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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.

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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;
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., 2011b; 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 (Lonta 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). Kalkert 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 (Lonta 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, Lonta 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; Lonta 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 body ownership.

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...
could be induced under such condition (Hara et al., 2011). However, since the active self-touch has never been employed in previous FBI studies, little knowledge exists about the neural mechanisms by which action modulates bodily self-consciousness. This study proposes a novel FBI paradigm involving active self-touch.

In the proposed method, the participants manipulate a master device so as to interact with their virtual body projected on an HMD, whereas a slave device synchronously or asynchronously gives the same stimulation to the participants’ body at the same location. For this task, the master–slave system should have both stroking and tapping functions to produce a more natural interaction. In addition, since the slave device manipulated by the participants contacts with the human body, the application of force sensor would be necessary to control the contact state and ensure the safety. This study also aims at achieving active-self-touch-enabled FBI experiments in the fMRI, as shown in Fig. 2. MRI-compatible robotics technologies have been mainly studied for medical applications (Krieger et al., 2005; Masamune et al., 1995; Taylor and Stoianovici, 2003), but recent studies also focus on the application to fMRI-based neuroscience studies related to human motor control and haptic perception (Dueñas et al., 2011; Gassert et al., 2006; Hara et al., 2009; Izawa et al., 2006; Riener et al., 2005). Regarding the design of MRI-compatible devices, it is necessary to note at least the following three points (Chinzei et al., 1999; Gassert et al., 2006):

- Ensuring safety: MRI uses a strong magnetic field, therefore all device components should be made of non-magnetic materials.
- Noise suppression in MR images: electric field caused by the device driving should not influence the MR images.
- Stable driving and sensing: the strong magnetic field and RF radiation from the MRI scanner should not disturb driving and sensing of the device.

For safety and the noise issues, typical actuators and sensors, such as DC motors and strain gages, should not be used in the MRI environment. Furthermore, since the participants have to lie on a bed in a gantry with approximate 70 cm diameter during MR imaging, the device has to be placed and operated in a very confined space; it would be very difficult for the participants to dynamically manipulate the device put on the abdomen or chest. In this study, a 2-DOF master–slave system, which enables the participants lying supine on a bed to perform active self-stroking and tapping, is designed so as to satisfy the aforementioned conditions.

### 2.1.2. Prototype of MRI-compatible master and slave devices

To realize active self-stroking and tapping of the participants’ back, the slave device has to be located below the participants; typically, little space can be found between human back and a bed of MRI scanner (see Fig. 2). For example, the bed of MAGNETOM 3T (Siemens), has a space whose dimension is approximate 1725 mm in length, 490 mm in width, and 65 mm in depth (without a mattress). So, the slave device must be designed to interact with the body in a highly limited space. Fig. 3(a) shows a prototype of the slave device. All the components are made of nonmagnetic materials, such as polyacetal, brass, aluminium, etc. In this prototype, we used two ultrasonic motors (USMs) with optical encoders (USR60-E3T, Shinesi Co.), timing belts, and pulleys to linearly drive two sliders set on aluminum low-profile guide systems (NK-02-17-1-300, igus). The movements of the two sliders are constrained by a parallel-link mechanism, so the horizontal (X direction) and vertical (Z direction) movements of a contact part can be realized by driving the sliders in the same and opposite directions, respectively. Further, providing velocity difference to the sliders which move in the same direction generates the coupling movement in X and Z directions. Since this slave device is located inside the gantry of MRI scanner in the actual application, the contact part is designed to be smaller so that the movement does not disturb the homogeneity of the magnetic field. Moreover, the USMs are located far from the isocenter of the MRI scanner in order to reduce the influence (noise and distortion) of the electrical field on the MR images as much as possible. The dimensions of the prototype device are 880 mm long, 215 mm wide, and 116.5 mm (maximum) high; these values are determined by reference to the size of the robotic scratcher used in previous study employing the FBI paradigm (Ionta et al., 2011). The maximum strokes in X and Z directions are 150 mm and 30 mm, respectively. In the actual setup, the slave device is intended to be placed under a urethane mattress which has a slit in the center. The contact part of the slave device can touch the participant’s body though the slit allowing to stroke their back region along the backbone. Additionally, the slave device can push against the participant’s back on the linear trajectory. Fig. 3(b) shows a prototype of the master device, made of the same materials as the slave device. A carbon-fiber rod with 1000 mm length is attached to a slider on a ceramic linear guide (RSR 9WZMS + 200LMS, THK), and the slider can freely move in X direction by pushing or pulling the rod end. Since the slider is attached to a timing belt rotating between two timing pulleys, the linear movement can be measured as rotational angle by an optical encoder linked with a timing pulley; the optical encoder is the same used on the USMs and therefore made of nonmagnetic material. The rod end also moves on the circumference of a circle with 1000 mm radius in vertical direction, so the rotational movement can be considered approximately as vertical movement. Hence, the rotational angle can be measured as the movement in Z direction by the other encoder on the slider. The current version of the master device has no force feedback function and is just used as a device to transmit the participant’s movements to the slave device.

### 2.1.3. MRI-compatible optical force sensor

One of the key points in our proposed method is that participants can interact with their own body through the slave device by manipulating the master device. To safely interact with the body, it is necessary to measure the interaction force in Z direction. This allows to place a limitation on the vertical movement of the slave device when an unexpected force is applied. The force measurement would also permit controlling the contact state between the slave device and the human body. For example, in self-stroking, the slave device could be controlled to apply a constant force to the body based on the measured force. Furthermore, we may realize a unique situation in which the participants manipulate the master device in the same manner but the slave device gives the different force feedback to the body. Regarding the force measurement in the MRI environment, force sensors based on a fiber-optic sensor (Gassert et al., 2008; Hara et al., 2009) and shielded strain gage (Rajendra et al., 2008) have been studied for the applications to haptic rendering and biomedical measurement. These force sensors have a main frame made of aluminum or rigid plastic which is subjected to the applied force. When the main frame is deformed by the applied force, the fiber-optic sensor or the strain gage detects...
the strain of the main frame. Here we propose a structure with a compression spring instead of rigid component to enable softer contact with the body. Fig. 4 shows a schematic cross-section diagram of the proposed force sensor and illustrates the principle of force measurement. The moving part made of polyacetal can go down up to 4.5 mm when a roller on the tip is vertically pushed; at this time, the applied force is supported by a PEEK (polyetheretherketone) compression spring (Nippon Chemical Screw & Co., Ltd.). Two plastic fiber cables (one for light irradiation, and the other for light reception) and a mirror tilted 45 degrees are fixed on the base. Since another mirror is attached to the moving part, the displacement produced when the roller was pushed can be measured via an amplifier of the fiber-optic sensor (FWDK10U84Y0, Baumer Electric). Given the spring constant, the applied force could be estimated by Hooke’s law simply. In general, a drift (or offset) due to residual strain appears when using a force sensor based on the deformation of a plastic frame over a long time. However, the use of a compression spring could decrease the drift because of the linear elasticity. Further, the roller is attached to the tip of the moving part to enable smooth movement in X direction, avoiding snagging the tip on the clothes of participants.

To verify the function of the proposed structure, the developed force sensor was characterized by means of an accurately-calibrated load cell (LTS-2KA, KYOWA). Quasistatic force was applied to the optical force sensor fixed on a stable board by moving the calibrated load cell on a linear stage with a micrometer. Fig. 5 shows the results when manually pushing down the tip of optical force sensor by approximately 2 mm; the measurement was repeated 5 times within 40 s. In the graph, the gradient of the red line indicates the spring constant (3.48 N/mm). Nonlinearity begins to appear over 6.5 N, but at lower force, the relationship between the displacement and the applied force is linear and corresponds to the spring constant.

2.1.4. Control system and bandwidth

Fig. 6 illustrates a block diagram of a position control system applied to the slave device. The motor driver of USM (D6060E, Shinsei Co.) is running in a velocity control mode, changing the rotational speed and direction by DC voltage (0–3 V) and TTL signals, respectively. In the applied control system, the rotational speed was properly adjusted for the position control by a PD controller using the error between the real and desired angles of USMs;
2. fMRI-compatibility tests

2.2.1. MRI scanners and conditions

To prove the MRI compatibility of our master–slave system, echo planar images (EPI) – the typical imaging sequence used for functional imaging of the brain – of vendor-supplied spherical phantoms (Siemens) were acquired using a 3 T (MAGNETOM Trio 3T, Siemens) and a 7 T (MAGNETOM 7T, Siemens) MRI scanner. The acquisition parameters for EPI are listed in Table 1. In this experiment, the slave device was driven near the isocenter of the magnet in the following modes:

- **No-driving mode (Baseline):** the motor drivers were turned OFF/ON and the slave device was not driven
- **Automatic mode:** the slave device was driven based on various sinusoidal inputs:
  - Amplitude: 50 mm (X), 10 mm (Z)
  - Frequency: 0.5 Hz (X), 0.25, 0.5, and 1.0 Hz (Z)
- **Master-slave mode:** the slave device was driven by manipulating the master device without delay
- **Compliance mode:** the tip of the slave device was vertically pushed and released in a compliance control mode with the following virtual dynamic parameters:
  - $K = 0.25$ and 0.5 N/mm ($M = 0.0$ kg, $D = 0.0$ Ns/mm)

2.2.2. tSNR in EPI data and distortion of MR images

First, temporal signal-to-noise ratios (tSNRs) in each MRI scanner were analyzed in order to investigate if the fMRI acquisition was disturbed by the driving of the master–slave system. The tSNR of a voxel at $(i, j)$ in the image of k-th slice can be calculated with the following equation (Krueger and Glover, 2001; van der Zwaag et al., 2012):

$$\text{tSNR}(i, j, k) = \frac{t(i, j, k)}{\text{SD}(i, j, k)}$$  \hspace{1cm} (1)

where $t(i, j, k)$ and $\text{SD}(i, j, k)$ are the temporal mean value and the temporal standard deviation of the voxel over time ($t$ images), which are expressed as follows:

$$t(i, j, k) = \frac{\sum_{n=1}^{t} t_n(i, j, k)}{t}$$  \hspace{1cm} (2)

$$\text{SD}(i, j, k) = \sqrt{\frac{\sum_{n=1}^{t} (t_n(i, j, k) - t(i, j, k))^2}{t - 1}}$$  \hspace{1cm} (3)

In Eqs. (2) and (3), $t_n(i, j, k)$ means a voxel value at $(i, j)$ in the image of k-th slice. If an ROI is defined as a $1 \times m \times n$ (X–Y–Z coordinates) voxel area in the center of the image, tSNR can be obtained by averaging tSNR $(i, j, k)$ over the area:

$$\text{tSNR} = \frac{\sum_{i=1}^{m} \sum_{j=1}^{n} \text{tSNR}(i, j, k)}{m \times n}$$  \hspace{1cm} (4)

Table 2 lists the tSNRs in all modes and the losses compared to the tSNR in the baseline condition of motor driver OFF. In this paper, the tSNRs were calculated with the ROIs of $20 \times 20 \times 4$ voxels in the center of the phantom. tSNR losses at 3 T were negligible for all modes (see Table 2), apart from the master–slave configuration in which a tSNR loss of 10% was observed. Such losses, which are significant, can be acceptable in fMRI experiments given the added value of the device. For the 7 T scanner, no significant losses were observed in the device ON, automatic, and compliance modes, while more than 30% tSNR loss was found for the master–slave mode. This tSNR loss was found to depend on the distance between the isocenter of the magnet and the device as shown in Table 2, and could likely be improved upon with a further increase of this distance; this measurement was performed only in the 7 T fMRI scanner because the patient bed had a slight curvature near the isocenter and the slave device could not be perfectly fixed at that position. From these results, it is necessary to locate the device a bit away from the isocenter of the magnet in the fMRI-based FBI experiment.

Distortions in the MR images were also assessed by comparing the image under the motor driver OFF with those under the other conditions. As an example, Fig. 7 shows the images of vendor-supplied spherical phantoms when the motor drivers were turned off (a) and the slave device was synchronously (<1 ms delay) manipulated via the master device (b). As can be judged from the subtracted images (c), there were no noticeable distortions between the two images. When scaling the difference images from $-1$ to $1$ of the maximum image brightness in (a), it can be seen that the minor changes were in Nyquist ghosting level (van der Zwaag et al., 2009). Nyquist ghost level changes (<1%) in echo planar images are typically acceptable for fMRI.

Table 1: EPI conditions in 3 T and 7 T MRI scanners.

<table>
<thead>
<tr>
<th></th>
<th>3 T MRI scanner</th>
<th>7 T MRI scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR (repetition time)</td>
<td>2 s</td>
<td>2 s</td>
</tr>
<tr>
<td>TE (echo time)</td>
<td>30 ms</td>
<td>20 ms</td>
</tr>
<tr>
<td>Resolution</td>
<td>$3 \times 3 \times 3$ mm</td>
<td>$2 \times 2 \times 2$ mm</td>
</tr>
<tr>
<td>Matrix size</td>
<td>$64 \times 64 \times 32$</td>
<td>$104 \times 104 \times 20$</td>
</tr>
</tbody>
</table>

Table 2: Temporal signal-to-noise ratio (tSNR) in EPI data.

<table>
<thead>
<tr>
<th></th>
<th>3 T MRI scanner</th>
<th>7 T MRI scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR ± SD</td>
<td>Loss (%)</td>
</tr>
<tr>
<td>No-driving mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver OFF</td>
<td>370 ± 44</td>
<td>239 ± 51</td>
</tr>
<tr>
<td>Driver ON</td>
<td>372 ± 46</td>
<td>243 ± 45</td>
</tr>
<tr>
<td>Automatic mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$f = 0.25$ Hz</td>
<td>355 ± 46</td>
<td>233 ± 33</td>
</tr>
<tr>
<td>$f = 0.5$ Hz</td>
<td>366 ± 45</td>
<td>253 ± 28</td>
</tr>
<tr>
<td>$f = 1.0$ Hz</td>
<td>373 ± 44</td>
<td>250 ± 32</td>
</tr>
<tr>
<td>Master-slave mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near isocenter</td>
<td>302 ± 50</td>
<td>150 ± 38</td>
</tr>
<tr>
<td>40 mm far</td>
<td>–</td>
<td>202 ± 27</td>
</tr>
<tr>
<td>60 mm far</td>
<td>–</td>
<td>205 ± 23</td>
</tr>
<tr>
<td>Compliance mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K = 0.25$ N/mm</td>
<td>340 ± 50</td>
<td>223 ± 23</td>
</tr>
<tr>
<td>$K = 0.5$ N/mm</td>
<td>350 ± 44</td>
<td>223 ± 23</td>
</tr>
</tbody>
</table>
of Tokyo, and we followed the ethical standards laid down in the Declaration of Helsinki.

2.3.2. Experimental setups: hardware and software

In the present study, we applied the proposed platform to an FBI experiment in the normal environment ahead of the MRI experiments in order to verify whether the platform was useful to induce the FBI. An experimental protocol based on the classic FBI paradigm (Aspell et al., 2009; Lenggenhager et al., 2007) was designed to verify whether the developed platform could induce the FBI under active self-touch. Fig. 8 shows the experimental setups and environment. A urethane bed was composed of two layers with approximate 50 mm thickness. The slave device was set under the upper layer and could contact with the participants' body through an 80 mm aperture of upper layer. The master device was also put under the upper layer so as to be located between the participants' legs. The participants could manipulate the master device in the X and Z directions by pushing or pulling the handle attached at the end of the carbon-fiber rod in parallel with the body (see Fig. 8(b)); the X position of the master device corresponded to that of the slave device. During the FBI experiment, the participants wore an HMD (HMZ-T1, Sony) to see their virtual body in stereovision.

The visual information was created by superimposing a photo of the participant's back, which was captured individually before the experiment, and its alpha channel on a photo of the ceiling (Fig. 9(a)). The stereoscopic view of virtual body was realized by displaying the composite graphics on the left and right screens of the HMD with a parallax difference, as shown in Fig. 9(b). According to the specifications of the used HMD, the users could experience a sense of depth if they were viewing an image or movie on a 150-inch screen located at 3.65 m away. A virtual space on the HMD was designed by OpenGl program so that the participants looked at the image of the ceiling from a distance of 600 in the coordinate system of the virtual space; 600 in the virtual space corresponded to 3.65 m in the real world. The images of the participant's back and its alpha channel were displayed 100 (approximately 0.61 m in the real world) short of the image of the ceiling. A virtual stick was linked with the movement of the master device was shown on the virtual body to enable the participants to see the stimulation produced by their own movements.

During the FBI experiment, we measured the crossmodal congruency effect (CCE) (Aspell et al., 2009; Pavani et al., 2000; Salomon et al., 2012). The CCE measure has been previously used to assess effects related to illusory body ownership in the FBI (Aspell et al., 2009), social effects (Salomon et al., 2012) as well as body ownership during action (Rognini et al., 2013). Taken together these previous results suggest that the CCE is a good candidate for measuring illusory ownership induced by active self-touch. For the CCE measurement, a light-vibration system was constructed by means of 3D graphics and 4 button-type vibrators – FM34F (3 V, less 60 mA, 13000 rpm (213 Hz), 1.4 g) produced by Tokyo Parts Industrial Co.,
The two upper vibrators were positioned to be approximately at the inner edges of participants’ shoulder blades and the other two lower vibrators were put 90 mm below the upper vibrators (Fig. 8). Instead of the LEDs, four virtual spherical markers were drawn in OpenGL and displayed at the same positions of the four vibrators on the virtual body. The color of the markers changed from white to red when they were activated. In this CCE measurement, a congruent condition was defined as the condition in which a visual distractor and vibrotactile stimulation occurred on the same elevation (both upper elevations or both lower elevations). On the other hand, if the pair was displayed on opposite elevations (e.g., upper elevations vs. lower elevation), it was an incongruent condition.

A GUI-enabled application was programmed in Visual C++ (Microsoft) in order to facilitate the experiment. Using this application, the experimenter could quickly configure experimental conditions, control parameters for the master–slave system, etc., via dialog boxes and keystrokes. Since the application also displayed and logged all the experimental data (position, velocity of the master and slave devices, force, reaction time, etc.) in real time, the experimenter could always control and observe the experimental information.

2.3.3. Procedure and conditions

The experimental protocol was based upon a previous study (Aspell et al., 2009; Lenggenhager et al., 2007). In this study, the FBI was compared and evaluated between temporally synchronous and asynchronous visual–tactile stimulations. Here we extended this investigation by using the active self-touch capability of our device. In the synchronous stimulation, the movements of master and slave devices were completely corresponding, so the participants experienced the stimulation at the same time and at the same location where they stimulated the virtual body. A constant 500 ms delay was introduced to the movement of the slave device in the asynchronous stimulation. The participants would thus feel the stroking stimulation 500 ms after the movement of virtual stick.

The experimental procedure was as follows: on each trial, the participants manipulated the virtual stick linked with the master device so as to stroke their virtual body displayed on the HMD, which gave either synchronous or asynchronous visual–tactile feedback. The stroking along the participants’ back was performed with the non-dominant hand for 30 s between two blue virtual markers displayed on the virtual body (Fig. 9(b)). The distance of virtual markers corresponded to 130 mm in the real environment. After 30 s stroking, four white virtual markers corresponding with the vibrators’ positions were displayed instead of the blue virtual markers. A CCE test including 4 conditions (4 pairs of visual distractor and vibrotactile stimulation) started 3 s after the white virtual markers appeared. In a CCE trial, the color of one of the four markers changed from white to red for 100 ms, and then one of the four vibrators were activated for 150 ms, as shown in Fig. 10. The pair of visual distractor and vibrotactile stimulation was randomly selected from 16 conditions. In this study, stimulus onset synchrony (SOA) was set at 100 ms as previous works demonstrated that the SOA maximizes the CCE (Gardner, 1988; Sengul et al., 2012; Shore et al., 2006). When the CCE test started, the participants immediately stopped stroking and viewed the four virtual markers. They were instructed to try to ignore the visual stimuli, and to respond to the location (up-down) of the vibrotactile stimulation on their back as rapidly as possible by pushing one of two buttons with their dominant hand; the participants pushed the upper button if they felt the vibration at the upper elevations, whereas the lower button was pushed for the vibrations at the lower elevations. Reaction time (RT) for button presses after the visual flash was recorded in each condition. Each trial consisted of 30 s of self-stroking followed by 4 CCE measurements and each block repeated 12 trials for 9 min. In total, 10 blocks were performed, randomizing the tactile feedback (synchronous or asynchronous) between blocks. There were 120 trials and 480 CCE measurements.

After each block, the participants were asked to answer to the following FBI questionnaire with a seven-point Likert scale; in this study, –3 and +3 meant “I strongly disagree with the statement” and “I strongly agree with the statement”, respectively. The FBI questionnaire was adapted from previous studies employing the FBI paradigm (Aspell et al., 2005; Lenggenhager et al., 2007). The first three questions were designed to correspond to the FBI, i.e., the experience of localizing the participants’ own body in the position of seen body (Q1 – “It seemed as if I was feeling the touch of the stick in the location where I saw the virtual body being touched”), sensing touch on the seen body (Q2 – “It seemed as if the touch I felt was caused by the stick touching the virtual body”), and the experience that the seen body was felt as if it was the participants’ body (Q3 – “I felt as if the virtual body was my body”). Questions 4 and 7 were used to assess other changes in bodily self-consciousness (Q4 – “It felt as if my (real) body was drifting towards the front (towards the virtual body)”); Q7 – “It appeared (visually) as if the virtual body was drifting backwards (towards my body)”. Question 9 was newly applied to examine the role of agency (Q9 – “I felt as if I was touching my back with the stick”). The other three
questions unrelated with the illusion were served as a control for the suggestibility (Q5 – “It seemed as if I might have more than one body”; Q6 – “It seemed as if the touch I was feeling came from somewhere between my own body and the virtual body”; Q8 – “It seemed as if I was in two places at the same time”).

Before the main experiment, the participants had a training session in order to get used to the experimental procedure and the device manipulation. In the training session, first, the participants performed 2 blocks of CCE measurement and we verified that the error ratio became less than 15%. They also tried both the synchronous and asynchronous stimulations for approximate 45 s, performing 4 conditions of CCE test.

3. Results

Fig. 11 plots the mean scores for the FBI questionnaire under the synchronous and asynchronous stimulations. First, the questionnaire scores were analyzed using a two-way repeated measures analysis of variance (ANOVA). A significant interaction ($F_{(8,80)} = 11.47, p < 0.01$) was found as well as significant main effects of the tactile synchrony ($F_{(1,10)} = 15.85, p < 0.01$) and question ($F_{(8,80)} = 16.26, p < 0.01$). A non-parametric test (Wilcoxon signed-rank test) revealed significant differences in the tactile synchrony for Q1, Q2, Q3, and Q9, in which the participants gave significantly higher positive scores in the synchronous stimulation compared to the asynchronous stimulation. No significant differences were found in the comparisons for the other questions. In the questionnaire, Q3 ($z = -2.89, p < 0.01$) is related to self-identification, whereas Q1 ($z = -2.76, p < 0.01$) and Q2 ($z = -2.76, p < 0.01$) are related to the mislocalization of touch to the viewed body. Q9 ($z = -2.65, p < 0.01$) evaluates the sense of agency during the experiment. Also, a post-hoc comparison (Ryan’s method) revealed that the scores for Q1, Q2, Q3, and Q9 are significantly higher than those for the other questions in the synchronous stimulation (all $p < 0.01$). These analysis results imply that the participants subjectively experienced the FBI.

For the CCE analysis, RTs for erroneous trials were removed from the analysis. In addition, outlier RTs below 200 ms or over 1.5 s were not analyzed. Mean RTs and errors for all conditions are listed in Table 3. The repeated measures ANOVA with 3 factors – visual–tactile synchrony (synchronous vs. asynchronous), side (same vs. different), and congruency (congruent vs. incongruent) – revealed a significant main effect of congruency ($F_{(1,10)} = 21.73, p < 0.01$) and a significant two-way interaction between side and congruency ($F_{(1,10)} = 16.16, p < 0.01$). No other effects and interactions reached significance ($p > 0.05$). Fig. 12 shows mean CCEs (RT in incongruent trials minus RT in congruent trials) for the synchronous and asynchronous stimulations.

![Table 3](image)

<table>
<thead>
<tr>
<th>Target-distractor congruency</th>
<th>Position of distractor</th>
<th>RT (SEM) (ms)</th>
<th>Error (SEM) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous stimulation</td>
<td>Same</td>
<td>469 (25)</td>
<td>2.6 (0.9)</td>
</tr>
<tr>
<td></td>
<td>Different</td>
<td>489 (21)</td>
<td>4.2 (1.3)</td>
</tr>
<tr>
<td>Incongruent</td>
<td>Same</td>
<td>575 (31)</td>
<td>10.6 (2.7)</td>
</tr>
<tr>
<td></td>
<td>Different</td>
<td>553 (32)</td>
<td>8.2 (2.4)</td>
</tr>
<tr>
<td>Asynchronous stimulation</td>
<td>Same</td>
<td>471 (29)</td>
<td>3.0 (1.1)</td>
</tr>
<tr>
<td></td>
<td>Different</td>
<td>496 (30)</td>
<td>2.9 (0.9)</td>
</tr>
<tr>
<td>Incongruent</td>
<td>Same</td>
<td>569 (31)</td>
<td>10.9 (2.8)</td>
</tr>
<tr>
<td></td>
<td>Different</td>
<td>555 (36)</td>
<td>7.6 (2.2)</td>
</tr>
</tbody>
</table>

Two-tailed $t$-test found a significant difference between the CCEs of same and different sides in the asynchronous stimulation ($t_{(1,0)} = 4.18, p < 0.01$) as well as in the synchronous stimulation ($t_{(1,0)} = 3.18, p < 0.01$). These results were corresponding with the classic CCEs in the FBI experiment with the SOA of 33 ms (Aspell et al., 2009).

4. Discussion

This paper described a novel robotic–haptic platform allowing experimentation with the FBI paradigm in an fMRI scanner. The results demonstrate that (1) the platform allows application of tactile stimulation on the participants’ back with a VR visual feedback, (2) a novel “active self-touch” condition in which the participants control the tactile stimulation could be realized with the platform, (3) the proposed setups do not introduce significant imaging artifacts, which were in compensable level, at 3T and 7T magnetic fields, and (4) the FBI induced with the active self-touch affects visual–tactile processing and subjective judgments of bodily self-consciousness. We will first discuss the findings of the current experiment followed by a general discussion of the affordances of this novel robotic platform to the field in general.

The main aim of the study was to validate the efficacy of the novel “self-touch” paradigm, made possible by the robotic platform in inducing bodily illusions. We have replicated and extended results of previous investigations of the FBI using passive stroking. Our results show that even when the touch is self-administered participants reported higher self-identification with the virtual body (Q3 – “I felt as if the virtual body was my body”), and mislocalization of touch (Q1 – “It seemed as if I was feeling the touch of the stick in the location where I saw the virtual body being touched”), as well as the perceived cause of the touch (Q2 – “It seemed as if the touch I felt was caused by the stick touching the virtual body”). Interestingly, a qualitative comparison of the magnitude of the
responses to the mislocalization of touch and the perceived cause of touch questions, showed that the current paradigm induced considerable higher ratings than in previous studies using similar visual scenarios (Aspell et al., 2009; Lenggenhager et al., 2007). This difference may stem from the active stroking conditions employed here, yet further investigations of this effect are required to compare the cognitive and neural mechanisms involved in the active and passive induction of the FBI. Behavioral results show that CCEs elicited followed the typical and spatial modulation (congruency-side effect) and were of similar magnitude to those obtained with different experimental setups (Pavani et al., 2000; Spence et al., 2004). However, the CCE effects did not show any synchrony dependent modulation. A similar result has been shown for CCE in the FBI using a SOA of 33 ms. We chose this SOA as it is considered to reflect multi-sensory integration (Shore et al., 2006). It is likely that using a longer SOA it would be possible to find a significant modulation of the CCE by synchonry as shown by Aspell et al. (2009) for a SOA of 233 ms. Furthermore, the fact that CCEs in the current experiment were measured after the stroking may have caused a reduced sensitivity to the synchrony manipulation.

Early investigations of the FBI have been mostly limited to behavioral measures of the illusion thus restricting our understanding of the brain mechanisms involved in the FBI (Ehrsson, 2007; Lenggenhager et al., 2007; Pfeiffer et al., 2013). The application of a robotic-VR platform has overcome this limitation, and allowed fMRI investigation of the neural correlates of the FBI allowing first insights into the neural underpinnings of this phenomenon (Ionta et al., 2011). However, our current platform has several advantages (interactive/active stimulation by the participants, various force feedback, etc.), which should facilitate further advancements in the field. The master–slave feature enabling the participants to control the self-stroking considerably broadens the scope of experimental paradigms possible and allows the investigations of agency and its interactions with other aspects of bodily self-consciousness. Agency has indeed been shown to be an important factor in self-recognition (Jeannerod, 2004; Salomon et al., 2011; van den Bos and Jeannerod, 2002), which affects hand ownership and visual–tactile integration (Rognini et al., 2013), and is associated with several brain structures (Farrer et al., 2003; Farrer and Frith, 2002; Salomon et al., 2009) which partially overlap with regions involved in multisensory mechanisms related to bodily self-consciousness. Additionally, the neural correlates of self-touch have been an important topic of interest (Blakemore et al., 1999a,b; Shergill et al., 2013). Investigations of self-touch in fMRI have been hindered by the difficulty in manufacturing platforms for well-controlled self-touch in the MR environment because of the strong magnetic field and high intensity RF radiation of the MRI. Our proposed platform permits to study of both stroking and tapping self-touch with control of force and temporal delays, making it an ideal platform for advancing this field of study as well. Additionally, the 2-DOP platform shown here could improve the control and safety of the contact between the robot and body regions by continuous monitoring of the force applied to the tactile stimulation. Finally, the current trend in fMRI-based neuroscience studies is the use of higher magnetic fields such as 7T and even 9.4T for human research allowing higher resolution imaging of the human brain (e.g. Da Costa et al., 2011; Martuzzi et al., 2012). Our platform has been designed and tested not only at a standard 3 T magnetic field but also at a higher 7 T magnetic field and has been shown to be compatible with both scanners.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jneumeth.2014.05.038.

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