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A novel manipulation method of human body ownership using an fMRI-compatible master–slave system

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HIGHLIGHTS

- We propose a novel method with VR and robotics technologies for the FBI paradigm.
- A 2-DOF master–slave platform is designed to allow "active self-touch" in fMRI.
- The fMRI-compatibility of the prototype is assessed in 3 T and 7 T MRI environments.
- We verify the applicability of the prototype in a classic FBI experiment.
- Our platform holds excellent potential for studies on bodily self-consciousness.

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ABSTRACT

Bodily self-consciousness has become an important topic in cognitive neuroscience aiming to understand how the brain creates a unified sensation of the self in a body. Specifically, full body illusion (FBI) in which changes in bodily self-consciousness are experimentally introduced by using visual–tactile stimulation has led to improve understanding of these mechanisms. This paper introduces a novel approach to the classic FBI paradigm using a robotic master–slave system which allows us to examine interactions between action and the sense of body ownership in behavioral and MRI experiments. In the proposed approach, the use of the robotic master–slave system enables unique stimulation in which experimental participants can administer tactile cues on their own back using active self-touch. This active self-touch has never been employed in FBI experiments and it allows to test the role of sensorimotor integration and agency (the feeling of control over our actions) in FBI paradigms. The objective of this study is to propose a robotic–haptic platform allowing a new FBI paradigm including the active self-touch in MRI environments. This paper, first, describes the design concept and the performance of the prototype device in the fMRI environment (for 3 T and 7 T MRI scanners). In addition, the prototype device is applied to a classic FBI experiment, and we verify that the use of the prototype device succeeded in inducing the FBI. These results indicate that the proposed approach has a potential to drive advances in our understanding of human body ownership and agency by allowing novel manipulation and paradigms.

1. Introduction

An important feature of human consciousness is our experience of the self as residing in a physical body. Three major aspects of bodily self-consciousness have been described: self-location, first-person perspective, and self-identification (body-ownership) (Blanke, 2012; Blanke and Metzinger, 2009; Ehrsson, 2012; Tsakiris, 2010). The sense of body ownership, on which this paper focuses, refers to the sensation that body or body-parts belong to the self. While this sensation of body-ownership is normally robust, neurological and psychiatric disorders often produce considerable changes in bodily self-consciousness (Heydrich and Blanke, 2013;

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Vallar and Ronchi, 2009) suggesting that the sensation of body ownership is mediated by specific brain mechanisms. Recently, technological advances have allowed experimental modification of bodily self-consciousness in healthy participants (Arzy et al., 2007; Ehrsson, 2007; Lenggenhager et al., 2007; Tsakiris and Haggard, 2005). Such studies typically employ multisensory visual–tactile stimulation to induce illusory embodiment of a virtual (Salomon et al., 2013b; Slater et al., 2008) or fake (Botvinick and Cohen, 1998; Ehrsson et al., 2005; Petkova and Ehrsson, 2008) body or limb. The discovery that applying tactile stimuli synchronously with visual stimulation of a viewed hand causes illusory ownership over the fake hand has been termed the rubber hand illusion (RHI). Similarly, the full body illusion (FBI) employs visuo-tactile conflicts to induce states in which self-location, first-person perspective, and body ownership are modified (Lenggenhager et al., 2007) and has been shown to mimic neurological states of out of body experiences (OBE) (Blanke et al., 2004). These studies have shown that the processing and integration of external sensory and body-related information are central to bodily self-consciousness. For example, Petkova and Ehrsson used a head-mounted display (HMD) and video cameras to induce "body swapping" (Petkova and Ehrsson, 2008). This allowed the participants to see their own body in the HMD, which was captured by the cameras on an experimenter's head who was facing to the participants. When the participants shook hands with the experimenter, the participants could feel as if they interacted with themselves with the experimenter's body. Similar results of illusory ownership of a virtual body have reported changes in self-location (Lenggenhager et al., 2007), tactile processing (Aspell et al., 2009), neural processing (Ionta et al., 2011), and thermal regulation (Salomon et al., 2013b). However, our body is also a dynamic system which acts on the environment through overt motor behavior. Recent studies have shown that motor signals related to self-movement also play an important role in bodily self-consciousness (Knoblich, 2002; Rognini et al., 2013; Salomon et al., 2013a). However, the integration of self-movement into classical illusory ownership paradigms has proved difficult, thus hindering understanding of these important effects (Tsakiris et al., 2006).

Novel versions of the RHI based on manipulating the sense of limb ownership and agency (the feeling of controlling one's movements) though visuo-motor correspondence rather than tactile stimulation have recently been reported (Tsakiris et al., 2006; Dummer et al., 2009; Kalkert and Ehrsson, 2012). For instance, Dummer et al. induced the RHI by synchronizing movement of a fake rubber hand with the participants' hands and showed that the active movement could augment the illusory effect (Dummer et al., 2009). Kalckert and Ehrsson enabled the participants to control the vertical movement of the index finger of a fake hand in the RHI experiment by mechanically connecting both fingers with a rod and showed a dissociation of ownership and agency (Kalkert and Ehrsson, 2012). While these studies have manipulated visuo-motor correspondence of the real and fake limbs there has been no experimentation regarding active-motor manipulation of visuo-tactile correspondence. Thus, to date little is known regarding the neural processes underlying the modification of the sense of ownership in bodily illusion through active self-touch. This gap has been primarily due to technical limitations in manipulating multisensory stimuli under dynamic conditions.

In classic studies on the bodily self-consciousness, visual and tactile stimulations have been physically delivered to the participants by experimenters. However, for precisely controlled visual and tactile stimulations, recent studies have turned to using virtual reality (VR) (Lenggenhager et al., 2007) and robotic (Duenas et al., 2011; Pearson et al., 2008; Pfeiffer et al., 2013) technologies. These ensure good repeatability, precise temporal–spatial control resolution, and dynamic manipulation of temporal synchrony. In addition to these, brain activity during the FBI has recently been investigated and electroencephalogram (EEG) and functional magnetic resonance imaging (fMRI) have been used for better understanding of the brain mechanisms involved in the bodily self-consciousness (Ionta et al., 2011). Hence, EEG- and fMRI-compatible visual–haptic technology has become important for the advancement of our understanding of embodiment processes. fMRI studies of the FBI prove to be a particular challenge as they require tactile stimulation of the participants' back while they are lying supine in a high magnetic field prohibiting the use of ferromagnetic equipments. Based on this background, the present paper proposes a novel approach using a robotics–haptics technology, along with VR, to allow the manipulation of bodily self-consciousness and body ownership by action, including application in MRI environments. In a related study, Ionta et al. used a robotic scratcher allowing one degree of freedom (DOF) consisting of an ultrasonic motor and a rack-and-pinion mechanism to enable stroking of the participants' back in the MRI (Duenas et al., 2011; Ionta et al., 2011). The robotic scratcher was well-controlled by a computer following the preprogrammed trajectory and could give the stroking stimulation on the participants' body with good repeatability. However, this device did not allow participants to control the tactile stimulation, which could have potential to give a new dimension (i.e. the role of self-generated sensorimotor signals) in the investigation of bodily self-consciousness. In the present study, we report a 2-DOF master–slave system with an optical force sensor that are designed and developed to be MRI compatible, and propose a novel approach to manipulate the body ownership. This paper describes the prototype device and its basic performance, and investigates if the prototype device has MRI compatibility for 3 T and 7 T MRI scanners. Furthermore, we show results using this prototype device applied to an FBI experiment (Aspell et al., 2009; Lenggenhager et al., 2007) to verify the applicability for manipulating of body ownership.

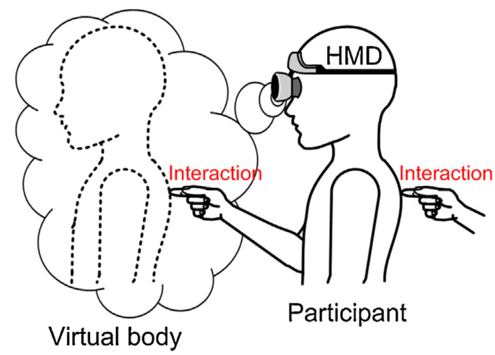

Fig. 1. Concept of active self-touch. In the active self-touch, the participant can touch with their virtual body and synchronously or asynchronously induce tactile stimulation on their own body.

2. Materials and methods

2.1. Design of an MRI-compatible robotic master–slave system

2.1.1. Specifications and design concept

In the classic FBI paradigm, stroking or tapping stimulation has been typically administered to the participants' body manually. By using novel robotic–haptic technology with VR, the present study introduces "active self-touch" in which the participants can interact with their virtual body by administering stimulation on their own body, as shown in Fig. 1. In a recently described system, we have been able to include the active self-touch into a somatic rubber hand illusion (RHI) paradigm (Ehrsson et al., 2005) by using a robotic master–slave system, and we already verified that the RHI