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RESEARCH ARTICLE

Virtual reality for assessment of patients suffering chronic pain: a case study

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Abstract The study of body representation and ownership has been a very active research area in recent years. Synchronous multisensory stimulation has been used for the induction of the illusion of ownership over virtual body parts and even full bodies, and it has provided experimental paradigms for the understanding of the brain processing of body representation. However, the illusion of ownership of a virtual body has rarely been used for patient evaluation and diagnosis. Here we propose a method that exploits ownership of a virtual body in combination with a simple brain computer interface (BCI) and basic physiological measures to complement neurological assessment. A male patient presenting a fixed posture dystonia featuring a permanently closed left fist participated in this case study. The patient saw a virtual body that substituted his own after donning a head-mounted display and thereby entering the virtual reality. The left virtual hand had the same posture as his corresponding real hand. After inducing virtual hand ownership by correlated visuo-tactile stimulation and dynamic reflections in a virtual mirror, the virtual hand would open either automatically or through a cognitive task assessed through a BCI that required him to focus attention on the virtual hand. The results reveal that body ownership induced changes on electromyography and BCI performance in the patient that were different from those in five healthy controls. Overall, the case study shows that the induction of virtual body ownership combined with simple electrophysiological measures could be useful for the diagnosis of patients with neurological conditions.

Keywords Body ownership · Immersive virtual reality · Pain · Assessment

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Introduction

The induction of body ownership over physical and virtual fake body parts has been a very active area of research in recent years (Blanke et al. 2002; Ehrsson 2007; Slater et al. 2009). Using synchronous multisensory stimulation it is possible to induce the illusion of body ownership over physical artificial limbs (Botvinick and Cohen 1998), virtual limbs (Slater et al. 2008) or even a whole fake body (Lenggenhager et al. 2007; Ehrsson 2007; Petkova and Ehrsson 2008; Slater et al. 2010).

This illusory ownership is the result of the coherent activation of different and concurrent sensory streams, usually dominated by vision, and it is most commonly induced by visuo-tactile synchrony (Botvinick and Cohen 1998; Ehrsson et al. 2004; Slater et al. 2008) and sensory-motor congruency (Tsakiris et al. 2007; Sanchez-Vives et al. 2010; González-Franco et al. 2010; Kalckert and

Ehrsson 2012). Another way of inducing body ownership is through physiological feedback techniques such as brain computer interface (BCI). For example, Perez-Marcos et al. (2009) showed that moving a virtual arm through a BCI induced an illusion of ownership of the virtual arm. Overall, the induction of illusory body ownership has provided experimental paradigms for the understanding of the brain processing of body representation (reviewed in Blanke 2012).

Illusory ownership of a fake arm can induce physiological changes such as a drop in skin temperature in the real arm (Moseley et al. 2008) or affect performance in tasks involving motor control (Newport et al. 2010). This suggests that such techniques could be used to induce physiological and/or behavioural changes in therapeutic contexts. However, although these results are well established, virtual body ownership has hardly been exploited in diagnosis or therapy.

The illusory ownership of a limb has been found useful to reduce phantom limb pain in amputees based on mirror reflection of the other real arm (Ramachandran et al. 1995). These results have also been shown using immersive virtual environment (IVE). For example, Murray et al. (2007) studied amputees while they experienced a virtual arm in the position and of orientation of their phantom arm, with its movements controlled by those of their existing other arm. These patients reported tactile sensations as if originating in the virtual arm as well as some relief over the phantom limb pain. Mercier and Sirigu (2009) showed that when patients were asked patients to imitate the movements observed in a virtual mirror where a virtual arm was moving automatically, they reported reduced phantom limb pain. Sato et al. (2010) showed that patients suffering from complex regional pain syndrome could experience some pain relief using a visual feedback system based on a virtual mirror combining movements from the affected and non-affected arms during a grasping task.

In relation to pain, IVEs have also been used as an attention distractor. For example, patients with severe burns felt less pain while their bandages were changed when they were immersed in an IVE where they saw virtual snow with which they had to play (Hoffman et al. 2000a, b). Multisensory manipulations leading to self-identification with a virtual body have also been shown to induce changes in pain threshold (Hänsel et al. 2011).

However, to our knowledge, virtual body ownership has rarely been used for diagnostic purposes. In this work we explore the utility of combining IVEs with BCI and basic physiological measures in order to complement neurological examination and diagnosis of a patient suffering from chronic pain, and a fixed posture dystonia of his left hand suspected to be of psychogenic origin. Contrasting the results obtained in this patient with those of five controls, we suggest that the induction of body ownership together with simple physiological measures can help in the assessment of such patients, and more generally in the diagnosis and therapy of neurological conditions.

Materials and methods

Ethical approval

The experiment had the approval of the ethics commission of the Hospital Clinic, Barcelona.

Participants

A case study was carried out on one male volunteer patient. In addition, five healthy males participated as controls. All participants, including the patient, gave written informed consent.

The patient was a 28-year-old man. He showed a fixed posture dystonia that had started 18 months before the experiment, manifested as a closed left fist. There were no relevant neurological disorders in his personal or family history. At the onset of his condition, his hand could be opened with some help and, according to relatives, was relaxed while sleeping. At the time of the first examination, however, his condition had worsened. His hand was permanently closed (also during sleep, according to relatives), and the only voluntary movement possible was a small extension of his little finger. The nail of the index finger by that time was causing skin lesions in the palm. He had been diagnosed with idiopathic fixed dystonia compatible with a psychogenic disorder in another centre, and we found no other alternative diagnosis. There were no positive findings in any of the laboratory tests for possible metabolic, toxic or infectious disorders. Normal serum copper ruled out Wilson's disease, and there were no signs of any degenerative disease. The brain and cervical MRI were normal. Nerve conduction studies did not disclose any sign of peripheral nerve lesion in median or ulnar nerves. Needle EMG showed motor unit action potentials firing in the wrist flexor as well as in the wrist extensor muscles. When the patient was requested to make a stronger fist, the firing rate of these action potentials increased together with the recruitment of other motor units. However, the action potentials did not disappear completely when the patient was requested to relax and open his fist. An anaesthetic block of both median and ulnar nerves at the elbow permitted some hand opening, but joint and soft tissue retraction prevented more than 10° extension of the metacarpo-phalangeal joints. A thorough clinical examination did not reveal any dysfunction elsewhere in the body.

The five control participants had a mean age of 25.4 ± 2.5 (SD) years. They were recruited by advertisement and via email amongst students at the University of Barcelona and were paid 10 € for their participation.

Materials

A stereo head-mounted display (HMD) was used to deliver the IVE. This was an NVIS SX111 which has a resolution of 1280 × 1024 and a field of view (FOV) of 76°H × 64°V per eye, and a total resolution and FOV of 2560 × 1024 and 111°H × 64°V, respectively. The display refresh rate was 60 Hz. A NVIDIA GeForce 480GTX graphics card was used to drive the HMD. For head tracking we used the Intersense IS900 tracker that was internally locked to a refresh rate of 60 Hz. Hand tracking was implemented with optical markers monitored through 12 cameras connected to an Optitrack motion capture system.

The geometry, clothes and skin texture of the virtual character that provided the virtual body representation were acquired from the company AXYZ design.

A hardware accelerated library for character animation (HALCA), as described in Gillies and Spanlang (2010), was used to blend the motions of the character. The synchronization of all the devices and signals was achieved with a custom implementation that is based on the VRPN protocol (Taylor et al. 2001), and the rendering of the virtual environment was done with XVR (Tecchia et al. 2010).

The electromyography (EMG) and electroencephalography (EEG) data were obtained using a gUSBAmp device sampling at 512 Hz with standard physiological electrodes (see dedicated section below for further details). The online and offline analyses of the physiological data were implemented in MATLAB using the gtec High-Speed Online Processing toolbox for MatLab Simulink.

Scenario

A virtual environment was developed in order to adapt the scenario as much as possible to the patient's reality (Fig. 1). The participant was asked to sit on a chair and to have his forearm resting on a small table nearby. When wearing the HMD the participant saw a virtual body substituting his own, with the left virtual hand closed and resting on a virtual table colocated with the real one and therefore in the corresponding position and orientation. The participant could see his virtual body by looking directly at it, as if looking at his own real body, but also in a virtual mirror that showed a mirror reflection of the body. The movements of the participant's real left arm were tracked and mapped to the virtual left hand, which would move in the same way, contributing to the generation of ownership (Sanchez-Vives et al. 2010). This could be seen directly from a first-person perspective and through the virtual mirror. To avoid problems of rejection of the virtual body due to physical appearance, care was taken not to show the face of the virtual body in the mirror, simply by placing the

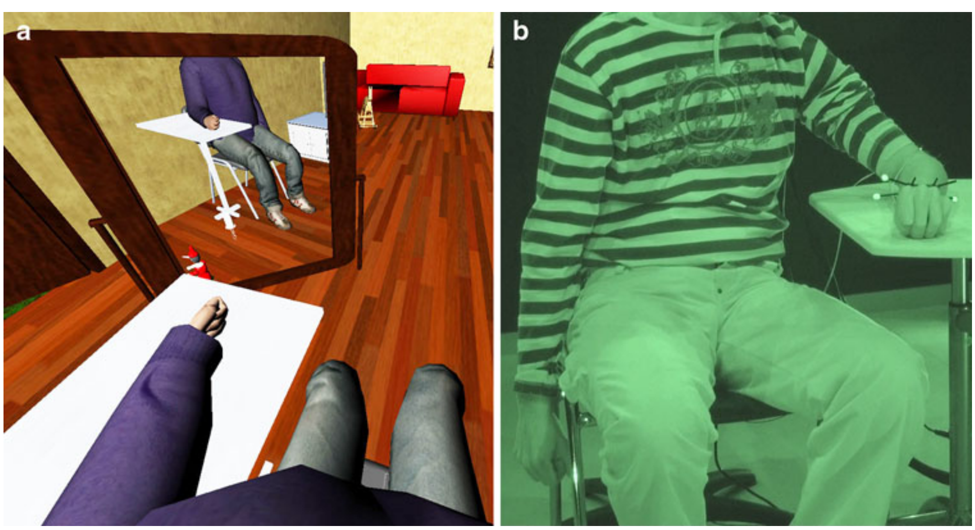

Fig. 1 **a** A first-person perspective of the virtual environment: the participant could see a virtual body colocated with his own, a *left hand* in the same position as his and his forearm resting in a table similar to where his forearm was located. The real hand was tracked in real time, and the virtual hand followed the movements of the real one. In order to introduce additional visual cues for virtual body ownership, the participant also saw the virtual body reflected in a mirror towards his *left*, where his reflected hand also followed his real-time movements. All representations were in 3D and seen in stereo. **b** The actual body of the patient. The optical tracker is on *top* of his *left hand*. The cables attached to his forearm were for the EMG recording. The participant was also wearing a head-mounted display (not shown)

virtual mirror in a position and orientation that showed only the body from the neck down (see Fig. 1). To further induce ownership over the virtual limb, we applied synchronous visuo-tactile stimulation using the method described by Slater et al. (2008). This was achieved using a soft ball attached to a 6-degrees-of-freedom Wand device whose tracking information determined the position of a virtual ball. As a result of this configuration, when the soft ball touched the participant's real hand, a corresponding virtual ball touched the virtual hand. The reflection of the body movements on the mirror was used to increase the sensorimotor correlations to induce body ownership (González-Franco et al. 2010).

Procedure

The participant was informed about the principles of immersive virtual reality and how the session would be organized. Then, he was given a consent form to sign. Next, the EMG and EEG electrodes were attached to the forearm, over the wrist flexors, and to the skull (FP1), respectively. Impedances were checked and the hand tracker was attached to the back of the participant's left hand. Then, he trained for a BCI task that was to be used in Part 2 of the experiment (see below). By means of the BCI, and over a 3 min period, the participant tried to reduce the size of a virtual ball as presented on a PC desktop monitor. Then, we proceeded to the main experiment, which was divided into three parts.

At the beginning of each part of the experiment, the position of the participant's left hand was realigned with the virtual one, and there was a check to ensure that the virtual hand correctly replicated the rotation of the real hand. Then the position of the virtual table and the visuo-tactile coupling were recalibrated to minimize incongruence between the tactile and visual inputs. The aim was to provide the participant with both sensorimotor and visuomotor correlations to maximize the chance of inducing body ownership.

The HMD was donned by the participant and calibrated to make sure that the subsequent scenario would be seen correctly. Once immersed in the virtual environment, virtual body ownership was triggered through 1 min of synchronous visuo-tactile stimulation, with the physical tracked ball repeatedly touching the participant's left hand and the corresponding virtual ball touching the virtual left hand (Slater et al. 2008). Then, depending on the section of the experiment, the virtual hand would open under specific conditions, and a task had to be completed. At the end of each part of the experiment, the HMD was taken off, and the participant was given some time to rest.

Part 1 was designed to study the impact of virtual embodiment on the muscular activity in the arm of the participant. After the induction of virtual body ownership, the virtual hand would open automatically to assess the impact of this on the participant's physiology and behaviour, as well as subjective experience. We had reason to believe from an earlier experiment (Slater et al. 2008) that when participants see their virtual limbs move, this triggers some muscle activity in the corresponding real limb. It was therefore hypothesized that the opening and closing of a virtual hand over which the participant felt ownership would have an impact on the EMG activity. The goal was to assess whether these changes would be greater in the patient or in the controls. The procedures were as follows:

(a) Induction of body ownership (through synchronous visuo-tactile stimulation).
(b) Resting period for EMG measure after visuo-tactile stimulation period.
(c) Progressive and automatic opening of the virtual hand.
(d) Resting period for EMG measure after opening.
(e) Progressive and automatic closing of the virtual hand.
(f) Resting period for EMG measure after closing.

The animation of the hand opening or closing lasted 20 s, and the evolution of the EMG across the whole experiment was recorded and analysed. Eight seconds of EMG measurements were recorded in steps (b), (d) and (f). These were used to compare the impact of the visual stimuli presented in steps (a), (c) and (e) with the same visual feedback and no tactile stimuli. Care was taken that the arm of the virtual patient was relaxed on the table during the control EMG measures.

Part 2 was designed to evaluate the possibility of a psychogenic disorder. After the induction of virtual body ownership, the virtual hand would open as the result of a concentration task measured through a BCI. For comparison of the effects of such a task between body-related and body-unrelated virtual objects, we asked the participant also to modify the size of a virtual ball using the same BCI strategy. It was hypothesized that if the reason for the patient to not be able to open his hand was psychogenic, then his performance in the BCI task would be different when the objective was to open the virtual hand compared to when it was to modify the size of a virtual ball. To evaluate this, the BCI was designed to detect concentration, and the performance of both the patient and the healthy participants was mapped either on the virtual hand or on the virtual ball (see details below). Since it was possible that while doing the task there would be a learning effect, the hand opening and ball modification conditions were repeated alternatively. With this strategy, we expected that any learning effect would be similar for the different conditions. The order of procedures was as follows:

(a) Induction of body ownership.
(b) Opening of the virtual hand using BCI
(c) Reducing the size of the ball using BCI
(d) Repeat (b).
(e) Repeat (c).

The EMG was measured throughout to assess the impact of the visual feedback on the muscular activity of the real hand. We hypothesized changes in EMG activity would occur as secondary effects of the visual input of the moving hand, as in Part 1.

Part 3 was designed to detect any changes in motor performance as a consequence of seeing the virtual hand open. The aim was to assess whether the feeling of ownership over a hand that looked healthy might provoke an improvement over the limited mobility. The rationale was equivalent to Part 1, but instead of measuring EMG activity, we explored changes in motor performance. The participant was asked to move his wrist, to turn the hand to the left, to the right and then lift it as much as possible. The virtual hand moved consistently with the participants' movements, but it appeared to be either closed or open.

In this particular case the wrist movement was chosen because the patient showed some limitation on the movement of this joint, but not as severe as in the fingers. During performance of the task, an experimenter loosely held the forearm of the participant to ensure that only the wrist joint would move. The order of procedures was as follows:

(a) Induction of body ownership.
(b) Task performance: rotating the wrist in the three different directions.
(c) Progressive and automatic opening of the virtual hand.
(d) Repeat (b).
(e) Automatic closing of the virtual hand.
(f) Repeat (b).
(g) Progressive and automatic opening of the virtual hand.
(h) Repeat (b).

In the case of the patient, this part was repeated twice to obtain more data, including a small interval where the patient was asked to relax his hand as much as possible. This part was not repeated for the controls.

A short interview was carried out as the last procedure at the end of the experimental trials. In the case of the control participants, the interview was preceded by a short body ownership questionnaire.

Electromyography measures

EMG recordings were obtained in order to study the participant's evolution and possible effects of the virtual experience. To record the EMG we used a pair of electrodes (active and reference) attached over the flexor carpi radialis muscle and one ground electrode placed over a proximal muscle, the trapezius. We chose to do a simple bipolar recording from the flexor carpi because the flexor carpi is a muscle that is activated when any movement in the lower arm occurs, which includes any finger or wrist movements.

The activity was sampled at 512 Hz and saved directly as raw data. In the offline analysis, the EMG was filtered with a band pass of 20 to 250 Hz. A notch filter was also applied to remove all AC line interferences. The main EMG feature used was the root mean square (RMS), computed with a sliding window of 500 ms. To analyse the EMG for parts 1 and 2, we considered the mean RMS activity during the induction of body ownership as a baseline measure. During this period the hand was resting on the table.

To assess whether a response was significantly different from baseline, we considered a 99 % confidence interval of the EMG baseline (mean $\pm$ 2.58 $\times$ s of RMS (EMG), where s was the observed standard deviation during the baseline). This value was used to assess the evolution of the RMS signal throughout the task. In Part 1 this measure was also used to test whether the activity in the 8-s EMG control period after automatic opening and automatic closing of the virtual hand was significantly different from the baseline activity.

Brain computer interface

In Part 2 we used a BCI based on EEG. We wanted the BCI to assess the concentration level of the participant, defined as the cognitive process of selectively focusing on one aspect of the environment while ignoring others. The EEG oscillations in the alpha band have been shown to decrease in power as tasks become more difficult and, at the same time, while power increases in higher-frequency bands (Ray and Cole 1985; Shaw 1996). This has often been interpreted as an indication that the alpha rhythm represents a form of cortical idling (Gevins et al. 1979; Pfurtscheller 1989). We exploited these features of the alpha rhythm for our BCI paradigm.

In order to record the EEG, one single electrode was placed in the prefrontal cortex FP1 position of the standard EEG recording (10–20), and the reference and ground electrodes were set with ear clips in the A1 and A2 positions. Even when a larger number of electrodes would have been potentially useful to assess a more complete EEG, previous work has shown that this procedure is enough to assess a concentration task (George et al. 2011; Lin and John 2006). Due to the critical effects of electrooculogram

(EOG) artefacts in the EEG signal taken from the FP1 area, an online EOG removal process was implemented using an RLS (recursive least squares) adaptive filter (He et al. 2004). The resulting output was used for the BCI.

The output of this filtering was used to implement an online "concentration-level detector". First, the alpha frequencies (8–13 Hz) were extracted with a bandpass filter; then, the band power over a 200-ms running window was estimated. Finally, the band power was normalized from 0 to 1 with an ad hoc division factor.

It was considered that the participant was in a state of concentration when the band power decreased below the 20 % of its mean activity for more than 500 ms. Each time this happened, the virtual hand opened further. In the control condition, each time this occurred, the virtual ball would become smaller (see Fig. 2). The participants intuitively felt this as a focusing task, and both tasks were calibrated to require the same effort.

The task ended either when participants reached a predetermined threshold of 0.5 (meaning that the ball was reduced to half the original size, or the hand half opened), or after 90 s spent performing the task. This time limit was introduced for the overall time of immersion in the virtual environment not to exceed 20 min.

To compare the performance between the different participants, we introduced a performance index. This performance index was based on the performance ratio, calculated as the best-reached threshold divided by the time to reach it. Thus, the performance ranged between 0 and 50 %, and the time ratio between 0 and 90 s. In addition, since there were some participants who performed better than others, we compared their performance ratio in each condition against the mean performance ratio across conditions. This was used to measure the impact of the change in the visual feedback on their BCI performance, independently of whether they were good or bad at the task. The reason for introducing this measure was because we were not interested in comparing the differences between participants, but rather the difference in performance for the different conditions: Would there be a difference when the task involved a virtually owned hand or a neutral object such as a ball? Would repeating the task improve performance?

Behavioural measures

In order to evaluate the mobility of the wrist, in Part 3 we analysed the rotation of the hand tracker. Participants were asked to place their hand on the virtual table in the initial resting position and relaxed. This was considered to be the central position. Then they were asked to rotate the hand towards the left, then go back to the central position, then rotate it upwards, then go back to the central position, then rotate it to the right and so on. The maximal rotation values in each direction were used as behavioural measures.

At the end of the task, the maximal rotation was measured twice for each of the six conditions, involving one of the three rotation directions and two aspects of the virtual hand (opened or closed). In the case of the patient Part 3 was carried out twice, and therefore, the maximal rotation was measured four times for each of the six conditions.

Results

Part 1: Impact of virtual embodiment on EMG activity

The RMS analysis of the EMG to detect muscle activity is represented in Fig. 3a for the patient (black line) and the control participants (grey lines). It is noticeable that from

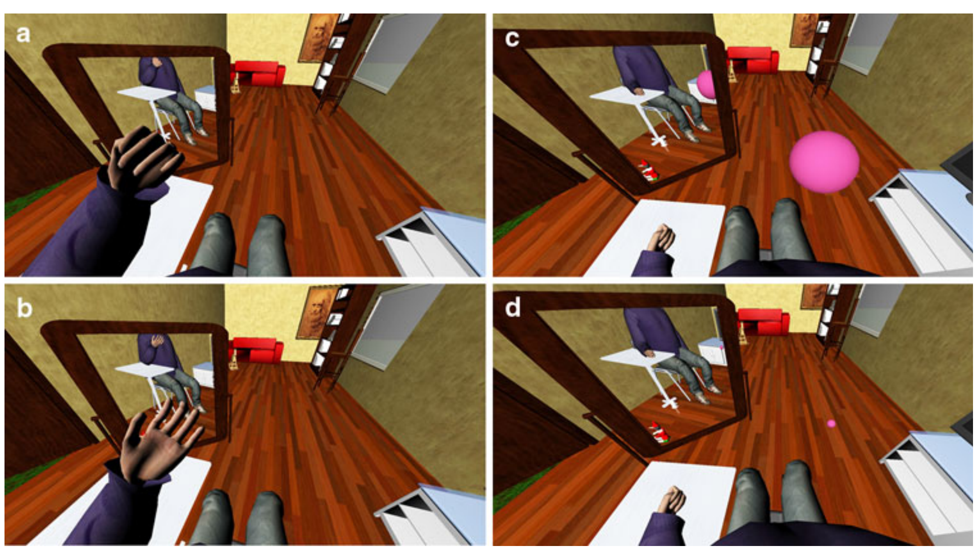

Fig. 2 **a** The *closed* virtual hand as seen from the participants' perspective. **b** The *open* virtual hand as seen from the participants' perspective. **c** The virtual ball of Part 2 before being reduced in size as seen from the participants' perspective. **d** The virtual ball with the size reduced, seen from the participants' perspective

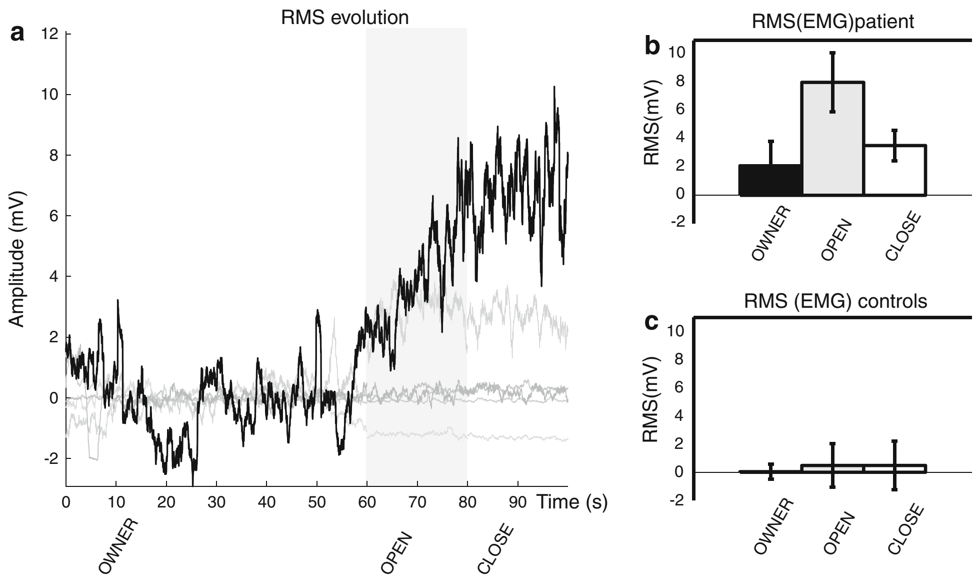

Fig. 3 **a** Evolution of the root mean square (*RMS*) of the EMG recorded during Part 1 of the experiment. The patient's RMS is plotted in *black* and the five controls' RMS in *grey*. The first block (*OWNER*, 0–60 s) corresponds to the induction of body ownership through visuo-tactile synchrony. The second block, highlighted in *grey* (*OPEN* 60–80 s), corresponds to the opening of the virtual hand. The third block (*CLOSE* 80–100 s) corresponds to the virtual hand closing. The patient's EMG activity was significantly higher than baseline 84 % of the time when the hand was opening and closing (the activity is considered significantly higher if the instantaneous value is bigger than a 99 % confidence interval of the baseline EMG). In the mean control participant a similar effect is elicited less than 23 % of the time. **b** The patient's mean RMS in the 8-s period after each of the stimulation sequences ended, that is, after each block (*OWNER*, *OPEN*, *CLOSE*). The *error bar* corresponds to the SD of the signal. The control measures after the visual or tactile stimulation show a difference in the impact of the IVE under similar conditions: a static virtual environment, no tactile stimuli and a hand on the table in a relaxed position. **c** The same plot for the mean control participant

the moment that the virtual hand started to open (grey block in Fig. 3a), the muscle activity became significantly larger in the patient (black line) than in the controls (grey lines). We considered the EMG activity to be significantly higher than baseline when the instantaneous value was greater than the upper bound of the 99 % confidence interval of the mean baseline activity. Under this criterion, a significantly higher EMG activity was found in the patient for more than 84 % of the time while the virtual hand was opening and closing (see Fig. 3a). A similar effect was also found in the average of the control participants, but it lasted for less than 23 % of the time that the hand was opening and closing. However, both the patient and the controls were requested to relax their muscles throughout Part 1 of the experiment, and the patient reported in the interview that he felt he had his forearm muscles relaxed.

Figure 3b, c show the RMS during the 8-s periods immediately after the visual stimulation sequence. The induction of ownership by itself, once the hand was in a static position, did not result in any significant change in the EMG activity in the patient or in the controls. However, after being exposed to the opening of the virtual hand, the patient showed an activity significantly greater than baseline, revealing higher muscle activity as a result of the opening movement of the virtual hand (we used the same 99 % confidence interval criterion as above but taking the mean activity through the whole 8-s period instead of the instantaneous value). This increase was not significant after the induction of the ownership, and also not significant after exposure to the hand closing (Fig. 3b). The control participants did not show a significant increase in any of the three conditions measured (Fig. 3c).

Part 2: Using a BCI paradigm to evaluate the concentration effect

The patient had a better BCI performance while concentrating on reducing the size of the ball than while concentrating on opening the virtual hand. This is shown by the shorter time necessary to carry out the task of reducing the size of the ball on both occasions. Changing the size of the ball took 42 s the first time (see Fig. 4a) and 28 s the second time (see Fig. 4c). However, opening the hand took 78 s and 58 s, respectively (Fig. 4b, d). The comparison between the different measures suggests that there was a training effect, but still the performance when the visual feedback was to diminish the size of the ball was always better than when it was to open the virtual hand (Fig. 4e).

Interestingly, the five control participants also displayed better BCI performance when they concentrated on

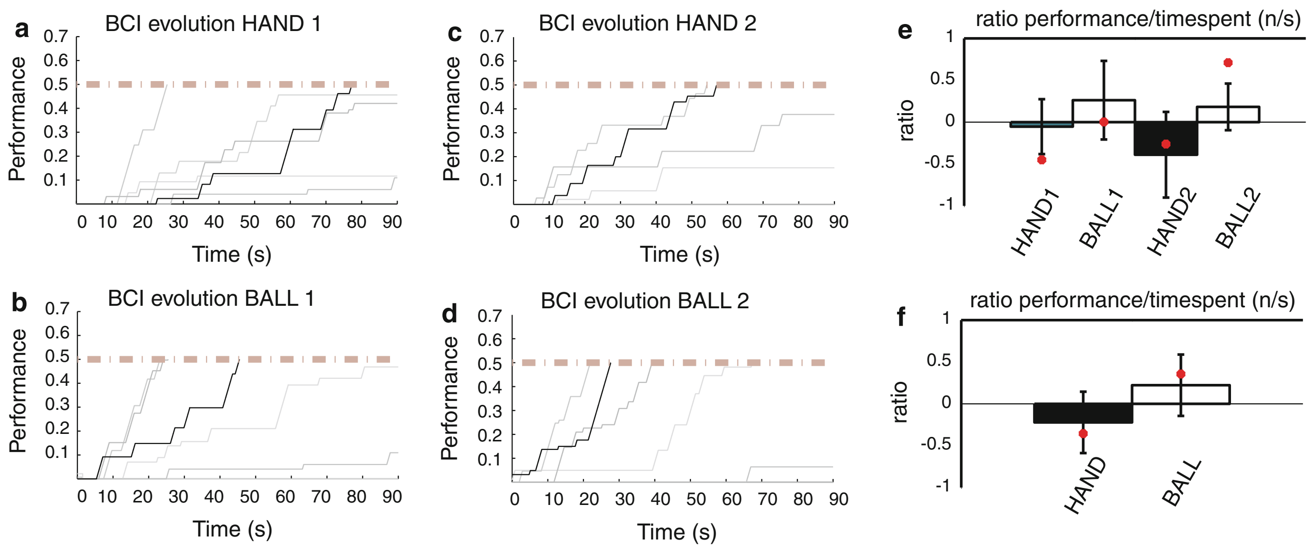

Fig. 4 **a** In *black*, the patient's performance across time for the first BCI trial involving the hand opening (*HAND1*). It took the patient 78 s to complete the task. In *grey*, the performance across time of the five controls. In certain conditions the performance across time of some control participants is difficult to see because the performance is 0 for the whole period. **b** The same plot for the second BCI trial involving the reduction of a ball (*BALL1*). It took the patient 42 s to complete the task. **c** The same plot for the third BCI trial involving the opening of a virtual hand (*HAND2*). It took the patient 58 s to complete the task. **d** The same plot for the fourth BCI task involving the reduction of a ball (*BALL2*). It took the patient 58 s to complete the task. **e** Performance of the patient compared to the controls for each of the four trials using the BCI performance index—that is, the results are shown in performance/time spent to achieve the task minus the mean performance/time ratio of each participant as baseline. The *bar chart* shows the mean and standard deviations for the five controls. The *dot* corresponds to the performance of the patient. **f** Comparison of the performance in the BCI trials involving a hand against the BCI trials involving a ball. The measure is the same as in the previous *panel*

reducing the size of the virtual ball rather than opening the virtual hand (Fig. 4f). However, the change in performance was larger for the patient: if we compare his performance ratio to the mean performance ratio across all control participants, we can see that it is larger than the mean (mean + 0.8 × SE) when the task involved the ball, but less than the mean (mean − 0.8 × SE of the mean) when the task involved the virtual hand (Fig. 4e).

Opening the virtual hand by focusing on it also provoked a larger increase in EMG activity in the patient than in control participants (Fig. 5a). The patient's muscular activity was significantly greater than baseline (i.e. above the upper bound of the 99 % confidence interval of RMS, EMG and baseline activity) for more than 70 % of the time when the task was to open the virtual hand, compared with 44 % of the time for the mean control participant. When the task consisted of reducing the ball size, the muscle activity of the patient was significantly larger than baseline only 3 % of the time. For the mean control participant it was 0 % of the time. Comparing the overall periods involving the hand and the ball using the same 99 % confidence interval criterion, the mean EMG of the patient was higher than that of the control participants during the time of the opening the virtual hand task. However, during the ball reduction task the EMG was not significantly different from that of the controls (Fig. 5b, c). Hence, the visual feedback of opening the hand by BCI had a larger impact on the EMG activity of the patient than in the control participants.

Part 3: Motor task performance: moving the wrist

The movements of the wrist towards the left, right and up directions were explored in both patient and controls (Fig. 6). The greatest movement limitation of the patient was in the up direction, when asked to lift the hand up away from the resting plane. The objective of this part of the experiment was to detect any possible changes in the motor task performance secondary to the visual aspect of the hand (closed or open). We did not find that the angle of any of the movements was affected by the aspect of the virtual hand, either in the patient or in the controls. This result is discussed below.

Discussion

Correct visuo-tactile or visuo-motor correlations between the real and a collocated virtual limb plus first-person perspective in an IVE are usually sufficient to induce a feeling of body ownership over the virtual limb (Slater et al. 2008; Sanchez-Vives et al. 2010; González-Franco

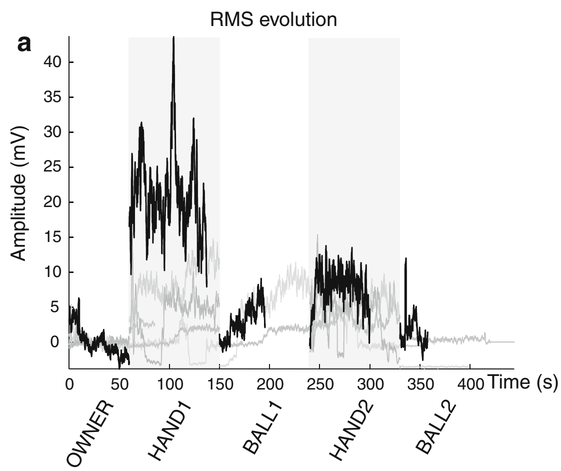

Fig. 5 RMS EMG activity during the BCI. **a** In *black*, the patient's RMS and, in *grey*, the RMS of the five controls. The first block (*OWNER*, 0–60 s) corresponds to the induction of the body ownership. The second block (*HAND1*, 60–150 s) corresponds to the first BCI trial where the task consisted of opening a virtual hand. The third block (*BALL1*, 150–240 s) corresponds to the second BCI trial, where the task was to reduce a virtual ball in size. The fourth block (*HAND2*, 240–330 s) corresponds to the third trial, with the hand opening as visual feedback. The fifth block (*BALL2*, 330–420 s) corresponds to the fourth BCI trial, with the ball reducing in size. Note some of the EMG signals are truncated because the task was completed in less than 90 s. **b** The mean RMS of the patient during the two BCI blocks involving visual feedback with the virtual hand or with the virtual ball. The EMG activity was significantly higher than the baseline (*OWNER* block) when the task was to focus on the hand than when it was to focus on the ball. **c** The same measure for controls did not show a significant difference

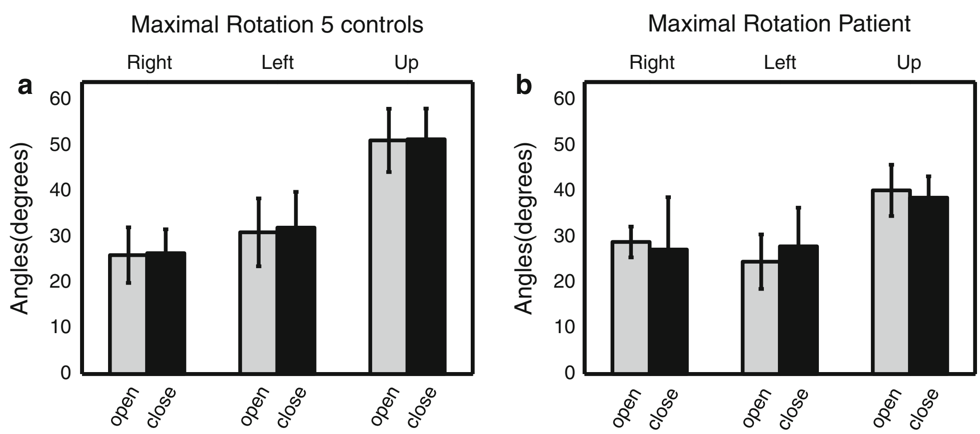

Fig. 6 **a** Maximal rotation in each direction for the control participants. The means and SD measures were obtained considering a relaxed hand resting on the table as the null rotation. Then the participant was asked to move *left*, *right* or to raise the hand separating it from the table. An experimenter softly held the forearm of the participant to ensure that the movement only involved rotations in the wrist. **b** The maximal rotation in each direction for the patient. Notice that the angle in the *up* direction is clearly smaller for the patient than for the control participants. However, there is no difference between the *opened* and *closed* hand

et al. 2010). In this case study we explored how the ownership of a virtual body could be exploited for the clinical assessment of neurological patients. We therefore assumed the results of previous work showing how visuo-tactile and visuo-motor congruent stimulation in a collocated virtual limb plus consistent mirror reflections are sufficient to induce body ownership. Indirect evidence such as anecdotal comments in the post-experimental interview, as well as physiological changes in the EMG activity during Part 1 of the study suggested that ownership of the virtual body was successfully achieved. The questionnaire responses of the control participants also suggest that this was the case (see Table 1). To interpret the results, we therefore assume that the patient experienced body ownership with respect to the virtual body and specifically of the arm.

The results in Part 1 illustrate that the exposure to the owned virtual hand opening and closing was sufficient to induce an increase in the EMG activity in the patient. This is consistent with the previous findings where ownership of a virtual hand induced EMG activity triggered by the

Table 1 Responses of the five control participants to the short questionnaire on body ownership

	Mean	SD
I felt as if the body in the mirror could be me	4.6	0.55
The movements the body made were my movements	4.2	0.45
I felt as if I had two bodies	1.8	0.84
The body I saw in the mirror was another person	2	0.71

Responses were between 1 and 5, where 1 meant "Not at all" and 5 meant "Very much"

movement of the virtual hand (Slater et al. 2009; Perez-Marcos et al. 2009). The exposure to the opening and closing of the virtual hand provoked an increase in EMG activity compared with baseline also amongst the controls. However, this increase in EMG activity was significantly stronger for the patient compared to the controls (see Fig. 3).

Overall, the changes in muscle activity were detected mostly during the opening of the virtual hand, but in the case of the patient, this tendency was over-expressed, especially while the virtual hand remained open. In addition, the patient also showed high muscular activity in the closing phase, well above the baseline one, something that did not occur for the controls. This was the case even though the patient had been requested to relax his arm and hand, with him reporting afterwards that he had indeed kept it relaxed. This effect could be related to his lack of mobility with respect to the controls: at the moment of the experiment, the patient had experienced his hand in a locked closed configuration for more than 1 year. We cannot assess to what extent the over-expression of the muscular activation could be due to a stress response with a misregulation of the motor activity or to an unconscious attempt to control his hand when exposed to the visual input of his virtual hand opening and closing. Future experiments with patients with fixed posture dystonia may reveal whether this aberrant muscle response to movements of the virtual hand is to be expected consistently in such cases. In any event, this possibility of exploring the response to movement of an internalized virtual hand illustrates the type of stimulation that can easily be achieved through an IVE system.

In Part 2, the patient was better able to use the BCI to reduce the size of the virtual ball than to open the virtual hand. As reported in Methods, both tasks were calibrated to require the same effort such that for the same performance it should have taken the same time. This difference could not be the result of training, since the procedures were repeated and averaged during the trial, and furthermore the patient had been trained before the start of the experiment. Interestingly, also the control participants performed better at using the BCI to reduce the size of the virtual ball than to open the virtual hand. However, the change in performance was greater for the patient than for the controls (Fig. 4f). This finding could be consistent with a non-organic origin of his condition and suggests a certain resistance to the opening of the (virtual) hand. The results of the EMG activity during the BCI task seem consistent with Part 1: the patient's EMG was significantly greater during the task involving the hand opening compared to the task involving changes in the ball size (Fig. 5c). However, such an interpretation should be considered with caution since it is possible that the muscular activity was due to contractions of the forearm related with attempts to perform the task. Overall, this was not the case in the control participants and points towards a misregulation of muscle activity in the patient.

The objective of Part 3 was to assess whether seeing an open, healthy-looking hand—the virtual one—would have any impact on the restricted mobility of the patient. Based on hand-tracking measurements, we explored the angle of movements of the patient while the hand was in the closed position, similar to his locked fist condition. However, in Part 3, the identification with an open or closed hand did not result in a detectable improvement of the patient's mobility. This finding apparently contradicts the results of Part 1 and Part 2: if exposure to a virtual hand changed EMG activity in a patient with a psychogenic condition, why would seeing the virtual hand open not provoke an increase in mobility? To a certain extent, the lack of a quantitative difference in mobility is not surprising. After more than 1 year with the hand closed, soft tissues might have retracted and prevented an improvement in mobility. It remains to be seen whether patients who have had such symptoms for a shorter time might obtain greater benefit from our approach. We could also argue that the short time of exposure to the virtual body was not sufficient to cause a therapeutic improvement in Part 3 of the experiment (Fig. 6). Although it is generally accepted that virtual reality can be beneficial for motor rehabilitation (Sveistrup 2004; Adamovich et al. 2009), this is often associated with motivation (e.g. Brütsch et al. 2010). All in all, Part 3 does show that a quantitative assessment of movement impairment is possible with the very same tools used for motion tracking and induction of body ownership. The data collected (Fig. 6) show a difference between the patient and the controls when required to move in the vertical direction. Future work with longer exposure periods to IVEs should determine whether virtual body ownership could be exploited at the advantage of rehabilitation therapies.

In summary, the EMG activity provoked by exposure to the opening and closing of the virtual hand (Fig. 3) and the changes in BCI performance (see Fig. 4f) suggest that the impact was stronger for the patient than for the controls. This indicates that the activity in muscles controlling the patient's postural abnormality was highly dependable on the state of the motor system in line with what occurs in healthy participants, which supports the likely non-organic origin of his condition. The changes in muscular activity and in BCI performance reported suggest that induced virtual body ownership could contribute to the utility of virtual reality for diagnosis and therapy in certain neurological conditions. In such a scenario, virtual body ownership would lead to patient identification with the virtual body seen from a first-person perspective and therefore contribute to strengthening the link between the brain activity and observed body movements (motor movements that may be impossible to perform with the real body). Thus, for example, if the performance of residual movements were amplified on a virtually owned hand, this could hypothetically reinforce the brain activity responsible for such residual movements and reinforce in this way the visuo-motor loops and other sensorimotor integration pathways.

Possible limitations of the study

One could argue that the changes in the EMG activity were merely due to surprise. However, if the increase in activity showed in Fig. 3 were only due to surprise, it would be expected that the reaction of the patient would not be stronger than that of the controls. Moreover, the fact that the increase also occurred in Part 2 (Fig. 5) also suggests that it was more than only an effect of surprise.

As mentioned earlier, we found that there were changes in BCI performance between opening a virtual hand and reducing a virtual ball, even when both tasks were calibrated to require the same performance, and were otherwise similar. This difference, which was observed both in the patient and in the controls, could be due to the different visual feedback. There is some evidence that the display of the feedback might affect BCI performance. In the review article by Neuper and Pfurtscheller (2010) it is argued that visual feedback results in better performance than auditory feedback and that continuous feedback is preferable to discrete. However, a different target should not affect performance: in both cases the environment is a rich interactive IVE. Moreover, all participants performed better with the ball than with the hand, despite the fact that these were in similar positions and of similar sizes. Assuming that the visuo-tactile and the visuo-motor synchrony induced virtual body ownership, then it is likely that body ownership was the factor that affected performance and that the impact of body ownership was different for the patient compared to the controls.

In the post-experimental interview the patient reported the feeling that it was a harder task to open the virtual hand than to reduce the ball size, but he could not give an explanation for that feeling. Some of the controls reported also similar difficulties when the target was their virtual hand, albeit their differences in performance were less than in the case of the patient. This could be explained considering that there was no ownership illusion over the ball. However, changing the virtual hand implies generating a contradiction between the situation of the real hand and of the virtual hand. If participants experienced the embodiment illusion, then this contradiction would be substantial. This contradiction would have a cognitive cost that would affect the performance over the BCI task. It has already been shown that the control of a virtual arm by BCI can induce illusory ownership of that arm, as well as EMG significant responses to the movement of the hand (Perez-Marcos et al. 2009). However, to our knowledge it has never been shown that virtual body ownership could affect a task requesting focussed attention (Fig. 5).

When asked some weeks after the conclusion of the experiment, the patient reported that the experience had been very useful and that after the experience he "knew what he had to do". However, in the following weeks the patient did not improve his condition. It can be argued that the experience of controlling a virtual hand through focussed attention induced some kind of illusion of control over the real hand, but it could also imply a positive feedback for patients to make a greater effort in controlling their problem. If the origin of the disease is psychogenic, this might have a positive impact, along the lines of virtual reality applications for psychotherapy (Rizzo and Kim 2005). The potential effect of this approach could be better for cases of psychogenic dystonia at earlier stages, before it becomes an organic problem due to the retraction of the tissues. Another possibility, in these cases, is that the patient might be suffering from an organic disorder that has not been yet identified (Schrag et al. 2004; Edwards et al. 2011). In this case, virtual reality could have an impact similar to its use in rehabilitation (Rizzo and Buckwalter 1997).

Our approach in this case also shows how a virtual environment can be adapted to a particular patient. Figure 1a illustrated the virtual representation of the body in the same position as that of the patient. The procedure described shows that inducing virtual body ownership led to the detection of differences between the patient and healthy participants using simple electrophysiological measurements, even though these differences could not be assessed with more traditional diagnostic procedures. Overall, even given the limited scale of this single case study, the evidence suggests that virtual body ownership together with relatively simple electrophysiological hardware—a single-surface EMG electrode, a single electrode BCI—can be exploited for the assessment of movement-related diseases during neurological exploration. We conclude that a body-centred IVE provides an opportunity to jointly assess the physiology and psychological factors involved in such difficult neurological cases.

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