & Ehrsson, 2012). While the active RHI has been used to examine embodiment for short time intervals, tool embodiment by long-term use has been demonstrated by neurophysiological evidence in primates (Iriki, Tanaka, & Iwamura, 1996; Maravita & Iriki, 2004) and by human behavioral evidence, such as improvements in tool control due to their incorporation into a plastic body representation (Cardinali et al., 2009; Jacobs, Bussel, Combeaud, & Roby-Brami, 2009). The tools previously examined included a rake to grasp objects (Farnè & Làdavas, 2000), a computer mouse (Bassolino, Serino, Ubaldi, & Ladavas, 2010), and a cane for blind people (Serino, Bassolino, Farne, & Ladavas, 2007).

1.2. Embodied prosthetic limb and postural stabilization

Prosthetic limbs are another example of external objects capable becoming embodied, which can be observed in our everyday environment. More than 94% of amputees due to accidents and vascular disease use prosthetic limbs (Pezzin, Dillingham, MacKenzie, Ephraim, & Rossbach, 2004). In amputees, prosthetic limbs functionally help daily life activities, such as work and leisure pursuits, and have a social role in that they compensate for the appearance of the missing limb (Murray, 2005). Consequently, the frequency of usage of prosthetic limbs positively correlates with amputees' quality of life (Akarsu, Tekin, Safaz, Goktepe, & Yazicioglu, 2013), suggesting that long-term use of prosthetic limbs has a positive effect on amputees' mental health. In contrast, qualitative studies have pointed out that long-term use of prosthetic limbs also results in psychological and physical effects, including embodiment (de Vignemont, 2007; Mills, 2013; Murray, 2004, 2008). Some studies have shown evidence of prosthesis embodiment using behavioral data. Fraser (1984) compared movement trajectories of prosthetic and intact arms in a unilateral amputee who had used the prosthesis more than ten years, and showed that the movements were comparable. The author claimed that this may stem from the use of similar neural networks in the motor system, and that prosthetic limb can become a part of a proficient user. Regarding body representations, long-term prosthetic arm users are likely to overestimate their proprioceptively felt stump lengths, that is, their arm representation extends toward the tip of prosthetic arm (McDonnell, Scott, Dickison, Theriault, & Wood, 1989). Furthermore, upper-limb amputee's peripersonal space can also expand so as to include the prosthetic arm when they wear their prosthesis (Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013).

A prosthetic upper-limb incorporated into an amputee's body may affect motor control over the whole body in addition to body representation. A recent qualitative study suggested that a prosthetic arm can maintain amputees' body posture (Wijk & Carlsson, 2015). Prosthetic arms (both functional and aesthetic) can compensate for asymmetric and/or disturbed body balance due to limb amputation, which may cause uneven load and consequently back and neck pain. The authors pointed out that everyday activities, such as walking and swimming, also benefit from stabilization engendered by use of an upper-limb prosthesis. Given this, it is natural to think that a *lower*-limb prosthesis would play a similar role because the legs bear one's body weight and generate one's gait. Indeed, studies have investigated the effects of a *lower*-limb prosthesis resulting in a perturbed postural control (Fernie & Holliday, 1978) and an asymmetric gait (Winter & Sienko, 1988). Moreover, because walking with a unilateral lower-limb prosthesis is likely to rely more on the intact side and thus show an asymmetric gait pattern, long-term use of the lower-limb prosthesis may cause musculoskeletal distortion (Gailey, Allen, Castles, Kucharik, & Roeder, 2008). In contrast, it remains unclear whether and how an upper-limb prosthesis modulates amputees' postural control and how the frequency of use and embodiment of an upper-limb prosthesis affects postural modulation; the suggestion by Wijk and Carlsson (2015) has yet to be empirically examined.

Human body posture is maintained by online comparison of the desired body parts' locations with their actual locations on the basis of multisensory afferent information supplied by those body parts, that is, a *feedback* system (Mergner & Rosemeier, 1998; Peterka, 2002; Peterka & Loughlin, 2004). Additionally, since the feedback system is not sufficient to maintain posture, anticipatory motor control computed by internal forward models is also used, that is, a *feedforward* system (Collins & de Luca, 1993; van der Kooij, Jacobs, Koopman, & Grootenboer, 1999). Both systems need to sense the current location of body parts and their movement sequence, although humans do not have organs by which to directly perceive these data. Instead, implicit body representation can play a key role as a template of a balanced body and a reference for postural control (di Fabio & Emasithi, 1997; Gurfinkel, Ivanenko, Levik, & Babakova, 1995). Thus, it is assumed that a coherent body