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Modulation of Bodily Self-Consciousness by Self and External Touch

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***Abstract*—The full body illusion (FBI) is a bodily illusion based on the application of multisensory conflicts that induce changes in bodily self-consciousness (BSC). This has been used to study cognitive brain mechanisms underlying body ownership and related aspects of self-consciousness. Typically, such paradigms employ external passive multisensory stimulation, thus neglecting the possible contributions of self-generated action and haptic cues to body ownership. In this study, the effects of both external and voluntary self-touch on BSC were examined with a robotics-based FBI paradigm. We compared the effects of classical passive visuotactile stimulation and active self-touch (in which experimental participants had a sense of agency over the tactile stimulation) on the FBI. We evaluated these effects using a questionnaire, crossmodal congruency task, and measurements of changes in self-location. The results indicated that both synchronous passive visuotactile stimulation and synchronous active self-touch induced illusory ownership over a virtual body, without significant differences in their magnitudes. However, the FBI induced by active self-touch was associated with a larger drift in self-location towards the virtual body. These results show that movement-related signals arising from self-touch impact the BSC not only for hand ownership but also for torso-centered body ownership and related aspects of BSC.**

***Index Terms*—Full body illusion, sense of body ownership, sense of agency, active self-touch, cognetics.**

I. Introduction

TWO central aspects of self-consciousness are the sense of body ownership (i.e., the feeling that one's body or body parts belong to him/her) and the sense of agency (i.e., the feeling of control over the body's actions) [1]–[4]. Several lines of evidence have suggested that these distinct phenomenological aspects of self-consciousness are dissociated at the neural level [1], [2]. For example, in somatoparaphrenia following focal brain damage, there may be a feeling that one's hand belongs to the self [5], [6] while damage to other brain regions may cause a loss of the sense of agency (but not hand ownership), as found in the so-called alien hand syndrome [7]–[9]. Similarly, in psychiatric conditions that cause alterations in the sense of self, there are conditions in which a dissociative experience of body ownership is a central symptom, as found in depersonalization [10], whereas schizophrenia patients experience a loss of agency [11]–[13] while body ownership is intact [14].

Recent experimental studies in healthy participants suggest that body ownership is grounded in the integration of multisensory signals [15]–[18]. These studies typically employ bodily illusions in which a multisensory conflict (i.e., between a tactile and a visual cue) is created to induce modulations of body ownership [19]–[24]. For example, in the full body illusion (FBI), participants wearing a head mounted display (HMD) see the body of an avatar (located about 2 m away) being stroked while their real bodies are also stroked by an experimenter [21]. When the seen and felt stroking are synchronous, a multisensory conflict arises as the visual information shows the stroking on the avatar's body while the tactile information indicates the participants' own bodies as the one being touched. This multisensory conflict gives rise to changes in bodily self-consciousness (BSC) in which the participants experience illusory ownership over the avatar's body as measured by subjective questionnaires, behavioral changes in perceived self-location, and alterations in physiological measures [17], [21], [25]–[27]. These FBI-related changes in the BSC are associated with the activation of a distributed brain network [15], [17], [26], [28]. Critically, the illusion is typically reduced or absent when the visual and tactile stimulations are asynchronous. Thus, modulations of body ownership can be achieved from passive multisensory stimulation in the absence of action cues, suggesting an independence of body ownership from agency-related motor mechanisms.

However, several studies have revealed that movement signals can impact hand ownership [29]–[33]. For example, Kalckert and Ehrsson showed that moving a finger with synchronous visual feedback was associated with elevated reports of both body ownership and agency for the moving hand [32]. Integrating virtual reality (VR) and transcranial magnetic stimulation (TMS), Bassolino et al. [34] and Franza et al. [34] demonstrated that changes in hand ownership and agency are even reported for TMS-induced movements when associated with VR-based feedback of visual hand movements. These effects are not limited to limbs, as the movement of a full-body avatar has also been found to lead to ownership over the avatar's body [30], [35], [36]. These results suggest

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that while actions may not be a necessary condition for the formation of body ownership, they seem sufficient to modulate body ownership.

One approach to investigate the interactions between body ownership and agency is based on self-touch. Self-touch has been suggested to provide important indications for body ownership by allowing to investigate the coupling of motor, proprioceptive, and dual tactile signals (from the touching limb and the touched limb). In a previous study, we compared the classical visuotactile rubber hand illusion (RHI) with a novel version of the RHI, including voluntary self-touch [37]. We found that active self-touch enhanced the illusion, suggesting that the additional information (i.e., motor, proprioceptive, and dual tactile signals) contributed to the sensorimotor conflict, giving rise to stronger illusory hand ownership. This is likely linked to the well-documented effect of sensory attenuation for self-generated actions [38].

Here, we experimentally investigate the effect of active self-touch on the ownership of the entire body, as tested using the RHI [37]. To achieve this, we employed a custom-made leader-follower robotic system [39], allowing participants to interactively touch a virtual body while experiencing synchronous or asynchronous touch on their real bodies (see Fig. 1). Because we already verified that only synchronous active self-touch induced the FBI [39], the present study compared this active self-touch-enabled FBI (a-FBI) to an FBI induced by synchronous passive visuotactile stimulation which was based on preliminary-recorded self-touch actions by the experimenter (the latter condition corresponded with previous experiments using the classical FBI [21]; c-FBI). In line with previous findings of sensorimotor signals on hand ownership, as tested during movement [3], [29] and self-touch [37], [40], we predicted that such sensorimotor signals may also contribute to ownership over the entire body. Hence, we hypothesized that synchronous active self-touch (i.e., a-FBI) would induce a stronger FBI and larger changes in self-location towards the virtual body than synchronous classical multisensory stimulation (i.e., c-FBI), which is not associated with such additional sensorimotor signals. We collected both subjective measurements of body ownership and agency (questionnaire) as well as objective measurements (crossmodal congruency effects and drift in self-location) that have been used in previous studies of body ownership [21], [31], [41], [42]. Using these experimental data, this paper discusses how the self-generated action and haptic cues contribute to the BSC from the viewpoint of cognetics [43].

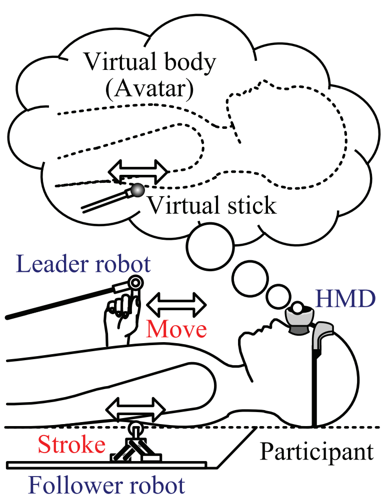

Fig. 1. Active self-touch-enabled FBI (a-FBI) paradigm. Experimental participants self-administer tactile stimulation towards their backs via a follower robot while seeing the back of their virtual body stimulated by a virtual stick whose movement is linked with manipulation of a leader robot.

II. Materials and Methods

A. Participants

19 healthy participants (4 females, 1 left-handed, mean age 25.2±1.0 (20 to 33) years) were recruited for the experiment. The sample size was based on previous studies using the classical FBI paradigm [21], [25], [41]. The experimental results of two participants could not be included in the final analysis as they were inattentive and did not comply with the experimental procedures. Accordingly, 17 participants constituted the final sample. All participants had normal or corrected-to-normal vision, normal touch perception, and no history of neurological or psychiatric conditions as assessed by self-report. The experimental protocol was approved by the Ethics Committee in School of Engineering, The University of Tokyo, and followed the ethical standards laid down in the Declaration of Helsinki. None of the participants had preliminary knowledge about the FBI as well as the experimental procedure and provided written informed consent before the beginning of the experiment. They were reimbursed for their participation in the experiment with 1000 JPY per hour.

B. Experimental setups

1) Leader and follower robots: A custom-made robotic system designed to adapt to both 3T and 7T MRI environments [39] was applied to induce the FBI in the participants while in a supine position (see Fig. 2). The robotic system consists of a leader robot (which is manipulated by the participants) and a follower robot (which provides the participants' backs tactile stimulus). The contact part of the leader robot, which worked together with two sliders on aluminum low-profile

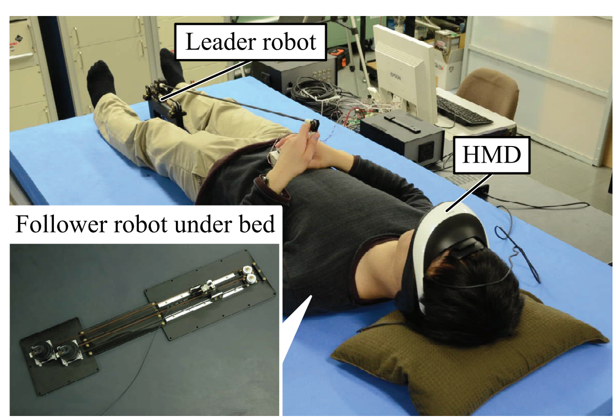

Fig. 2. fMRI-compatible leader-follower robotic system for studies on FBI and related bodily illusions.

guide systems (NK-02-17-1-300, igus) by parallel links, was driven by two ultrasonic motors (USMs: USR60-E3NT, Shinsei Corp.) and belt-drive mechanisms. The contact part could move in the horizontal (along the body) and vertical (towards the body) directions by controlling the rotational directions and velocities of the USMs. In the present study, only the horizontal movement was controlled based on the manipulation of the leader robot to present a stroking stimulus to the participants' backs in line with classical FBI studies [21], [41]. A custom-made optical force sensor using a fiber optic sensor (FWDK10U84Y0, Baumer Electric) and a polymer optic fiber cable (OLPC-S51D2B, COMOS) was embedded into the contact part to measure the contact force when the follower robot touched to the participants' bodies. In the leader robot, the slider smoothly moved on a ceramic linear guide (RSR 9WZMS+200LMS, THK) by manipulating the end of a carbon-fiber rod of 1 m in length. The horizontal and vertical movements were measured by optical encoders on the slider.

The position of the follower robot was controlled using a proportional-derivative (PD) controller ($K_p = 8.0$ V/rad and $K_d = 0.015$ V·s/rad) based on the movement of the leader robot in the a-FBI or prerecorded target trajectories in the c-FBI. A compliance controller using the contact force measured by the optical force sensor was applied to the vertical movement to avoid applying an unexpected force to the participants' bodies by the follower robot. In this study, only a virtual spring with a low stiffness ($K = 0.5$ N/mm) was applied to the compliance controller to achieve a robotic soft-touch to the participants' backs, ensuring their safety.

2) Experimental display: During the experiment, the participants viewed via a screen-type HMD (HMZ-T1, Sony) an image of their own body (virtual body) as if floating between a ceiling and their physical bodies. We avoided immersive-type HMDs such as Oculus Rift and Vive to correspond the experimental condition with those in previous studies [21], [39], [41]. The image was created by superimposing photos of the ceiling and the participants' individual backs with a distance in virtual environment before the experiment. A virtual stick that moved together with the manipulation of the leader robot was rendered on the image in 3D graphics. The experimental scene was displayed on the left and right screens of the HMD with a parallax of 25 mm in a side-by-side stereoscopic view. The headphones of the HMD were employed to present the participants sound cues and white noise during the experiment.

3) Crossmodal congruency system: A pseudo light-vibration system that applied a visual distractor and vibrotactile stimulus to the participants was used to measure the crossmodal congruency effect (CCE) [44]; the details are described in Section II-C2. Vibrotactile stimuli were presented to the participants' backs using four button-type vibrators (FM34F, Tokyo Parts Industrial Co., Ltd.). The positions of two vibrators (upper vibrators) were approximately adjusted at the inner edges of the participants' shoulder blades, and the others (lower vibrators) were positioned at approximately 90 mm below the upper vibrators, following a previous FBI study [41]. Four spherical virtual markers were rendered on the virtual body instead of distractor lights, and the flashing of a distractor light was expressed by changing the color of the virtual marker from white to red. Before the experiment, the positions of the virtual markers on the virtual body were individually adjusted to correspond to the locations of the vibrators on the participants' backs. A custom-made response device with two push-button switches was used to report the position of the activated vibrator.

4) Experimental environment: Fig. 3 illustrates the experimental system. The participants were lying supine on a urethane bed of two layers (each with 50 mm thickness). The leader and follower robots were located under the upper layer, and the vibrators were fixed on the surface to be positioned at the planned locations of the participants' backs. Two motor drivers (D6060E, Shinsei Corp.) drove the USMs of the follower robot in a velocity control mode based on the command voltage from a desktop computer. The optical encoders on the leader and follower robots measured the rotational angles, and the computer acquired the data in pulse trains. The displacement at the tip of contact part caused by the robotic touch was measured using the fiber optic sensor and was used to estimate the contact force based on Hook's law. The activation of the four vibrators and notification by the button press action in the CCE measurements were controlled using digital signals. All input/output (I/O) controls were performed using a data acquisition card (NI PCIe-6323, National Instruments) installed on the desktop computer. The sampling time was set as 1 ms (i.e., 1 kHz sampling rate), which enabled both the device control and rendering the stereoscopic virtual scene on the HMD in real time. The parameters for the experiment and device control were easily configured via custom-made GUIs programmed in Visual C++ (Microsoft), and all experimental conditions and device statuses were observed as numerical values or graphs on a monitor.

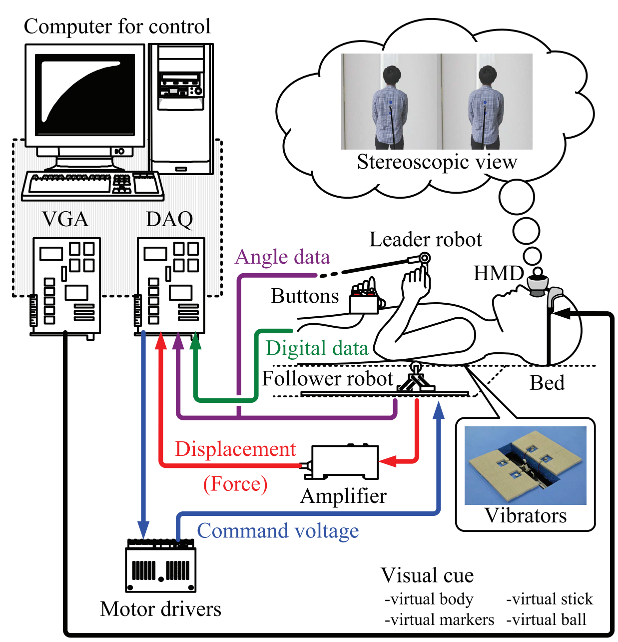

Fig. 3. Experimental system for active self-touch-enabled FBI in supine position. Follower robot stroked participants' backs through an 80.0 mm aperture in upper layer of urethane bed.

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TABLE I
ADAPTED FBI QUESTIONNAIRE

	Questionnaire item	Type of item
Q1	It seemed as if I were feeling the touch of the stick in the location where I saw the virtual body being touched	Illusion
Q2	It seemed as though the touch I felt was caused by the stick touching the virtual body	
Q3	I felt as if the virtual body was my body	
Q4	It felt as if my (real) body was drifting towards the front (towards the virtual body)	Control
Q5	It seemed as if I might have had 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	
Q7	It appeared (visually) as if the virtual body were drifting backwards (towards my body)	
Q8	It seemed as if I were in two places at the same time	
Q9	I felt as if I were touching my back with the stick	Agency

C. Dependent measures

1) FBI experience: We assessed the participants' subjective experiences during the a-FBI and c-FBI using an FBI questionnaire adapted from previous FBI studies [21], [41], [45]. The questionnaire items are listed in Table I and were shown to the participants in the same order between the experimental blocks, as in previous FBI research. The first three were illusion items that were designed to assess the illusory sensations, i.e., mislocalization of touch (Q1: touch referral), sense of touch on the virtual body (Q2: touch referral), and self-identification of body ownership (Q3: self-identification). The last item (Q9: agency) was added to gauge agency for one's own movements during the experiment. The other five items (Q4 & Q7: illusory movement, Q5: self-identification, Q6: disembodiment, and Q8: bi-location [45]) were unrelated to the FBI and served as controls for suggestibility (i.e., control items). These items, while similar to experimental questions, are typically not modulated by multisensory stimulation leading to bodily illusions such as the FBI and RHI [14], [19], [32], [46] and thus served to test for potential suggestibility effects. At the end of the experimental block, the participants were asked to answer the FBI questionnaire on a seven-point Likert scale (-3: "I strongly disagree with the statement" to +3: "I strongly agree with the statement"); 0 was considered as a neutral rating allocated for uncertain experience. The questionnaire was designed such that if the participants experienced the FBI, the ratings for the illusion items should be significantly higher than 0 and the ratings for the control items. In addition, we expected that a sense of agency in the a-FBI (as indexed by Q9) would increase the CCE magnitude as voluntary self-touch was shown to enhance illusory ownership in the RHI paradigm [37].

2) Crossmodal congruency effect: The CCE has been used as a measure of visuotactile integration in peripersonal space in several experimental settings [31], [42], [44], [47]. Furthermore, Aspell et al. experimentally demonstrated that the magnitude of the CCE can be used as a proxy to objectively assess participants' FBI experiences [41]. Thus, we employed a similar CCE measurement with the crossmodal congruency system in the current experiment.

First, the crossmodal congruency system randomly displayed a pair of visual and vibrotactile stimuli. The participants were asked to discriminate the location where they felt the vibrotactile stimulus (shoulder blades or lower back) by pressing one of the two buttons on the response device as quickly as possible while ignoring the visual distractor. The location of the vibration at the shoulder blades (upper elevation) or the lower back (lower elevation) were reported by pressing the upper or lower button with the index and middle fingers, respectively. The reaction time (RT) from the onset of the vibration to the button press action was measured and recorded for each condition. The CCE was expressed as the difference between RTs in the incongruent and congruent conditions (i.e., when the visual and tactile stimuli were at the same elevations (congruent), otherwise (incongruent)). The CCE was also calculated for each distractor side (i.e., when both the visual distractor and vibrotactile stimulus were presented on the right or left side (same), otherwise (different)). The CCE test started 2.5 s after the virtual markers appeared on the virtual body. In each CCE measurement, the color of a virtual marker changed for 100 ms, and then a randomly-selected vibrator on the participants' backs was activated for 150 ms. A stimulus onset asynchrony (SOA) of 100 ms was chosen because previous studies demonstrated that the CCE is maximized for such SOA [48], [49]. Following previous findings on the classical FBI [41], we predicted larger magnitudes of CCE during a-FBI than during c-FBI.

3) Self-location: The embodiment of an artificial or virtual body is typically associated with a phenomenon called as proprioceptive drift. In the RHI, this refers to the fact that during synchronous stroking of the fake and real hands, one's own hand is incorrectly localized as being closer to the fake hand [50]–[53]. In the FBI, such modulations of self-location have also been found in the illusion-inducing condition [21], [41]. Previous studies developed a mental ball drop (MBD) task to measure self-location in which participants on a bed were asked to indicate the moment when they thought a ball that they had dropped from their hand had reached the floor [26], [46] (also see [45] for a similar task in the VR environment). In the current experiment, in the supine position, self-location was measured using a variant of the MBD task.

As depicted in Fig. 4, just after each experimental block, a green virtual ball was presented that "dropped" towards the participants' physical bodies from the virtual body (see Fig. 4(a)). The virtual ball started to "drop" from the virtual body to the physical body 3.0 s after it first appeared in the virtual

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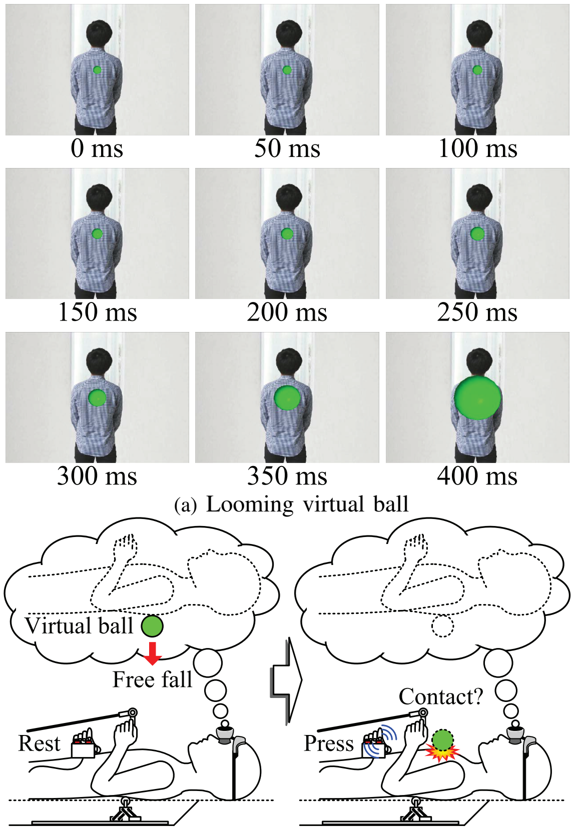

Fig. 4. Measurement of changes in perceived self-location based on MBD task. (a) Display of looming virtual ball on HMD during measurement. (b) Reaction to looming virtual ball. Participants held response device on their stomachs and pressed button with their dominant hand.

scene. The participants were asked to press a button on the response device when they felt that the virtual ball had reached their physical bodies, and the RT was recorded, as illustrated in Fig. 4(b). Note that no tactile cue was administered even if the virtual ball reached their physical bodies. The participants also performed the same task at the beginning of the main experiment before any experimental manipulation in order to obtain baseline RT. Thus, a drift in self-location towards the virtual body would manifest as shorter RTs in the a-FBI and c-FBI than that in the baseline. Furthermore, if the a-FBI induced larger changes in self-location than the c-FBI, the mean RTs in the a-FBI would be shorter than those following in the c-FBI.

4) Behavior data: In the present study, we tracked how the participants manipulated the leader robot during the experiment to investigate the relationship between the participants' movements and illusory experience in an exploratory analysis. In the a-FBI, the position of the leader robot was logged every 1 ms. The representative movements (mean stroke distance and mean of absolute stroke velocity) were calculated, and the behaviors in the CCE measurement phase were excluded when calculating the mean of absolute stroke velocity because the participants were not allowed to move the leader robot during the phase. The follower robot automatically moved based on one of six prerecorded trajectories in the c-FBI. The representative movements were extracted from the trajectories.

D. Experimental procedure

Fig. 5 shows an experimental procedure for comparison of the a-FBI and c-FBI. First, the participants underwent a training session in which they manipulated the leader and follower robots in a supine position to familiarize them with the robotically-mediated stroking procedure. At this time, the participants experienced both stimulation types (active self-touch and classical passive stimulation) for a few minutes until the experimenter felt they thoroughly understood the instructions. Additionally, a CCE test (16 conditions $\times$ 2 repetitions) was performed; we verified that for all participants, the error rate was less than 15%.

In the main experiment, the participants lying supine on the urethane bed were asked to gaze at the virtual body displayed on the HMD. At the beginning of the experiment, the participants first performed three trials of the previously described self-location measurement based on the MBD paradigm (Section II-C3). This was done to assess the baseline for the measurement of self-location; the mean RT of three measurements was considered as the baseline RT. An experimental trial began with stroking stimulation to the participants' backs for 30 s in either active self-touch or classical passive stimulation. During the a-FBI, the participants manipulated the leader robot with their non-dominant hands, which simultaneously provided haptic stimuli to their backs via the follower robot. In the c-FBI, the participants placed the tip of the leader robot close to their chests without any manipulation. The movement of the follower robot was randomly selected from six trajectories, which were prerecorded when the experimenter performed the same task. After the stimulation phase, a CCE test including four CCE conditions was performed for 15 s. Although a previous study reported that the learning effect caused by

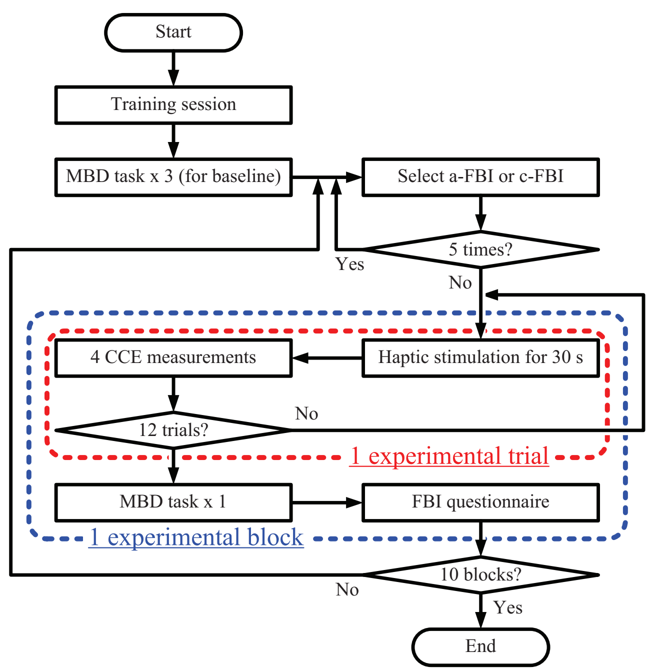

Fig. 5. Experimental flowchart for investigating effects of external and voluntary touch on FBI.

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continuous and repeated measurements may decrease CCE magnitude [54], it is expected that the alternations of tactile stimulation and CCE measurement would reduce it. The participants pressed the buttons on the response device with their dominant index or middle finger in the CCE test to respond to the vibration as fast as possible. Their dominant and non-dominant hands were placed near the belly and chest, holding the response device and robotic tip, respectively. This experimental trial was repeated 12 times in an experimental block, and the measurement of self-location and the FBI questionnaire were performed at the end of the experimental block. A total of 10 experimental blocks were conducted by randomizing the order of two stimulation conditions between the blocks (5 times each), and 240 CCEs were acquired in each condition. One experiment took approximately 2.5 h. During the experiment, white noise was played on the headphones of the HMD to relax the participants as well as to mask noise from the environment and the robots.

E. Data analysis

In the present study, 95% confidence intervals (CIs) were adopted, and thus the level of statistical significance was defined as $p < 0.05$.

Mean ratings for the FBI questionnaire items, which are discrete quantities, were analyzed with non-parametric tests (Friedman test and Wilcoxon signed-rank test) as the Shapiro-Wilk test detected several significant deviations from normal distribution in both the a-FBI (Q6: $W = 0.808$, $p = 0.003$, Q7: $W = 0.860$, $p = 0.015$) and c-FBI (Q6: $W = 0.892$, $p = 0.049$). We first applied the Friedman test, which is a non-parametric version of one-way repeated measures analysis of variance (ANOVA), to the mean ratings with a within-participants factor of *Questionnaire item*. If significant, then the mean ratings for the illusion items were compared with the mean of the ratings for the five control items using a two-tailed Wilcoxon signed-rank test (a non-parametric alternative to t-test) to investigate the influence of suggestibility. The level of significance was corrected for multiple comparisons with the Bonferroni method (i.e., corrected $\alpha = 0.05/3 = 0.0167$). The difference in the mean ratings for the illusion items (Q1 to Q3) and agency item (Q9) between a-FBI and c-FBI were also analyzed using a two-tailed Wilcoxon signed-rank test.

In the CCE measurement, we began by analyzing mean RTs, which are continuous quantities, in all conditions by using a three-way repeated measures ANOVA with within-participants factors of *Stimulation type* (active self-touch vs. classical passive stimulation), *Congruency* (congruent vs. incongruent), and *Distractor side* (same vs. different). Similar to previous CCE studies [42], [49], RTs in erroneous trials and below 0.2 s or over 1.5 s, which were considered preemptive or delayed responses, were removed from the analysis. If the three-way interaction was significant, the Tukey's honestly significant difference (HSD) test was used for post-hoc analysis of the CCE. The error rate (i.e., the percentage of erroneous judgments) was also analyzed in the same manner. Furthermore, a Dunnett's test using mean CCEs in the first experimental block was used to analyze potential differences in the mean CCEs between the first and all later experimental blocks and to examine if the CCE was degraded by the repetitive measurements [54].

As for the measurement of self-location based on the MBD paradigm, only 15 participants were analyzed because data recording failed in first two participants. We first focused on the differences in mean RTs between baseline, a-FBI, and c-FBI. Mauchly's sphericity test was performed to validate a repeated measures ANOVA (as the homoscedasticity between the levels, i.e., the sphericity assumption is always met for designs with only two levels of a repeated measures factor, this test was not performed to analyze the mean RTs in the CCE measurement). If the Mauchly's sphericity test was violated ($p < 0.05$), the degree of freedom in a one-way repeated measures ANOVA with a within-participant factor of *Reaction time* was adjusted using the Greenhouse-Geisser's epsilon. If the ANOVA reported a significant main effect, we further investigated the change in self-location. The change in self-location (i.e., difference between mean RTs in the a-FBI/c-FBI and baseline) was first analyzed with a two-tailed one-sample t-test to investigate if it was significantly shorter than 0.0 ms (i.e., smaller than the baseline RT). Additionally, the statistical difference in the changes in perceived self-location between the a-FBI and c-FBI was analyzed using a two-tailed paired t-test.

Finally, we investigated the possible relationship between the participants' movement data and illusory ownership (i.e., embodiment of the seen body (Q3) and drift in self-location towards the virtual body) in 15 participants. The mean stroke distance and mean of absolute velocity in each experimental trial were considered as representative features of the participants' movements and were statistically analyzed between the a-FBI and c-FBI. The correlation was statistically examined with the Pearson correlation coefficient (PCC). Additionally, the statistical differences in the movement data between the a-FBI and c-FBI were analyzed using a two-tailed paired t-test.

III. Experimental Results

A. FBI questionnaire

Fig. 6 expresses questionnaire results as box-and-whisker plots involving individual plots. Mean ratings over 0 were found for the illusion items in both the a-FBI (Q1 (mislocalization of touch): $M = 2.05$, SEM $= 0.15$; Q2 (sense of touch on the virtual body): $M = 1.85$, SEM $= 0.17$; Q3 (embodiment of the virtual body): $M = 0.21$, $SEM = 0.38$) and c-FBI (Q1: $M = 2.13$, SEM $= 0.15$; Q2: $M = 1.78$, SEM $= 0.18$; Q3: $M = 0.09$, SEM $= 0.38$). The mean ratings of all control items were below 0 (a-FBI: $M = -0.58$, SEM $= 0.33$; c-FBI: $M = -0.76$, SEM $= 0.34$). As for the suggestibility, the planned post-hoc comparisons with the corrected $\alpha = 0.0167$ were performed because the Friedman test reported a significant main effect of *Questionnaire item* for both the stimulation conditions (a-FBI: $\chi^2(8) = 96.07$, $p < 0.001$; c-FBI: $\chi^2(8) = 80.52$, $p < 0.001$). The results indicated that the mean ratings of the illusion items were significantly higher than those of the control items in both the a-FBI (Q1: $z = 3.62$, $p < 0.001$; Q2: $z = 3.62$, $p < 0.001$; Q3: $z = 2.91$, $p = 0.002$) and c-FBI (Q1: $z = 3.62$, $p < 0.001$;

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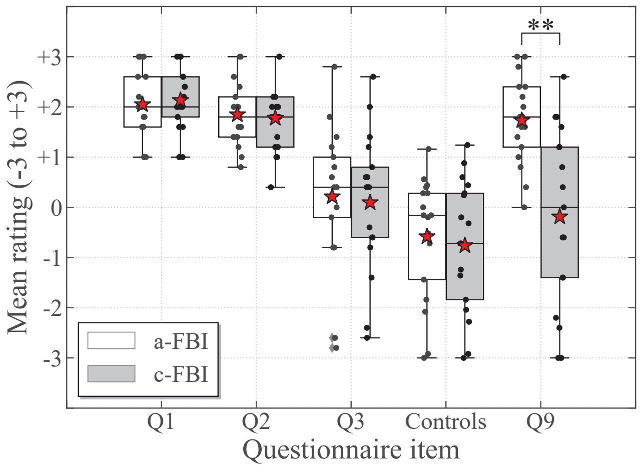

Fig. 6. Results of FBI questionnaire. Whiskers, gray diamond shapes, and red stars indicate 95% CIs, outliers, and mean ratings of 17 participants, respectively (**: $p < 0.01$). Black dots represent individual plots for each item. Results for "Controls" show mean ratings from Q4 to Q8.

Q2: $z = 3.62$, $p < 0.001$; Q3: $z = 3.29$, $p < 0.001$). The Wilcoxon signed-rank test indicated a significant difference in Q9 (agency) between the two stimulation conditions ($z = 3.59$, $p < 0.001$) but not in the illusion items (Q1: $z = -1.13$, $p = 0.313$; Q2: $z = 0.27$, $p = 0.814$; Q3: $z = 0.68$, $p = 0.524$).

These data indicate that the participants could have a sense of agency only in the a-FBI but that it does not affect the illusory experience.

B. CCE measurement

The mean RTs and errors for all conditions are listed in Table II. Fig. 7 compares the CCEs in the two stimulation conditions. The three-way repeated measures ANOVA revealed significant main effects of *Stimulation type* ($F_{1,16} = 4.93$, $p = 0.041$, $\eta_p^2 = 0.236$) and *Congruency* ($F_{1,16} = 85.90$, $p < 0.001$, $\eta_p^2 = 0.843$); the main effect of *Distractor side* was not significant ($F_{1,16} = 0.21$, $p = 0.655$, $\eta_p^2 = 0.013$). The two-way interaction between *Congruency* and *Distractor side* ($F_{1,16} = 25.04$, $p < 0.001$, $\eta_p^2 = 0.610$) was significant, while any other significant interactions were not reported (*Stimulation type* × *Congruency*: $F_{1,16} = 0.200$, $p = 0.661$, $\eta_p^2 = 0.012$; *Stimulation type* × *Distractor side*: $F_{1,16} = 3.51$, $p = 0.078$, $\eta_p^2 = 0.171$; three-way interaction: $F_{1,16} = 3.68$, $p = 0.073$, $\eta_p^2 = 0.187$). Concerning the error rate, the three-way repeated measures ANOVA showed significant main effects of *Congruency* ($F_{1,16} = 13.81$, $p = 0.002$, $\eta_p^2 = 0.463$) and *Distractor side* ($F_{1,16} = 8.23$, $p = 0.011$, $\eta_p^2 = 0.340$), but no significant main effect was reported in *Stimulation type* ($F_{1,16} = 1.08$, $p = 0.314$, $\eta_p^2 = 0.063$). As for the interactions, significant two-way interactions were found in *Stimulation type* × *Congruency* ($F_{1,16} = 5.62$, $p = 0.031$, $\eta_p^2 = 0.260$) and *Congruency* × *Distractor side* ($F_{1,16} = 8.23$, $p = 0.011$, $\eta_p^2 = 0.338$) but not in the others (*Stimulation type* × *Distractor side*: $F_{1,16} = 0.00$, $p = 1.00$, $\eta_p^2 = 0.000$, three-way interaction: $F_{1,16} = 0.116$, $p = 0.743$, $\eta_p^2 = 0.007$). There were no significant differences in the mean CCEs across blocks (Dunnett's test), indicating that repetitive measurements in the present study did not degrade the CCE magnitude.

TABLE II
MEAN RTS AND PERCENTAGES OF ERRONEOUS DISCRIMINATION FOR VIBROTACTILE STIMULI

Target-distractor congruency	Position of distractor	RT (SEM) ms	Error (SEM) %
a-FBI: Active self-touch			
Congruent	Same side	499 (25)	1.8 (0.3)
	Different side	531 (29)	2.3 (0.8)
Incongruent	Same side	593 (26)	7.1 (1.5)
	Different side	566 (25)	4.7 (1.3)
c-FBI: Classical passive stimulation			
Congruent	Same side	531 (31)	3.5 (0.9)
	Different side	543 (32)	3.7 (0.9)
Incongruent	Same side	615 (30)	6.4 (1.0)
	Different side	592 (29)	4.3 (0.8)

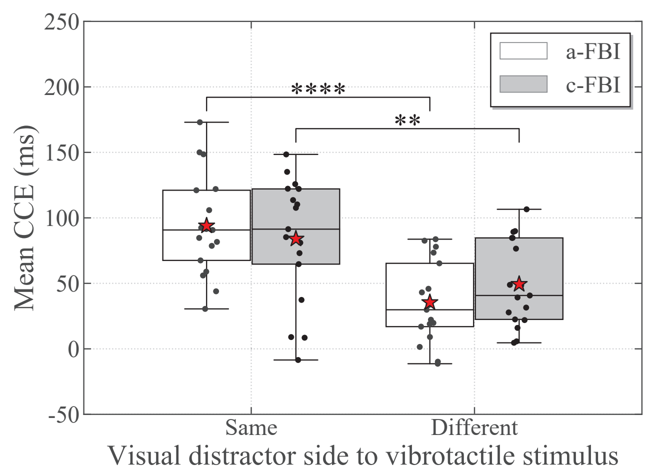

Fig. 7. Results of CCE measurement. Whiskers and red stars indicate 95% CIs and mean CCEs of 17 participants, respectively. Black dots represent individual plots for each condition. Significant differences were analyzed using Tukey's HSD test (**: $p < 0.01$, ****: $p < 0.001$).

These data show that voluntary self-touch does not significantly contribute to the CCE, although classical CCE trends [44] can be found in both the a-FBI and c-FBI.

C. Measurement of self-location

The mean RTs (SEMs) were 675 (13) ms in the baseline, 648 (12) ms in the a-FBI, and 663 (13) ms in the c-FBI, respectively. First, we applied the one-way repeated measures ANOVA corrected by the Greenhouse-Geisser's epsilon ($\varepsilon = 0.725$). As the ANOVA revealed a significant effect ($F_{1.45,20.29} = 6.36$, $p = 0.012$, $\eta_p^2 = 0.312$), the change in self-location was further analyzed with the planned post-hoc comparisons. Fig. 8 shows changes in self-location in the two stimulation conditions. Numerically, both self-location measures were smaller than 0.0 ms, suggesting that participants felt their self-location was closer to the virtual body. However, the two-tailed one-sample t-test indicated that the drift in self-location was significantly smaller than 0.0 ms in

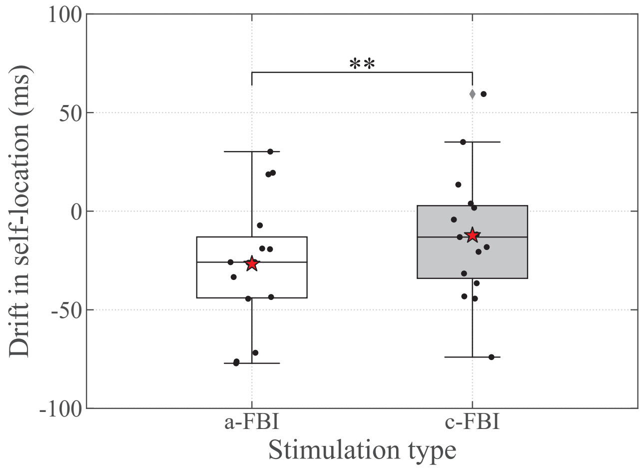

Fig. 8. Results of MBD-task-based self-location measurement. Whiskers, gray diamond shapes, and red stars indicate 95% CIs, outliers, and mean drifts in self-location of 15 participants, respectively (**: $p < 0.01$). Black dots represent individual plots for each condition. 0.0 ms indicates no difference from baseline RT, and negative value means drift in self-location towards virtual body on HMD.

the a-FBI ($M = -23.9$, SEM $= 8.5$, $t_{14} = -3.10$, $p = 0.004$) but not in the c-FBI ($M = -10.7$, SEM $= 8.2$, $t_{14} = -1.43$, $p = 0.087$). Additionally, the two-tailed paired t-test found a significant difference in the drift in self-location between the two stimulation conditions ($t_{14} = -3.11$, $p = 0.004$) with a larger change in the self-location in the a-FBI.

These statistical results imply that voluntary self-touch may induce larger changes in perceived self-location.

D. Behavior data

The mean stroke distances (SEM) were 72.81 (1.30) mm in the a-FBI and 63.66 (0.25) mm in the c-FBI, respectively. The two-tailed t-test indicated a significant difference in the mean stroke distance between the two stimulation conditions ($t_{14} = 6.63$, $p < 0.001$) with longer movements in the a-FBI, which may have influenced the questionnaire and/or self-location responses. In both stimulation conditions, we correlated mean stroke distances with both the ratings of self-identification (Q3) and self-location measurements. However, further analysis revealed no significant correlation between the mean stroke distance and body ownership (a-FBI: PCC $=$ 0.018, $p = 0.880$; c-FBI: PCC $= -0.066$, $p = 0.572$) nor the drift in self-location (a-FBI: PCC $= -0.082$, $p = 0.482$; c-FBI: PCC $= 0.072$, $p = -0.541$). Similarly, for the mean of absolute stroke velocity (a-FBI: 61.29 (3.07) mm/s; c-FBI: 52.10 (0.23) mm/s; $t_{14} = 2.92$, $p = 0.011$), no significant correlation was found neither with the ratings of self-identification (a-FBI: PCC $= 0.150$, $p = 0.198$; c-FBI: PCC $= 0.089$, $p = 0.450$) nor the self-location measurements (c-FBI: PCC $= 0.146$, $p = 0.211$; c-FBI: PCC $= 0.076$, $p = 0.518$). A significant difference was only found between the two stimulation conditions ($t_{14} = 2.92$, $p = 0.001$) with faster movement in the a-FBI.

IV. Discussion

The main purpose of this study was to investigate whether the addition of self-generated action and haptic cues can modulate the FBI. This was examined by comparing the questionnaire and behavioral measurements of the a-FBI with those of the well-established c-FBI. For the FBI questionnaire, positive ratings were observed for the illusion items in both the stimulation conditions, and low ratings of the control questionnaire items suggest no influence of suggestibility. These results indicate that the participants experienced the FBI (i.e., body ownership of the virtual body) in both the a-FBI and c-FBI conditions. However, contrary to our hypothesis, no significant differences were found in the magnitude of subjective body ownership between the two conditions. Thus, while the participants felt strong agency only in the a-FBI and not c-FBI, the active control of the tactile feedback did not significantly modulate or enhance the magnitude of body ownership, supporting previous evidence for a dissociation between the senses of body ownership and agency [3]. This finding contrasts with that of our previous work on hand ownership using active self-touch, wherein it was found that illusory ownership over a virtual hand was higher for active movements as the sense of agency increased [37]. However, the present study differs from previous studies in several aspects of their experimental design, i.e., differences in the stimulation manner (stroking in the present study vs. tapping in the previous study), participants' posture (supine vs. seated), stimulated body part (back vs. hand), and perspective of the virtual body (third-person viewpoint vs. first-person viewpoint). In addition, the omission of asynchronous condition might affect the contrast in the illusory experience between the a-FBI and c-FBI. Therefore, further studies using active stimulation in hand and body ownership paradigms are needed to elucidate which of these parameters account for the difference between the two findings.

In addition to subjective reports, we employed a CCE task that has been previously used to assess perceptual changes during the FBI. While our results replicated previous body-related CCE findings [41], [42] showing that the mean CCE on the same side of the body was significantly higher than that on the different side, no differences between the a-FBI and c-FBI were found. Thus, in line with the results of the subjective questionnaire measures, the current CCE findings provided no evidence for the differential modulation of visuotactile bodily processing through the induction of the FBI using self-generated action and haptic cues. This is again compatible with the disassociation of body ownership and agency [3]. One must however take into account that contrary to a previous study using the CCE task during the FBI [41], no asynchronous visuotactile condition was employed here. Thus, as the comparison was between two illusion-inducing conditions, the contrast might be smaller than expected.

Regarding the self-location measurements, the results indicate that the a-FBI was associated with a large drift in self-location towards the virtual body (i.e., shorter RTs than the baseline) as compared to the c-FBI condition. This finding is in line with a previous study that investigated the role of active self-touch in the RHI [37]. In the present study, these larger changes in self-location in the a-FBI were not associated with similar increases in the questionnaire and CCE results. One possible explanation may be that the efferent signals present in the a-FBI condition impact implicit measures, but not or fewer explicit subjective measures of the FBI (i.e., indexed by the questionnaire). Indeed, previous studies have reported dissociation between subjective and self-location measures, for example, suggesting that these may reflect different aspects of illusory ownership [14], [55]. Further studies are required to investigate these issues more directly.

V. Study Limitations

One limitation of this study is the absence of an asynchronous visuotactile condition, as mentioned above. We have previously shown the synchronous vs. asynchronous modulation of body ownership in an active self-touch-enabled FBI [39] and an active self-touch-enabled RHI [37], [40]. Thus, we chose not to use an asynchronous condition to allow more repetitions of the synchronous visuotactile induction (and the active versus passive conditions) as well as repeated CCE measurements. This however limits the inferences from the CCE measurements, which showed no differences between the a-FBI and c-FBI conditions. Furthermore, it is possible that the absence of a control (no illusion) condition may have caused the participants to recalibrate their responses compared to experimental setups in which they experience asynchronous visuotactile feedback. Finally, the analysis of the movements (i.e., mean stroke distance and mean of absolute stroke velocity) indicated some differences between the a-FBI and c-FBI conditions, yet these were not significantly related to measures of body ownership. While we do not believe that these movement differences impact the magnitude of the FBI (which was indeed similar in most measurements), further studies in which the passive stimulation is matched to the active stimulation would assist in controlling for such possible confounds.

VI. Conclusion

In this study, we aimed at testing the possibility of eliciting an FBI based on active, self-generated movement, and haptic cues, and to compare its characteristics with those of the classical passive visuotactile FBI. Our results indicated that voluntary self-touch is applicable to induce the FBI in line with previous results using movement (both active and passive) to induce bodily illusions [22], [24], [37], [39], [56]. Contrary to our previous findings targeting hand ownership [37], the a-FBI was not subjectively experienced as stronger than the c-FBI; however, changes in self-location were larger in the a-FBI condition in accordance with the previous RHI study. The present study extended previous researches on the interactions between body ownership and action [3], [29], [31], [33], [36], [53], [57] by indicating that active self-touch can modulate the experience of ownership over a full body.

Research on the FBI and related bodily illusions induced by active self-touch may impact various fields. For instance, we have recently succeeded in experimentally modulating the self-other discrimination of healthy people in different paradigms using active self-touch. We thus described changes in sensorimotor processing [58], auditory perception [59], and thought consciousness [60] and argue that such changes may also affect other systems involved in self-other discrimination, including mental-cognitive [61] and affective systems [62]. Finally, we believe that automatized body illusions, merging insights from robotics and cognitive science for the investigation of consciousness and cognition (i.e., cognetics) [43], will advance the understanding and tailoring of specific treatment options for several clinical conditions, ranging from psychiatry [59], [60] and neurodegeneration [63] to stroke-related rehabilitation procedures [64].

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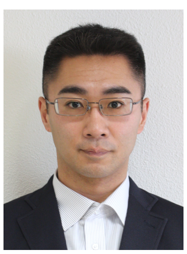

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