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Using Body Ownership to Modulate the Motor System in Stroke Patients

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Abstract

Recent findings suggest that body ownership can activate the motor system in the absence of movement execution. Here, we investigated whether such a process promotes motor recovery in stroke patients. A group of patients with left-hemisphere damage (N = 12) and chronic motor deficits completed an immersive virtual reality training (three sessions of 15 min each week for 11 weeks). Patients sat still and either experienced (first-person perspective) or did not experience (third-person perspective) illusory ownership over the body of a standing virtual avatar. After the training, in which the avatar walked around a virtual environment, only patients who experienced the illusion improved gait and balance. We argue that representing the virtual body as their own allowed patients to access motor functioning and promoted motor recovery. This procedure might be integrated with rehabilitative approaches centered on motor execution. These findings also have an impact on the knowledge of the motor system in general.

Keywords

body ownership, motor system, immersive virtual reality, rehabilitation, motor deficits

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Motor deficits following strokes are among the most common causes of disabilities in human adults (Duncan et al., 1992) and, hence, restoring motor functions is one of the key goals in rehabilitation. A large number of people who regain the ability to walk still experience mobility, gait, endurance, limb strength, and balance deficits, which lead to walking difficulties during daily activities (Jorgensen et al., 1995; Mayo et al., 2002). Any method of treating motor deficits is guided by the principles of (a) promoting adaptive plasticity and compensation processes within the damaged system and (b) developing novel strategies in motor learning (Winstein & Wolf, 2008). Consequently, most of the existing approaches are based on training sessions that stimulate active and repetitive motor practice of the impaired body parts (Rossetti et al., 2005). However, this logic strongly relies on action execution, an ability that can be impaired or even almost unavailable in those kinds of patients. This, in turn, makes it highly challenging to provide relevant input to the motor system to trigger the optimal treatment.

Some evidence suggests that the motor system may be activated by the subjective experience of being the owner of one's body (*body ownership*; Gallagher, 2000) without any actual motor execution (for a discussion, see Pyasik, Furlanetto, & Pia, 2019). Humans' enduring and omnipresent perceptual status that the body belongs to the self is known to arise and be maintained from body-related afferences (i.e., visual, tactile, proprioceptive, and auditory signals) that constantly reach the physical body. Whenever someone else touches

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your face, for instance, you immediately feel (and perhaps see) the touch, and you experience the face as your own. Crucially, a number of recent studies have shown that body ownership can be sufficient to act on motor functioning independently from any real action. Within a neuropsychological perspective, for instance, recent articles have described a delusion of body ownership due to brain damage in which simply viewing someone else's arm triggered the patient's misperception of that arm as their own to the point where that arm became a part of the patient's own body schema (for a review, see Pia et al., 2016). Crucially, such pathological embodiment is also extended to the movements of that "alien" arm. Indeed, the seen movements of the alien arm are misattributed to the patients' own will, and they interfere with the actual movements of the patient's own arm (Garbarini et al., 2013), evoke a reflexive defense response (Fossataro et al., 2016), and affect patients' representation of body size and shape (Garbarini et al., 2015) or external space (Ronga et al., 2018) exactly as these things would normally occur with the patient's own arm movements.

In intact brain functioning, a similar embodiment of an external object (i.e., a rubber hand) can be induced in healthy participants by means of an experimental manipulation known as the rubber-hand illusion (Burin, Garbarini, et al., 2017; Costantini & Haggard, 2007; Kalckert & Ehrsson, 2017; Longo et al., 2008; Ricci et al., 2004; Tsakiris & Haggard, 2005). In this case, the seen fake hand is misrepresented as part of one's own body so that its movements are misattributed to the participant's own will, which is also represented at the implicit level (i.e., the intensity of a stimulus delivered by the rubber hand to the participant's body is attenuated in exactly the same manner as when participants deliver the stimulus themselves (Burin et al., 2018; Burin, Pyasik, et al., 2017; Pyasik, Salatino, et al., 2019). Such experimentally induced embodiment can also be triggered for the whole body by means of the full-body illusion in virtual reality. In this case, the entire body (i.e., a life-size virtual avatar) is incorrectly perceived as one's own body, so that its movements are misattributed to the self; this is also reflected by the increased degree of physiological arousal corresponding with the increased motor efforts of the avatar, which mirrors arousal during one's own motor efforts (Kokkinara et al., 2016).

Capitalizing on this evidence, we reasoned that inducing a strong feeling of ownership of a virtual body that could perform movements of any complexity and duration might contribute to restoring motor functions in stroke patients. Possibly, only observing the avatar's movements, without being requested to execute any action, might activate the brain systems involved in actual motor execution and planning and promote recovery. We tested this hypothesis by employing immersive virtual reality in a group of stroke patients assessed for a variety of motor deficits (i.e., general mobility, gait, endurance, balance, lower limbs strength, and cognitive–motor interactions). Participants completed an 11-week training in which they experienced (in the first-person perspective) or did not experience (in the third-person perspective) illusory ownership of a virtual avatar that walked forward in a virtual environment, while participants were sitting on a chair. We hypothesized that participants' motor functions would improve after the training in the first-person perspective (i.e., the embodiment group) but not in the third-person perspective (i.e., the control group).

Statement of Relevance

Motor deficits following strokes are among the most common causes of disabilities in human adults, making restoring motor functions one of the key goals in rehabilitation. In the present research, we tested whether simply observing one's own body might activate motor functioning so as to promote motor recovery. We gave patients with chronic motor deficits due to a stroke 3 months of immersive virtual reality training in which they could experience (or not experience) illusory ownership over the body of a gender-matched, life-size walking avatar. The illusory-ownership condition resulted in significant improvement in gait and balance. This work demonstrates that body ownership per se (i.e., without any motor execution) can promote motor recovery by activating the motor system. These findings are important for both current rehabilitative approaches and knowledge about the motor system in intact brain functioning.

Method

Participants

Twelve patients with left-hemisphere damage (four female; 10 right-handed; age: M = 58.67 years, SD = 10.25; education level: M = 11.83 years, SD = 2.89; lesion onset: M = 7.33 months, SD = 4.9) were recruited from the Aphasia Experimental Laboratory at Fondazione Carlo Molo Onlus, where they were being treated for chronic nonfluent aphasia (no comprehension deficits) with conventional treatments. No other kind of treatment was administered. Written informed consent was obtained, and all procedures were approved by the ethical committee of the University of Turin (Project "Comprendere i meccanismi del sé corporeo in azione e riabilitare i disturbi attraverso la realtà virtuale immersiva"; Protocol No. 100960). No part of the study was preregistered. Raw data of each single patient have not been made available on a permanent third-party archive because the ethical committee does not permit public archiving of anonymized information. Readers seeking access to the data should contact the Corresponding Author L. Pia. Access can be granted only to single individuals in accordance with ethical procedures governing the reuse of sensitive clinical data. The inclusion criteria were the presence of balance, gait, and mobility deficits as indexed by a score below the cutoff in at least two of the eight tests included in the assessment battery.

Assessment battery

Participants completed eight tests. The Dynamic Gait Index (DGI; Marchetti et al., 2008), which evaluates gait, balance, and fall risk in usual steady-state walking and during more challenging tasks across a 15-min period. It is composed of eight functional tests that are performed by the participant; the maximum score is 24, and the cutoff (i.e., increased incidence of falls) is 19.

The Timed Up and Go test (Podsiadlo & Richardson, 1991) determines patients' fall risk and measures their ability to balance, move from a sitting to standing posture, and walk. The patient starts in a seated position and then is asked to stand up, walk, turn around, and walk back to the chair where he or she started. All of this is timed by the experimenter; the cutoff (i.e., increased risk of falling) is 14 s.

The 10 Meter Walk Test (Bohannon, 1997) is a performance measure to assess walking speed in meters per second (m/s) over a short distance and determines functional mobility, gait, and vestibular functions. The participant is asked to walk for 10 m, and the intermediate 6 m are measured to allow for acceleration and deceleration. Moreover, the test can be conducted at a normal comfortable speed or at a maximum speed. The cutoff is 0.8 m/s.

The Wisconsin Gait Scale (WGS; Rodriquez et al., 1996) evaluates gait problems and is useful for monitoring the effectiveness of rehabilitation training. The patient is observed while walking, and scores are given for specific tasks. The score ranges from 13.35 to 42; the higher the score, the more seriously the gait is affected.

Walking While Talking (Verghese et al., 2002) is a dual-task measure of divided attention used to examine cognitive–motor interactions and especially to identify fallers. The test is easy and generally takes 10 min. The patient is asked to walk for 6 m, turn back, and return (for a total of 12 m walked). In the simple version, patients are asked to recite the alphabet aloud while walking (note that the start may not be the letter "a"). The score is the time needed to complete the distance; the cutoff is 11.46 s (Verghese et al., 2007).

The Berg Balance Scale (BBS; Berg et al., 1992) is used to determine patients' ability to safely balance throughout approximately 20 min during a series of predetermined tasks. The test consists of 14 items, and each item is rated on a 5-point ordinal scale ranging from 0 to 4; 0 indicates the lowest level of function and 4 the highest level of function. The cutoff (i.e., greater risk of falling) is 45.

The 30 Seconds Sit to Stand Test (Jones et al., 1999) is designed to assess leg strength and endurance. The participant is seated in the middle of a chair in a specified position: back straight, feet shoulder-width apart and placed on the floor and one foot slightly in front of the other one, and arms crossed at the wrists and held against the chest. The participant must stand and sit as much as possible in 30 s. If patients use their arms, they receive a score of 0. Otherwise, the score is the total number of correctly executed stands within 30 s. The cutoff is 20.

The Rivermead Mobility Index (Nair & Wade, 2003) assesses functional mobility in gait, balance, and transfers in approximately 5 min. The test consists of 14 self-reported items and one direct-observation item. Items progress in difficulty and are scored as 0 (no) or 1 (yes). The maximum score of 15 indicates better mobility performance, whereas a score of 0 indicates an inability to perform any of the activities on the measure. Exclusion criteria were a degree of cognitive impairments precluding the ability to understand the instructions. Demographic and clinical data are provided in Table 1.

Apparatus and stimuli

Participants sat on a chair in a dimly lit room and were immersed in the virtual environment with an Oculus Rift CV1 (Oculus VR, Irvine, CA) equipped with two PenTile organic light-emitting diode displays (1,080 × 1,200 pixels, refresh rate = 90 Hz, field of view = 110° with 6 degrees of freedom). The scenario was written and implemented using the Unity3D platform (Unity Technologies, San Francisco, CA).

Procedure

The experiment consisted of an embodiment phase and a training phase. In the embodiment phase, participants

Table 1. Demographic and Clinical Data of the Patients

	Patient's ID											
Variable	1	2	3	4	5	6	7	8	9	10	11	12
Gender	Male	Male	Female	Male	Female	Male	Male	Male	Female	Male	Female	Male
Age (years)	70	53	54	69	69	55	40	44	64	67	66	53
Education (years)	13	13	8	18	13	13	11	11	8	13	13	8
Handedness	Right	Right	Right	Right	Right	Right	Left	Right	Right	Right	Left	Right
Etiology	Ischemia	Ischemia	Hemorrhage	Ischemia	Ischemia	Ischemia	Hemorrhage	Ischemia	Hemorrhage	Ischemia	Ischemia	Hemorrhage
Onset[a]	2,204	1,461	3,026	3,366	1,628	2,164	2,021	555	4,768	441	7,060	3,332
Lesion (CT/MRI)[b]	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, insula	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal	Frontal, temporal, parietal
Dynamic Gait Index												
Before training	16	8	14	3	3	18	7	6	6	8	11	11
After training	22	14	23	7	12	23	8	6	6	8	11	11
Timed Up and Go												
Before training	15.48	24.09	10.33	50.28	35.02	7.49	22.63	24	76.2	35.02	24.45	17.93
After training	8.86	22.14	9.52	54.55	35.56	7.8	23.46	22.7	60.06	30	17.82	14.29
10 Meter Walk Test												
Before training	0.83	0.55	1.2	0.28	0.19	2.56	0.47	0.31	0.12	0.26	0.36	0.61
After training	1.33	0.7	1.3	0.27	0.25	2.62	0.64	0.43	0.18	0.33	0.47	0.7
Wisconsin Gait Scale												
Before training	18.1	29.2	19.7	31.65	27.5	15.1	26.9	29.15	30.5	29.65	27.1	25.1
After training	16.1	19.85	16.1	26.65	25.9	13.35	26.9	29.15	30.5	29.65	27.1	25.1
Walking While Talking												
Before training	11.53	23.4	9.91	54.88	28	7.27	23.22	38.05	84.45	59.2	15.2	36.68
After training	9.56	27.28	9.78	38.88	48.49	7.52	30.22	26.77	79.95	55.97	30.1	28.75
Berg Balance Scale												
Before training	41	34	47	23	35	51	30	20	19	29	32	42
After training	51	51	54	38	32	56	30	20	19	27	31	40
30 Seconds Sit to Stand Test												
Before training	11	0	14	0	4	12	9	5	4	11	7	11
After training	13	0	12	7	5	14	7	5	6	9	9	9
Rivermead Mobility Index												
Before training	10	14	12	7	6	14	8	5	5	4	12	12
After training	13	14	14	7	8	15	7	5	5	4	13	12

Note: The table shows raw scores for the eight tests included in the assessment battery.
[a]Onset values indicate the number of days between the disease and the first day of the assessment. [b]Lesions were identified via either computed tomography (CT) or MRI and were either to the anterior cerebral artery or the middle cerebral artery.

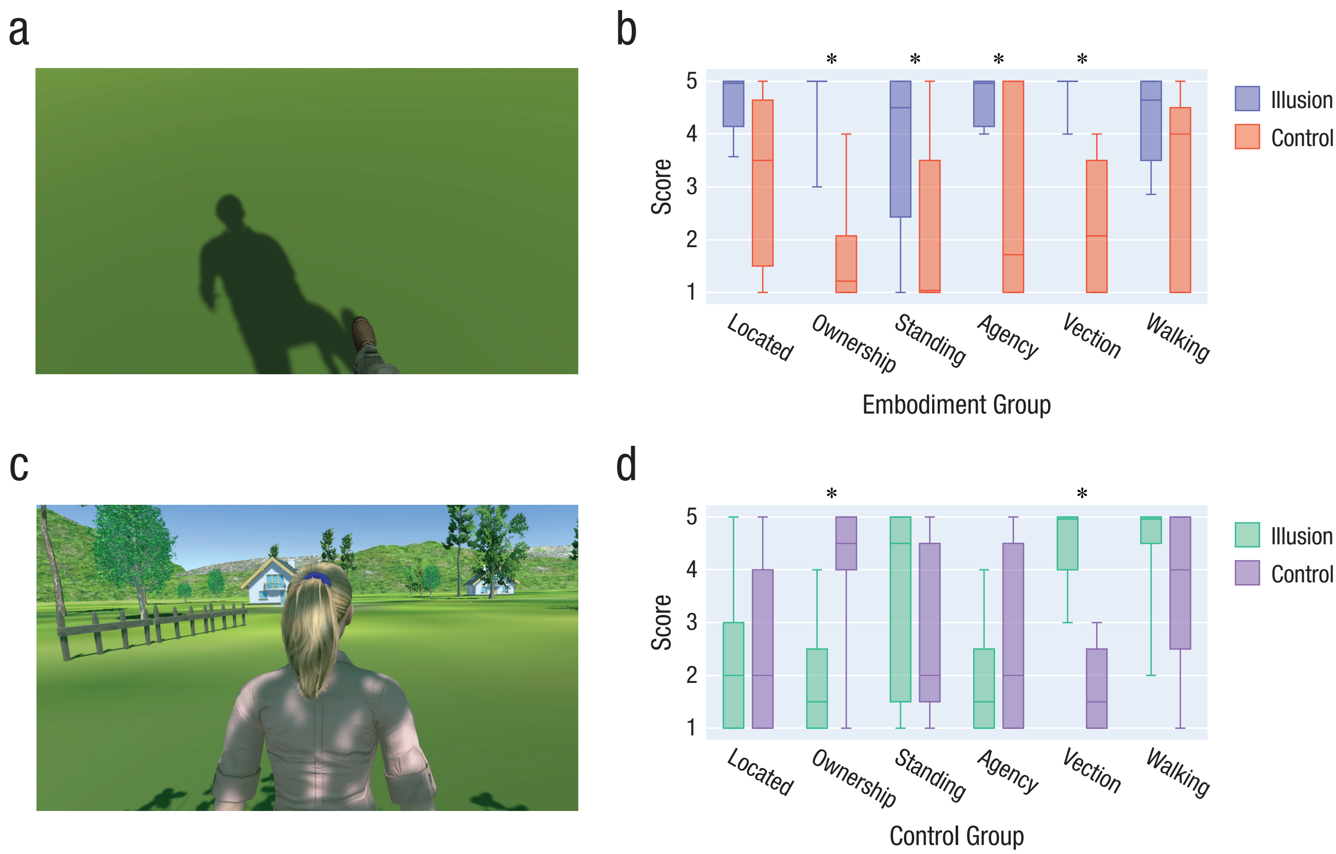

Fig. 1. Representations and results from the embodiment phase. The screenshots show (a) a first-person perspective when looking down (as patients saw in the embodiment group) and (c) a third-person perspective (as patients saw in the control group). The boxplots show scores for the illusion and control questions on each of six topics, separately for the (b) embodiment group and (d) control group (scores were given on a Likert-type scale ranging from 1 to 5). The upper and lower edges of the boxes represent the first and third quartiles, and horizontal lines represent the medians. Minimum and maximum values are represented by whiskers. Asterisks indicate significant differences between illusion and control items ($p < .05$).

were told that they would see a gender-matched, life-size standing virtual avatar that would start walking forward. The avatar could be seen from a first-person perspective (the virtual body was spatially coincident with the patient's physical body; see Fig. 1a) or a third-person perspective (the virtual body was seen about 1 m in front of the patient's physical body; see Fig. 1c). During a 15-min session, the avatar walked around the environment (a park with trees, grass, and houses), and the walking direction was changed online approximately every 2.5 min (and it was verbally announced to the participant). At the end of each session, participants completed a questionnaire (see Table 2), adapted from two published studies (Burin et al., 2019; Kokkinara et al., 2016), that evaluated their feelings of ownership and agency over the avatar on a Likert-type scale ranging from 1 to 5. After 1 week, each participant completed another session from the other perspective. The order of the two sessions was counterbalanced across participants.

In the embodiment phase, all participants had illusory ownership and agency in the embodiment condition (first-person perspective) but not in the control condition (third-person perspective; i.e., scores for the illusion questions were significantly higher than scores for the control questions in the embodiment condition but not in the control condition). The presence of an identical pattern in the embodiment phase allowed us to randomly assign each participant to one of the two conditions, namely, first-person perspective (the embodiment group) or third-person perspective (the control group) for the training phase. Note that first-person perspective and third-person perspective are typically employed as the embodiment condition and the control condition, respectively, because they entail the same engagement and cognitive load, but they differ in terms of perspective and the subsequent illusion of ownership (Burin et al., 2019; Kokkinara et al., 2016; Petkova et al., 2011). Unpaired-samples t tests showed that the two groups did not differ in terms of

Table 2. Items on the Questionnaire Administered in the Embodiment Phase

Topic	Illusion item	Control item
Located	During the experiment, I felt as if my body were located where I saw the virtual body located.	During the experiment, I felt that my actual body disappeared.
Ownership	During the experiment, I felt that the virtual body was my own body.	During the experiment, I felt that the virtual body belonged to someone else.
Standing	During the experiment, I felt that I was standing upright.	During the experiment, I felt that I had more than one body.
Agency	During the experiment, I felt that the leg movements of the virtual body were caused by my movements.	During the experiment, I felt that I was being dragged.
Vection	I felt that I was moving through the space.	I felt that the world was moving past me.
Walking	I felt that I was walking.	I felt that the movements of the virtual body were controlled by someone else.

Note: This table is adapted from one used in two previously published studies (Burin et al., 2019; Kokkinara et al., 2016). In this study, the Likert-type scale that participants used to provide their responses was reduced to range from 1 to 5 to simplify each part of the task. Furthermore, the original questions were rearranged in order to create real (illusion) and control questions. "Located" refers to self-localization, "ownership" is concerned with the subjective strength of the ownership illusion, "standing" assesses the feeling of movement, "agency" is concerned with the sense of motor control, "vection" refers to the feeling of moving in space, and "walking" refers to the subjective feeling of walking.

demographic and clinical data (age: p = .334, education: p = .172, lesion onset: p = .522).

The training phase consisted of three sessions of 15 min per week for 11 weeks. In the first 4 weeks, the avatar's walking speed was set at 0.92 m/s; in the second 4 weeks, it was 1.35 m/s; and in the last 4 weeks, the speed reached 1.57 m/s. The only difference with respect to the embodiment phase was the presence of little white squares on the grass, which turned red if the avatar walked on them. This was added to further attract participants' attention to the walking legs. At the end of the training phase, participants were evaluated again with the test battery to measure motor deficits.

Statistical analysis

With regard to the questionnaire, illusion and control questions were compared using a Wilcoxon signed-rank test (data were not normally distributed on a Shapiro-Wilk test: first-person perspective: $W = 0.76$, $p < .001$; third-person perspective: $W = 0.84$, $p < .001$).

With regard to the battery of tests to measure motor deficits, each score was normalized (from 0 to 1) through a quantile transformation. Data were normally distributed for all tests, except for the DGI and 30 Seconds Sit to Stand Test (for which we performed the Wilcoxon signed-rank test and Mann-Whitney U test; p values were Bonferroni-corrected). In all the other tests, we performed a mixed-effects analysis of variance (ANOVA) with one within-subjects factor (time: before training, after training) and one between-subjects factor (group: embodiment, control). Post hoc comparisons were performed with paired- and unpaired-samples t tests, correcting for multiple comparisons with the Holm-Bonferroni method. The effect size for nonparametric analysis was represented by the matched-pairs rank-biserial correlation r. For parametric analyses, η_p^2 is reported for the ANOVAs, and Cohen's d is reported for the t tests.

To further check whether the improvement could be explained by other characteristics, we ran several multiple linear regressions for each test. The dependent variable (i.e., the improvement) was the difference between the raw scores before training and after training (thus, a negative value indicated an improvement), and we used age, lesion onset, and group (first-person perspective or third-person perspective) as regressors.

Finally, we analyzed the correlations between questionnaire-item scores and the improvement in the tests (measured as explained above) using a Pearson correlation coefficient with Bonferroni correction for multiple tests. We performed post hoc power analyses for ANOVAs, Wilcoxon signed-rank tests, and Mann-Whitney U tests to assess the quality of our results.

Results

With regard to the questionnaire, for the embodiment group (first-person perspective), the median score for the illusion question was significantly higher than the median score for the control question for ownership (z = 35, p = .01, r = .94; illusion: Mdn = 4.5, interquartile range [IQR] = 0; control: Mdn = 1, IQR = 1), standing (z = 14, p = .05, r = .87; illusion: Mdn = 4.5, IQR = 2.5; control: Mdn = 1, IQR = 1.5), agency (z = 20, p = .03, r = .91; illusion: Mdn = 5, IQR = 1; control: Mdn = 1.7, IQR = 4), and vection (z = 36, p = .007, r = 1; illusion: Mdn = 5, IQR = 0; control: Mdn = 2, IQR = 2; see Fig. 1b for results and Table 2 for questionnaire topics). For the control group (third-person perspective), the score for the illusion question was significantly lower than the score for the control question for ownership (z = 4.5, p = .03, r = −.75; illusion: *Mdn* = 1, IQR = 1; control: *Mdn* = 4.5, IQR = 1), and the illusion score was significantly higher than the control score for vection (z = 36, p = .007, r = 1; illusion: *Mdn* = 5, IQR = 2; control: *Mdn* = 1.5, IQR = 1; see Fig. 1d).

With respect to the assessment of motor deficits, in the 10 Meter Walk Test, the mixed-effects ANOVA showed a significant effect of time, $F(1, 10) = 25$, $p < .001$, η^2 = .71. Post hoc comparisons showed that the score was significantly higher, $t(5) = 5.87$, p(corrected) = .002, d = 0.47, 95% confidence interval (CI) for the difference between groups = [.06, .16], in the embodiment group before (M = .67, SD = .2) compared with after (M = .56, SD = .22) the training (see Fig. 2a). For the BBS, the mixed-effects ANOVA showed a significant group effect, $F(1, 10) = 9.01$, p = .01, η^2 = .48, and an interaction effect of group and time, $F(1, 10) = 8.29$, p = .02, η^2 = .45. Post hoc analyses with paired- or unpaired-samples two-tailed t tests showed that the score after the training was significantly higher, $t(10) = 3.98$, p(Holm-Bonferroni corrected) = .01, d = 2.3, 95% CI for the difference between groups = [.23, .8], in the embodiment group (M = .79, SD = .2) than in the control group (M = .28, SD = .21; see Fig. 2b).

For the WGS, the mixed-effects ANOVA revealed a significant effect of time, $F(1, 10) = 7.58$, p = .02, η^2 = .43, and a significant interaction effect of group and time, $F(1, 10) = 7.61$, p = .02, η^2 = .43. Post hoc analysis showed that the score after the training (M = .22, SD = .16) was significantly lower, $t(5) = 2.76$, p = .04, d = 0.93, 95% CI for the difference between groups = [.02, .5], than the score before the training (M = .48, SD = .35) only for the embodiment group. Moreover, the score after the training was significantly lower, $t(10) = −3.74$, p(corrected) = .004, d = 2.16, 95% CI for the difference between groups = [−.69, −.18], in the embodiment group than in the control group (M = .65, SD = .2). However, only the difference after training between the two groups survived the Holm-Bonferroni correction for multiple comparisons (p = .01). The scoring is reversed for this test, which accounts for the decrease in the mean of the embodiment group indicates better performance (see Fig. 2c).

The mixed-effects ANOVA for the Rivermead Mobility Index showed a significant effect of time, $F(1, 10)$ = 5.89, p = .036, η^2 = .37, and interaction of group and time, $F(1, 10) = 5.5$, p = .04, η^2 = .36. Post hoc analysis revealed that the score after the training (M = .72, SD = .24) was significantly higher, $t(5) = −2.83$, p = .04, d = 0.51, 95% CI for the difference between groups = [−.26, −.01], than the score before the training (M = .59, SD = .24) in the embodiment group. Moreover, the score after the training was significantly higher, $t(10) = 2.37$, p = .04, d = 1.36, 95% CI for the difference between groups = [.02, .75], in the embodiment group than in the control group (M = .34, SD = .27). However, in this case, none of them survived the Holm-Bonferroni correction (see Fig. 2d).

The Wilcoxon signed-rank test for the DGI showed that the score after the training (*Mdn* = 0.84, IQR = 0.27) was significantly higher, z = 0, p(corrected) = .04, r = −1, than the score before the training (*Mdn* = 0.59, IQR = 0.7) in the embodiment group. Furthermore, the Mann-Whitney test showed that the score after the training was significantly higher, U = 32, p(corrected) = .03, r = −.78, in the embodiment group (*Mdn* = 0.84, IQR = 0.27) than in the control group (*Mdn* = 0.41, IQR = 0.52; see Fig. 2e).

With respect to the multiple linear regressions, age and lesion onset were not able to explain the difference in the scores of any of the tests, contrary to the group variable, which was significant for the DGI ($p < .001$), WGS (p = .019), and BBS (p = .021). For these tests, we performed further simple linear regressions with group as the only regressor. A significant regression equation was found for all of them—DGI: $F(1, 10) = 53.88$, $p <$ .001, R^2 = .844; WGS: $F(1, 10) = 10.16$, p = .01, R^2 = .504; and BBS: $F(1, 10) = 9.74$, p = .011, R^2 = .493. The estimated unstandardized coefficients associated with the experimental group were −6.333 ($p < .001$) for the DGI, 3.883 (p = .009) for the WGS, and −9.333 (p = .01) for the BBS. In all cases, the intercept coefficient was not significant ($p > .7$). Because an improvement is denoted by a negative value, belonging to the experimental group led to an improvement. This was true also for the WGS, in which scoring was reversed—thus, the positive coefficient.

Finally, concerning the correlation analysis, a significant negative correlation was found between ownership scores and the DGI (r = −.9, $p < .05$). We also found quite high correlations between ownership and the WGS and BBS, although they were not significant (rs = .661 and −.644, respectively). Again, as above, the negative correlation found between the tests and ownership scores indicates that the stronger the illusion, the stronger the improvement.

Post hoc power analysis showed that the achieved power for most of the significant tests was more than .80, and in the other cases, it ranged between .60 and .77.

Discussion

Here, we investigated whether illusory ownership over a virtual walking body (in the absence of actual movements) might promote recovery from a variety of

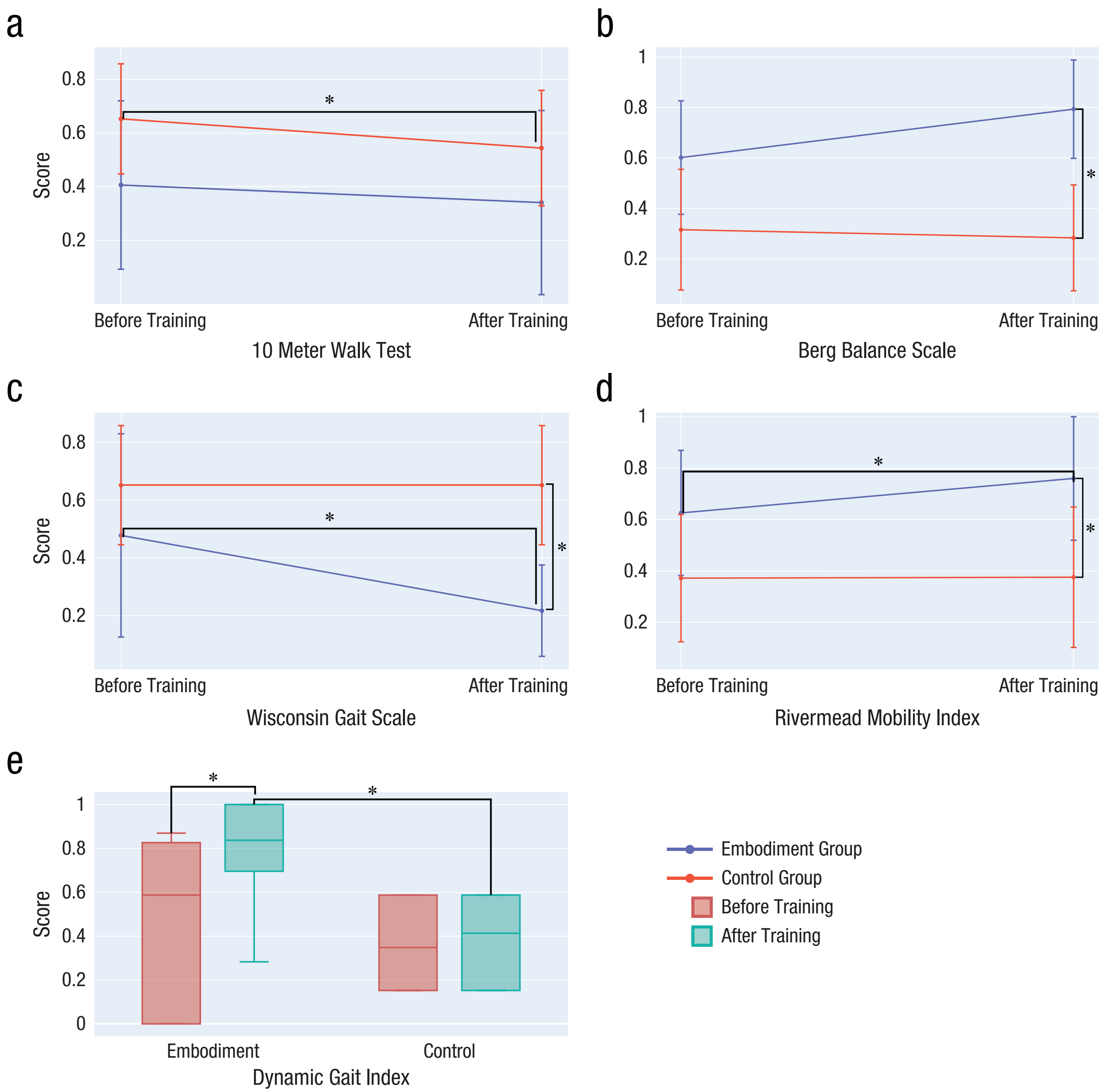

Fig. 2. Mean score before and after training for the (a) 10 Meter Walk Test, (b) Berg Balance Scale, (c) Wisconsin Gait Scale, (d) Rivermead Mobility Index, and (e) Dynamic Gait Index. Results are shown separately for the embodiment and control groups. Because of the quantile transformation, normalized scores are reported (scoring is reversed for the Wisconsin Gait Scale). Errors bars show standard deviations. Asterisks above horizontal brackets indicate significant differences from before to after training, and asterisks to the right of vertical brackets indicate significant differences between groups ($p < .05$).

residual motor deficits after patients have had a stroke. After 3 months of training, only the observation of an embodied walking avatar (i.e., from the first-person perspective) resulted in successfully improving gait and balance deficits. This set of novel findings shows that simply experiencing the body and its movements as one's own contributes to the improvement of motor abilities in stroke patients.

In the embodiment phase of the study, viewing the virtual body from a first-person perspective (embodiment group), but not a third-person perspective (control group), elicited an illusory experience of owning, controlling, and moving the body, consistent with previous data (Burin et al., 2019; Kokkinara et al., 2016). Specifically, when participants took a first-person perspective, the scores for the illusion questions were significantly higher than the scores for the control questions for ownership, agency, and standing. In turn, when participants took a third-person perspective, such a pattern was not present, thus confirming that this latter perspective was an appropriate control condition, as already demonstrated (Burin et al., 2019; Kokkinara et al., 2016; Petkova et al., 2011).

It is worth emphasizing that the illusory experience of owning a virtual body is strongly affected by the spatiotemporal congruency among the sensorimotor signals (i.e., vision, touch, proprioception, and motor-related information). Indeed, the illusion emerged whenever participants saw, from the first-person perspective, a part of the avatar's body being stroked synchronously with their own corresponding hidden body part or when a motion-capture system provides visuomotor synchrony between the avatar and the participant's movements. On the contrary, the incongruencies can decrease, or even break, the illusory effect (Kokkinara & Slater, 2014). However, the presence of the illusion in response to a walking avatar while participants are seated (i.e., when visual, kinesthetic, and motor information do not match) has already been demonstrated (Kokkinara et al., 2016). Additionally, the illusory ownership of a moving rubber hand in the absence of any movement of the participant's hand has also been repeatedly reported (Burin et al., 2018; Burin, Pyasik, et al., 2017; Pyasik, Salatino, et al., 2019; Tieri et al., 2015). All of these findings can be explained by the fact that when the illusion is very strong, incongruent cues could remain unprocessed, at least to some extent (Maselli & Slater, 2013). Hence, in the present study, simply seeing a life-size virtual body from a first-person perspective as a substitute for one's own body might dominate and override incongruent visuomotor stimulations.

With respect to the training phase, the embodiment group significantly improved in gait and balance deficits as quantified by four standard tests (i.e., BBS, WGS, DGI, and Rivermead Mobility Index, uncorrected) after an 11-week training. On the contrary, such improvement was not present in the control group. The regression analyses ruled out age and lesion onset as variables able to explain the improvement. Moreover, the two groups did not differ before completing the training in any test of the full battery, thus excluding any a priori difference. All of these data indicated that belonging to the embodiment group accounted for the improvement in DGI, WGS, and BBS scores, thus corroborating the role of the adopted perspective.

It is worth emphasizing that in the embodiment group, patients experienced both ownership and agency. Hence, one might ask to what extent the recovery is specifically related to one of these two factors. Our data suggest that ownership, more than agency, might be crucial because the improvement of motor deficits was positively correlated with the strength of the illusion of ownership and not with other aspects of the illusion. Another important point to discuss with respect to the nature of the four tests for which we found significant improvement is that they can be considered among the more structured within the whole battery, whereas others (10 Meter Walk Test, Timed Up and Go, Walking While Talking, and 30 Seconds Sit to Stand Test) are much more simplistic. Hence, one possibility is that those most complete tests were able to capture the improvement, whereas the others could not detect small differences. Nonetheless, the four above-mentioned tests focused mainly on gait and balance, whereas the entire battery assessed other components of walking behavior, such as general mobility, endurance, lower limbs strength, and cognitive–motor interactions. This, in turn, might indicate that the training improved those specific abilities only.

How can these results be explained within the current knowledge of motor rehabilitation after a stroke? Recovering from any kind of neurologically based motor deficits (including those of mobility, gait, and balance) necessarily requires the acquisition (or reacquisition) of an appropriate motor repertoire through movement generation, online adjustment, practice, and so on. There is wide agreement that, in intact brain functioning, such processes of motor control and learning are subserved by neurocognitive mechanisms known as internal models (Kawato, 1999; Wolpert & Kawato, 1998). There are two kinds of internal models: The forward model predicts the body-state consequences of a performed movement, whereas the inverse model goes in the opposite direction by determining the motor commands necessary to achieve a desired body state. These considerations indicate that post-stroke motor relearning is also a process of acquiring both forward and inverse internal models appropriate for each behavior (Kiper et al., 2016; Wolpert et al., 2001); indeed, it has been demonstrated that internal models can be impaired in stroke patients (Gomez-Andres et al., 2020; Takahashi & Reinkensmeyer, 2003). However, in patients with motor deficits, namely, impairments within the efferent system (as in our sample), the forward model is more likely than the inverse model to be impaired. Clinically, it can be hypothesized that whenever forward mechanisms deteriorate (or even are not available), the system could still deal with the inverse model. We put forward the idea that the representation of the walking avatar as the patient's own body (as in the embodiment group) might be embodied within patients' sensorimotor system as their own desired body state. Then, such a set of information could feed the inverse model and determine the appropriate motor command useful to reach the changes in bodily states. Repeating this process, as in training, could progressively instantiate (or reinstantiate) forward-model functioning and facilitate motor recovery.

The present findings are also important with respect to the general understanding of the motor system in intact brain functioning. It is worth noting that the mechanism we report here differs from the classical action-observation component attributed to the functionality of the mirror neuron system. Indeed, it is known that the cortical areas involved in the execution of movements can be activated by simply observing actions performed by other people (Gallese et al., 1996; Rizzolatti et al., 1996). Interestingly, it has been demonstrated that action observation is effective in neurorehabilitation (Buccino, 2014). However, in the present study as well as in previously published articles (Banakou & Slater, 2014, 2017; Burin et al., 2018, 2019; Burin, Pyasik, et al., 2017; Kokkinara et al., 2016), the effects on the motor system did not occur in the third-person perspective, which is basically an action-observation condition. Hence, such a mechanism is specifically related to the observation of one's own body rather than any other body.

Another important point is related to the role of body ownership in motor functioning. Indeed, this is not surprising because human actions are achieved through the body (Gallese & Sinigaglia, 2010), which is then a perceptual object necessary for any successful interaction with the environment (Georgieff & Jeannerod, 1998). This is not trivial but, rather, is consistent with data showing that during action execution, body ownership contributes to motor monitoring by estimating limb positions (Faivre et al., 2017), tuning commands (Shibuya et al., 2018), adjusting errors (Nielsen, 1963), and enhancing the subjective experience of authorship (Banakou & Slater, 2014, 2017; Kilteni & Ehrsson, 2017). Our findings add to this evidence showing that body ownership has a role per se in building and maintaining motor functioning: It might act on the motor system activity even in the absence of any efferent signals, such as motor intentions, motor execution, feedforward predictions, causes preceding effects, and so on. In other words, only seeing one's own body moving would be enough to trigger the neurocognitive processes subserving action preparation. It is known that the motor system highly relies on the optimal integrations of a large variety of signals that are weighted according to the given context and to actual availability. Hence, the evolutionary meaning of such afferent-based mechanisms might be to guarantee access to the motor system in those extreme situations in which the efferent information is not available, as with damages to the motor system, for instance.

In conclusion, we provide evidence that the mere experience of the body and its movements as one's own, without any real action execution, has a positive effect on rehabilitation of gait and balance deficits after stroke. We suggest that such an observational component might be combined with traditional poststroke rehabilitative training therapies of gait and balance (Eng & Tang, 2007; Wevers et al., 2009). It is necessary to acknowledge the limitations of the present study. The level at which body ownership activates the motor system and allows gait and balance recovery is not fully clear. In a recent functional-MRI investigation, Sacheli and colleagues (2017) demonstrated that gait motor imagery seen from a first-person perspective induced a higher activation of premotor/motor brain structures with respect to an imagery-imitation task that resembled a third-person perspective. Hence, the fact that the walking avatar in the first-person perspective might have automatically triggered gait motor imagery, and the following activation of motor functioning, is an interesting possibility. Strictly related to this point is the fact that we reported improvement of gait and balance but not of aspects of walking skills such as general mobility, endurance, lower limbs strength, and cognitive–motor interactions. Whether this is a specific aspect of the training or only a lack of sensitivity of the assessment battery (see above) is something that must be investigated in future studies. Another important limitation of the study is that we were not able to access patients' radiological data, despite the fact that participants were fully comparable in terms of deficit severity. This would have allowed us to investigate the neural correlates of the improvement as well as the signature of patients' lesions and dysfunctions. A further limitation is that even though the achieved power was always more than the conventional threshold, our sample was small; the sample size should be increased in future studies. Lastly, we were not able to administer the test battery in a follow-up phase to check the stability of the changes. From a clinical point of view, this is a crucial point to be faced.

Transparency

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Author Contributions
A. Giachero, L. Pia, M. T. Molo, D. Burin, and M. Pyasik conceived the study and data-analysis plan. M. Calati and A. Giachero recruited patients and administered the

standard assessment. F. Cabria, R. Tambone, and D. Burin administered the training. R. Tambone and M. Calati prepared and conducted the data analysis. D. Burin, M. Pyasik, R. Tambone, and L. Pia wrote the manuscript. All the authors discussed the results, contributed to the revision of the manuscript, and approved the final manuscript for submission.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Open Practices

Data and materials for this study have not been made publicly available, and the design and analysis plans were not preregistered.

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