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Motor imagery in spinal cord injury patients: Moving makes the difference

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Both real action control and execution and motor imagery abilities require knowledge of the spatial location of body parts, in other words efference copy information and feedbacks from the sensory system (Frith *et al.*, 2000, Philos. Trans. R. Soc. Lond. B. Biol. Sci., *355*, 1771). Spinal cord injuries induce severe motor disability, due to a damage of the descending motor pathways (Cramer *et al.*, 2007, Exp. Brain. Res., *177*, 233). Patients' motor imagery competences are variably reported as either normal or defective (Decety & Boisson, 1990, Eur. Arch. Psychiatry Clin. Neurosci., *240*, 39; Lacourse *et al.*, 1999, Behav. Brain Sci., *104*, 73). We explored biomechanical constraint effects in Spinal Cord Injury (SCI) patients, as they are considered the most reliable indexes of motor imagery abilities (Parsons, 1987b, Cogn. Psychol., *19*, 178). Sixteen spinal cord injuries patients and 16 neurologically unimpaired subjects have been administered with (1) the Hand Laterality Task (HLT), in which subjects were asked to judge the laterality of a rotated hand; and (2) the Mirror Letter Discrimination Task (MLD), in which subjects were asked to judge if a rotated character was in its correct upright position or mirror-reversed form. Our patients did not present the effect of stimulus orientation, neither did they show any effect related to biomechanical constraints. Based on these data, the hypothesis is that SCI patients' performance may be ascribed to the use of a different strategy to solve the tasks, based on memory rather than on mental rotation.

The vast majority of human behaviours imply an active interaction with the surrounding environment. Thus, performing a motor action involves the awareness of the location of body parts in space. This ability is strongly related to successful integration of the motor

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efference copy and the feedback from the sensory systems (Frith, Blakemore, & Wolpert, 2000). More interestingly, this integration is fundamental not only for performing real movements, but also during the mental simulation of the action (Frith *et al.*, 2000; Parsons, 1994). This latter process is called Motor Imagery (MI), and it corresponds to the active process of internally representing a motor command without an effective overt movement as outcome (Jackson, Lafleur, Malouin, Richards, & Doyon, 2001; Parsons, 1987b).

In a standard MI paradigm, subjects judge the laterality of a body segment by means of a mental rotation of their own body part to match the mentally rotated body segment with the visually presented stimulus (Parsons, 1987a,b). Current models of body parts' laterality recognition postulate different cognitive stages to perform this task (Parsons, 1987b, 1994). Firstly, an implicit visual analysis of the stimulus occurs, independently from action simulation (Gentilucci, Daprati, & Gangitano, 1998a,b; Parsons, 1987b, 1994; Parsons *et al.*, 1995; Sekiyama, 1982). Then, participant's own body part internal representation is mentally rotated to reach the position of the target stimulus (Parsons, 1987a,b), as a function of the action-related knowledge and of the kinematic constraints of the real body segment (Gentilucci *et al.*, 1998a,b; Parsons, 1987b, 1994; Parsons *et al.*, 1995; Sekiyama, 1982). Therefore, the ability of imaging a movement is necessarily conditioned by the *effect of biomechanical constrains* (Brady, Maguinness, & Ni Choisdealbha, 2011; Conson, Pistoia, Sara, Grossi, & Trojano, 2010; Parsons, 1987b, 1994). This effect consists in faster response times and higher accuracy in judging body parts displayed in a position easy to reach with a real movement, i.e. *simple positions* (Brady *et al.*, 2011; Conson *et al.*, 2010; Parsons, 1987b, 1994; Parsons, Gabrieli, Phelps, & Gazzaniga, 1998). Conversely, for stimuli orientated in position anatomically difficult to reach, that is *unusual positions*, there is a disadvantage leading to slower reaction times and lower accuracy (Parsons, 1987b, 1994; Parsons *et al.*, 1998; Sekiyama, 1982). Thus, the *effect of biomechanical constraints* is considered a specific index of motor act simulation (Gentilucci *et al.*, 1998a,b), and its lack indicates the use of a general Visual Imagery (VI) strategy instead of a motor one (Conson *et al.*, 2010; Parsons, 1987b, 1994).

The relation between imagined action recall and real movement execution is anatomically supported by the overlap of brain regions involved in MI with those of real action execution, such as the left intraparietal sulcus (Bonda, Petrides, Frey, & Evans, 1995; Corradi-Dell'Acqua, Tomasino, & Fink, 2009) and the premotor cortex (Bonda *et al.*, 1995; Ehrsson, Spence, & Passingham, 2004; Parsons *et al.*, 1995). Furthermore, MI deficits have been demonstrated in patients affected by movement disorders (Conson *et al.*, 2010; Coslett, Medina, Kliot, & Burkey, 2010; Fiori *et al.*, 2013; Fiorio, Tinazzi, & Aglioti, 2006). Conson *et al.* (2010) demonstrated that in Locked-in Syndrome (LIS), the complete disconnection of the descendent motor pathways negatively impacts MI (Conson *et al.*, 2008, 2010). Similarly, chronic pain patients, even though without cortical damages, show MI deficit (Coslett *et al.*, 2010; Schwoebel, Friedman, Duda, & Coslett, 2001).

Spinal Cord Injury (SCI) is a neurological condition associated with motor disability due to damages of the descending motor pathways (Cramer, Orr, Cohen, & Lacourse, 2007). Previous studies investigating MI in these patients found quite variable results (Alkadhi *et al.*, 2005; Cramer *et al.*, 2007; Decety & Boisson, 1990; Lacourse, Cohen, Lawrence, & Romero, 1999), reporting both anomalies in the dynamics of event-related potentials and in patterns of cortical activation during MI (Cramer *et al.*, 2007; Lacourse *et al.*, 1999) and spared behavioural abilities and brain activations (Alkadhi *et al.*, 2005; Decety & Boisson, 1990; Hotz-Boendermaker *et al.*, 2008). However, these reports do not focus on the effects induced by the complete lack of motor efferences on the strategy adopted to perform the task.

The aim of this study was to investigate the impact of sensory and motor information flow interruption on MI and VI abilities. To this aim, we relied on a modified version of the Hand Laterality Task (HLT; Fiori *et al.*, 2013; Parsons, 1987a,b). We focused on the *effect of biomechanical constraints*, rather than on a simple comparison between hand orientations, as the presence of this effect is an important index of a strategy based on the active process of internally representing a motor command without an effective overt movement (Brady *et al.*, 2011; Conson *et al.*, 2010; Jackson *et al.*, 2001; Parsons, 1994). Consequently, some evidences suggest that the lack of this effect is indicative that the task has not been carried out using a strategy based on the simulation of the movement, but rather by means of a general VI strategy (Conson *et al.*, 2010; Nico, Daprati, Rigal, Parsons, & Sirigu, 2004). Accordingly, the *effect of biomechanical constraints* allows to test directly whether or not there has been an access to the second level of the MI model (Parsons, 1987b, 1994).

As MI abilities require peripheral inputs, we hypothesize that the deafferentation presented by SCI patients, disconnecting the motor system, but sparing cortical areas, might impact this cognitive process. If patients have a different performance compared with unimpaired subjects in both the MI and the VI tasks, then the damage in the descending motor pathways prevents any access to mental rotation-based strategies (Gentilucci *et al.*, 1998a,b; Parsons, 1987b, 1994). Alternatively, if SCI patients fail only at the MI task, a severe impairment in accessing MI strategies, but not general VI strategies could be hypothesized, suggesting an impairment limited to the second level of the MI model (Conson *et al.*, 2010; Parsons, 1987b, 1994). Finally, a third prediction postulates that if SCI patients are competent in both tasks (even in case they perform less accurately than unimpaired subjects, but still showing the typical effects – i.e., the *effect of biomechanical constraints* – for these tasks), one might infer that the interruption of motor inputs does not completely prevent MI and VI, but rather makes these processes less efficient (Nico *et al.*, 2004). To ensure that impairments in MI are not a general visuo-spatial rotation deficit, we have also employed a control task, the Mirror Letter Discrimination (MDL), in which stimuli consist of letters instead of body parts (Jordan, Heinze, Lutz, Kanowski, & Jancke, 2001; Pelgrims, Michaux, Olivier, & Andres, 2010). It has been demonstrated that VI of alphanumeric stimuli activates different cortical networks, not specifically involving motor areas (Jordan *et al.*, 2001; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998).

Importantly, one could hypothesize that patients with impaired sensorimotor pathways related to a specific body region (i.e., the hands) could show specific defects in implementing motor acts within the same body district. Paraplegic patients, being affected by a spinal lesion that does not abolish upper limb movements and sensation, could show some variable motor and sensory impairment in their upper limbs as a function of the precise level of spinal cord damage. Thus, we also took into account the difference between paraplegic and quadriplegic patients to further explore the role of the degree of deafferentation on MI. In summary, we investigated, by means of a reliable task, the contribution of motor information to MI in paralysed patients without cortical injury.

Material and methods

Subjects

Spinal Cord Injury patients have been enrolled at the Unipolar Spinal Unit of Niguarda Ca' Granda Hospital (Milan, Italy), from January 2010 to June 2010. A clinician working at the Hospital Unit signalled patients eligible for the study to the experimenter. Only patients who satisfied the inclusion or exclusion criteria were administered with the experimental tasks, after they consented to participate. Exclusion criteria for patients were: (1) comorbidity with other neurological and psychiatric disorders; (2) severe neoplastic pathology; (3) severe global cognitive impairment, resulting for instance from a head trauma, as determined through the Raven's Coloured Progressive Matrices (RCPM) (Carlesimo *et al.*, 1996; Raven, Court, & Raven, 1996; Table 1). Inclusion criteria were (1) presence of an established SCI, with a traumatic aetiology; and (2) a time interval from the lesion onset between 3 months and 1 year. Twenty-four SCI patients were screened for eligibility, but only 16 of them, meeting the inclusion or exclusion criteria, have been included in the study. Excluded patients mainly presented with severe global cognitive impairment due to brain injury. For all patients, the screening was administered within the 7 days preceding the experimental evaluation. Sixteen right-handed SCI patients (15 men, mean age 42.313 ± 17.10 years, mean education 13.38 ± 4.47 years, mean time from SCI onset 7 ± 3.07 months; clinical and neurological variables of each patient are reported in Table 1) and 16 right-handed controls (15 men, mean age 43.44 ± 17.48 years, mean education 12.18 ± 3.39 years), recruited from a pool of volunteers at the University of Pavia, participated in the study. None of the subjects had previously taken part in experiments investigating MI.

The patient group is equally composed of paraplegic and quadriplegic patients (Table 1). The neurological level of the injury, defined as the most caudal level of the spinal cord below whom there are normal sensory and motor functions on both sides of the body (Maynard *et al.*, 1997), was determined using the American Spinal Injury Association Impairment Scale (ASIA) (Maynard *et al.*, 1997; Table 1). All patients suffered from a SCI between C3 and D8.

Table 1. Neuropsychological variables: RCPM's corrected scores and HRSD score are indicated for each patient. Clinical variables: Diagnosis (Quadriplegic or Paraplegic) lesion, motor and sensory level and ASIA (A = no motor and sensory function is preserved; B = partial sensory, but not motor function is preserved) are reported for each patient

Subject	RCPM	HRSD	Diagnosis	Lesion level	Sensory level	Motor level	ASIA
1	30.1	10	Quadriplegic	C6	Low cervical	Low cervical	A
2	29.2	2	Paraplegic	T8	High chest	High chest	A
3	28.5	2	Paraplegic	T4	High chest	High chest	A
4	30.3	12	Quadriplegic	C5	High cervical	Low cervical	A
5	26.4	5	Paraplegic	T4	High chest	High chest	A
6	27.4	6	Paraplegic	T4	High chest	High chest	A
7	27.9	7	Quadriplegic	C5	High cervical	Low cervical	A
8	33.8	5	Quadriplegic	C4–C5	High cervical	High cervical	A
9	30.8	5	Paraplegic	T3	High chest	High chest	A
10	28.3	7	Paraplegic	T2	High chest	High chest	A
11	27.2	1	Paraplegic	T3	High chest	High chest	B
12	27.8	5	Paraplegic	T1	Low cervical	Low cervical	A
13	33.8	8	Quadriplegic	C4	Low cervical	Low cervical	A
14	25.8	4	Quadriplegic	C4–C5	Low cervical	High cervical	A
15	35.4	6	Quadriplegic	C3	High cervical	High cervical	A
16	31.6	7	Quadriplegic	C5–C6	Low cervical	Low cervical	B

Note. RCPM, Raven's Coloured Progressive Matrices; HRSD, Hamilton Rating Scale for Depression; ASIA, American Spinal Injury Association Impairment Scale.

The study was conducted in accordance with the ethical standards of the declaration of Helsinki and an informed consent was obtained from all subjects. The research protocol and the informed consent form have been approved by the Ethics Committee of the A.O. Niguarda Ca' Granda.

Experimental tasks

Hand Laterality Task (HLT)

In the HLT, subjects were requested to indicate whether an image represents a right or a left hand (Conson *et al.*, 2010; Gentilucci *et al.*, 1998a,b; Parsons, 1987b, 1994). Stimulus naturalness was enhanced using real photos of a male hand. Left and right hands were presented in four orientations (0°, 90°, 180°, and 270° in clockwise direction) and in dorsum and palm perspective (Figure 1). All our quadriplegic patients presented with tracheotomy or outcome of this surgery practice, making it impossible for them to provide a vocal answer, adequate and reliable for the overall experiment duration. To avoid the use of two different response means in the experiment for paraplegic and quadriplegic patients, we adopted a common procedure that both could bear: eye-gaze movement. We instructed subjects (and controls to keep the procedure consistent) to answer directing their eye gazes towards one of the two alternatives presented on a response sheet (Figure 2b). This procedure has been reliably applied in a similar previous study (Conson *et al.*, 2010; Fiori *et al.*, 2013).

The HLT was composed of a total of 192 stimuli (i.e., hand rotated), administered in two sessions of the same length (96 stimuli in each session). Every session was composed of 6 blocks, each block containing 16 randomized stimuli. Thus, during the experiment,

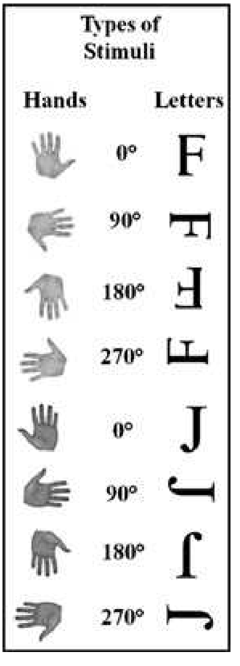

Figure 1. Schematic presentation of the stimuli used in Hand Laterality Task (HLT) and Mirror Letter Discrimination (MLD). Left hands (back and palm) and letters (F and J) are shown for each orientation (0°, 90°, 180°, 270°).

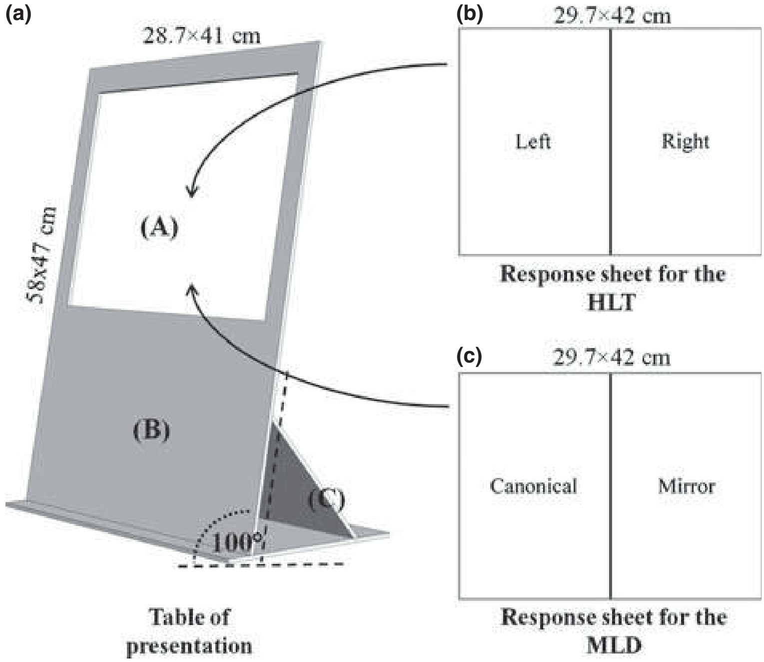

Figure 2. Details of the tools used to administer the experimental tasks. (a) 3D sketch of the Table of Presentation (TOP) with measures: front part (A) in which stimuli were inserted, the TOP opening (B) where the response sheets were fixated and the support in the back of the TOP (C) that allows stimuli presentation. (b) Response sheet used for the Hand Laterality Task (HLT). (c) Response sheet used for the Mirror Letter Discrimination (MLD).

each stimulus appeared 12 times in a random order. The random order was the same for all subjects. Nevertheless, being the stimuli randomized in blocks, we have been able to control for carry-over effects due to order influences, allowing at the same time an easy and reliable manual administration of the stimuli.

The HLT allows to investigate the effects of stimulus orientation and biomechanical constraints (Nico *et al.*, 2004; Parsons, 1987b; Sekiyama, 1982). The *effect of stimulus orientation* consists in a peak in error rates in judging 180° oriented hands (Cooper & Shepard, 1975; Nico *et al.*, 2004; Shepard & Metzler, 1971). This phenomenon also characterizes a variety of visuo-spatial rotation tasks, not strictly related to action simulation, such as VI of alphanumeric characters (Booth *et al.*, 2000; Harris *et al.*, 2000; Jordan *et al.*, 2001). Therefore, an *effect of stimulus orientation* alone indicates the use of more general visuo-perceptual processes involved in VI rather than the use of MI (Jordan *et al.*, 2001; Shepard & Metzler, 1971). On the other hand, the *effect of biomechanical constraints* is a more specific index of MI strategy as it is related to the real movement of the body segment (Conson *et al.*, 2010; Parsons, 1987b).

Mirror Letter Discrimination Task (MLD)

As a control task, we used the MLD, in which subjects were requested to indicate, using the same answering procedure as in the HLT, whether a displayed letter was in its correct upright position or mirror-reversed orientation (Figure 1). Previous works demonstrated that rotation of letters instead of body parts involves general VI operations rather than action-related MI processes (Alivisatos & Petrides, 1997; Booth *et al*., 2000; Gogos *et al*., 2010; Jordan *et al*., 2001; Pelgrims *et al*., 2010). Moreover, the MLD allows separating VI from MI deficits. In fact, alphanumeric stimuli typically present the *effect of stimulus orientation* (Alivisatos & Petrides, 1997; Booth *et al*., 2000; Gogos *et al*., 2010; Jordan *et al*., 2001; Pelgrims *et al*., 2010). The number of stimuli and the order of presentation were equal to the HLT (see Section HLT). We maintained the same conditions in both tasks to have homogeneous experimental situations, even though the 270° and 90° orientations are not essential to compute relevant indexes in the MLD. The letters used in the MLD, 'F' and 'J', have been chosen because their asymmetry is similar to that of the hands (Pelgrims *et al*., 2010). Subjects were instructed to mentally rotate the presented image until the 'top' was up and then to decide whether the stimulus was a letter in a correct upright position or a mirror form. These instructions have been proven to be useful to reduce the inter-individual variance in rotation strategies (Hochberg & Gellman, 1977; Jordan *et al*., 2001).

Apparatus and procedure

We used a plastic Table of Presentation (TOP; Figure 2a) and two transparent response sheets to administer the tasks (Figure 2b, c). The TOP is a rectangular plywood platform, which measures 58 × 47 cm. The bottom part of the TOP is used for stimuli presentation (Figure 2a), while in the top part the response grid appropriate for the trial is placed (Figure 2b, c). The back of the TOP has a support that allows stimuli presentation at a correct visual angle of 80° of inclination (Figure 2a).

To monitor subjects' eye movements, and to register the response on line, we developed two transparent response grids (Figure 2b, c). For the MLD task, the two response alternatives were 'canonical' (correct upright position) and 'mirror', printed respectively on the left and the right side of the response grid (Figure 2c), while for the HLT the answer sheet had two alternatives printed on them, 'left' and 'right' (Figure 2b), congruent with the participant's left and right perspective. An examiner was seated in front of the subjects and reported the responses on the grid. To avoid biases, the examiner was blind to which stimulus was displayed. The HLT and MLD was composed each of 192 stimuli;therefore, subjects had to judge a total of 394 stimuli in the experiment. The experiment has been implemented as an individual session for both SCI patients and controls.

Both SCI patients and controls sat in front of the TOP with their arms and hands resting on a table. Subjects were instructed to respond as quickly and accurately as possible. The tasks were administered to patients and controls in a reversed order. The TOP was located in front of the subject at 50-cm distance. In the HLT task, patients and controls had both hands out of sight, lying palm-down. The experimental stimuli were displayed on a paper sheet (A3 format, 29.7 × 42 cm), centrally printed on a white background.

Data analysis

Data have been analysed using Statistical Package for Social Sciences (SPSS 13.0©, Chicago, IL, USA). Accuracy was recorded for each stimulus of the HLT and MLD, and averaged at each degree of rotation (0°, 90°, 180°, 270°; Table 2). This averaged accuracy has been introduced in an analysis of variance as dependent variable. For *Post-hoc* comparisons, the estimated marginal means comparison (Bonferroni corrected) method has been applied to investigate main effects and the Student's *t* test (Bonferroni corrected) to follow up the interactions.

Table 2. Patients' and controls' average percentage of correct responses (± SEM) as a function of stimulus orientation for both HLT (collapsed between left/right and palm/back conditions) and MLD (collapsed across F/J and correct upright position/mirror-reversed form conditions). For the HLT is also reported the average percentage of correct responses (SEM) for postures of hand stimuli simple and unusual

	HLT		MLD	
Orientations	Controls Mean	SCI Patients Mean	Controls Mean	SCI Patients Mean
0°	95.18 (1.09)	95.31 (2.19)	97.53 (1.03)	96.48 (1.16)
90°	89.06 (2.07)	93.88 (1.83)	95.05 (1.42)	93.75 (1.77)
180°	80.86 (4.80)	92.71 (2.19)	76.30 (7.26)	93.88 (1.33)
270°	90.23 (1.92)	95.18 (1.92)	94.01 (1.27)	95.44 (1.18)
Simple	93.75 (1.82)	94.53 (2.54)	–	–
Unusual	82.29 (3.35)	94.27 (2.04)	–	–

Note. HLT, hand laterality task; MLD, mirror letter discrimination.

Moreover, in order to exclude subjects who performed poorly because of factors such as failure to engage in the task, inability to understand the task, inability to maintain the correct attentional levels, we assessed, in both tasks, the individual's performance on those trials that required no rotation (0° for the right and left hands – palm-down conditions – in the HLT and 0° for the 'F' and 'J' in the correct upright position in the MLD). As validity criterion, we chose to consider performances below chance level (in other words, below 50% of correct answers). Furthermore, this analysis helped in controlling eye-gazes reliability. Due to clinical constraints we could not perform a test–retest reliability check, but answers at 0° can be considered as an internal control as in these conditions stimuli are not rotated. Consequently, correct answers at 0° can be used to evaluate whether subjects' eye gazes are made by chance.

The influence of the demographic variables (age and education) was investigated using the Pearson's correlation coefficient. We averaged the performance for each angle of rotation in the HLT and MLD, obtaining an overall performance index for both tasks. Thus, we correlated this overall performance index in the two tasks with age and education, in both SCI and control group.

Finally, to investigate the influence of clinical and cognitive variables in SCI patients, we performed correlations between the overall performance and the Hamilton Rating Scale for Depression (HRSD) and the RCPM score (Pearson's parametric correlation). Paraplegic patients by definition are affected by a spinal lesion that does not abolish upper limb movements and sensation. Thus, these patients could present some variable motor and sensory impairment in their upper limbs that could influence the results. To explore this influence, we correlated the overall performance at the HLT and MLD with the level of spinal cord lesion, the sensory level and the motor level of each patient (Spearman's non-parametric correlation).

Results

Effect of the stimulus orientation

The presence of the effect of stimulus orientation allows to speculate about the cognitive strategy adopted to solve a mental rotation task. Such a pattern of performance is not detectable if no VI has taken place (Jordan *et al.*, 2001; Parsons, 1987b; Shepard & Metzler, 1971).

To explore the effects of the stimulus orientation, we performed a repeated measures ANOVA with Task (HLT and MLD) and angle of rotation (0°, 90°, 180°, and 270°) as within-subject factors and group (control and SCI groups) as between-subject factor. Results showed a significant main effect of the angle of rotation ($F_{1.213,36.394} = 16.897, p < .001$) and group ($F_{1,30} = 5.451, p = .026$) and a significant two-way interaction between angle of rotation and group ($F_{1.213} = 9.895$, $p = .002$; Figure 3). We did not find any significance, or interactions, for Task (all *p*s > .05). The analysis of the main effect of angle of rotation showed a significant difference between stimuli presented at 0° versus 90° ($p = .003$), 180° ($p < .001$) and 270°($p = .002$) and additionally differences between stimuli at 180° with respect to 90°($p = .002$) and to 270° ($p = .004$). Comparing SCI patients and controls to explore the main effect of group, we found that patients have a greater accuracy than controls ($p = .026$). To follow up the two-way interaction between angle of rotation and group, resulting from the ANOVA, we compared SCI patients and controls and we found that this interaction is driven by a significant difference between groups at 180° rotated stimuli ($t_{20.385} = -3.106, p = .005$; Figure 3).

Effect of biomechanical constraints

To detect the presence of the *effect of biomechanical constraints* (Parsons, 1987b), we contrasted *simple* and *unusual postures* of body stimuli of the HLT (Conson *et al.*, 2010; Parsons, 1987b, 1994). We averaged accuracy obtained in the most simple postures to reach with real movements, that is hand postures requiring a minimal mental rotation of body segments from the actual position of the hands (90° oriented left hand and 270° oriented right hand, dorsal view) and accuracy obtained in the most unusual postures, i.e., hand postures requiring the most articulated movement simulation (270° oriented left hand and 90° oriented right hand, palm view; Table 2).

We performed a repeated measures ANOVA with position of the hand (*simple* and *unusual*) as within-subjects factor and group (control and SCI patients) as between-subjects factor. A significant main effect of position of the hand ($F_{1,30} = 14.064, p = .001$)

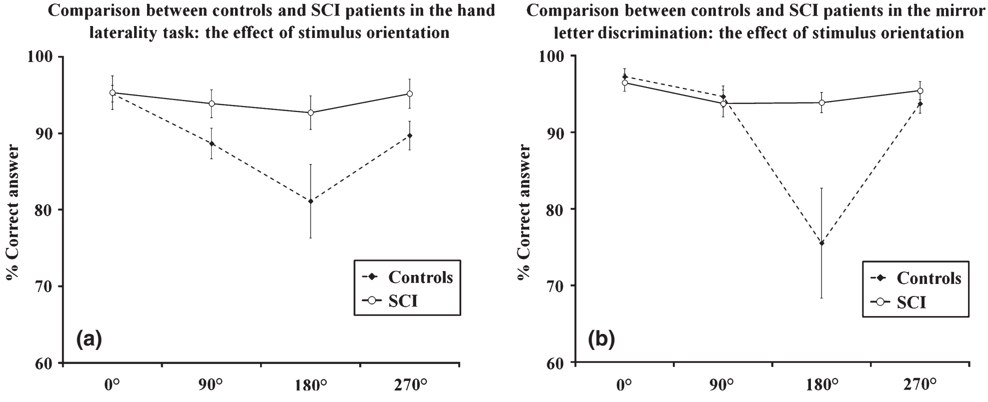

Figure 3. Accuracy data for the healthy controls (dotted line) and SCI patients (continuous line). For the Hand Laterality Task (HLT) (a) data have been collapsed across the palm-up/palm-down and the left/right hand conditions. The Mirror Letter Discrimination (MLD) data (b) have been collapsed for the F/J letter and correct upright position/mirror-reversed form conditions.

and group ($F_{1,30} = 6.0512, p = .020$) was found. Furthermore, data revealed a significant two-way interaction between position of the hand and group ($F_{1,30} = 13.042, p = .001$; Figure 4).

The analysis of the main effect of position of the hand showed a significant difference between stimuli presented in *simple* versus *unusual* postures, with the latter being more difficult to recognize ($p = .001$). Comparing SCI patients and controls to explore the main effect of group, we found that patients perform more accurately than controls ($p = .020$). Exploring the two-way interaction, *Post-hoc* comparison between SCI patients and controls showed that SCI patients are not affected by *the effects of biomechanical constraints*, performing the task more accurately than controls for *unusual postures* ($t_{25.210} = -3.654, p = .001$; Figure 4). On the other hand, the two groups did not show significant differences for *simple postures* ($p > .05$).

In the previous analysis, we treated the patients group as a single entity. However, we were also interested in assessing if the interruption of specific motor and sensory pathways may impact on MI abilities. Thus, we performed an additional analysis, directly contrasting the performance of quadriplegic and paraplegic patients to control for the type of motor deficits. The repeated measure ANOVA, with position of the hand (*simple* and *unusual*) as within-subject factors and patients type (quadriplegic versus paraplegic) as between-subject factor, did not detect any significant difference (Figure 5). Thus, the effects found in the previous group analysis cannot be attributed differently to quadriplegic and paraplegic patients.

Correlation with demographic and clinical variables

The influence of the demographic variables (age and education) was investigated using the Pearson's correlation coefficient. We averaged the performance for each angle of rotation in the HLT and MLD obtaining an overall performance. Thus, we estimated the Pearson's coefficient between the overall performances in the two tasks and age and education, in both SCI and controls. We did not find any significant correlation in either of the groups (all ps > .05).

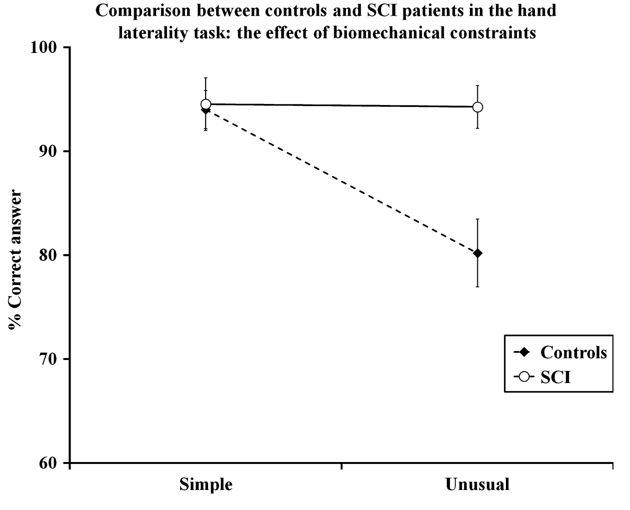

Figure 4. Accuracy data (bars represent standard errors of the mean) in healthy controls (dotted line) and Spinal Cord Injury (SCI) patients (continuous line) for *simple* and *unusual* postures.

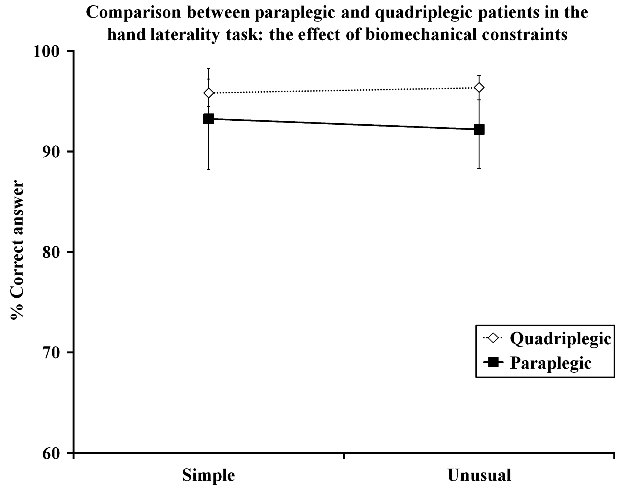

Figure 5. Quadriplegic (dotted line) and paraplegic patients (continuous line) samples' accuracies (bars represent SEM) in judging *simple* and *unusual* postures.

Clinical variables have been investigated only in SCI patients. We correlated the HRSD and the RCPM scores with the overall performances indexes. These measures could be indicative of an influence of apathy HRSD and of the general cognitive level RCPM on the task's performance. These analyses did not reveal any significant correlations (all *p*s $>$ .05). We can conclude that the results at the HLT and at the MLD are not due to a scare cooperation in executing the tasks or to diverse visuo-spatial and abstract reasoning skills among patients.

Moreover, to determinate if specific features of SCI sample could influence the performance, we performed Spearman's correlation with the level of lesion, the motor level and the sensory level and the time since injury. Also these analyses did not show significances (all *p*s $>$ .05). We did not include the ASIA score and the lesion type in the correlation analysis as all except two patients fell in the same category at these measures (see Table 1).

Discussion

Since birth, we are active agents in the environment (Berlucchi & Aglioti, 2010). This implicit knowledge that our bodies belong to us and that we act in the world is given not only by the integration of sensory and motor signals but also by the cognitive processing of such information (de Vignemont, 2010). Among the cognitive abilities that contribute in our action control, MI allows recalling and simulating the outcome of an action without any overt motor output (Berlucchi & Aglioti, 2010; Frith *et al.*, 2000; de Vignemont, 2010). This ability might be used in everyday life to predict the outcome of a motor act (Wolpert, Doya, & Kawato, 2003).

Spinal Cord Injury involves damages to the spinal canal's structures and interrupts the flow of information below the damaged portion of the spinal column (Alkadhi *et al.*, 2005; Cramer *et al.*, 2007). Consequently, SCI patients suffer from an acutely acquired disconnection of the efferent motor outputs and afferent sensory inputs between the lower body parts and the cortical and subcortical structures. Previous studies found divergent results, reporting both impaired and spared MI abilities in these patients (Alkadhi *et al*., 2005; Cramer *et al*., 2007; Decety & Boisson, 1990; Hotz-Boendermaker *et al*., 2008; Lacourse *et al*., 1999).

In the present work, we behaviourally investigated the possibility that SCI patients, who can no longer perform movements, retain the ability to mentally represent an action outcome. We administered a sample of 16 SCI patients and a matched group of healthy volunteers with the HLT. This task detects the presence of the *effect of biomechanical constraints*, related to the use of MI (Conson *et al*., 2010; Parsons, 1987b, 1994; Parsons *et al*., 1998). In addition, to disentangle body specific from general VI impairments, we also employed the MLD, that allows to obtain a reliable index of VI, the effect of stimulus orientation (Fiori *et al*., 2013; Jordan *et al*., 2001; Pelgrims *et al*., 2010). By means of this experimental design, we found substantial differences between SCI patients and controls, interestingly for both the alphanumeric and the body stimuli processing.

First, patients do not show the typical effects of the stimulus orientation, in other words an error peak for the most difficult stimuli (180° oriented stimuli). Patients reach a greater accuracy than controls for 180° rotated stimuli. Usually, accuracy decreases as a function of the tilting increment: an increase in tilting requires a complete rotation of the mental representation of the stimulus to match it with the to-be-judged stimulus (Jordan *et al*., 2001; Shepard & Metzler, 1971). This effect of stimulus orientation, thus, is strictly related to the use of a VI-based strategy (Conson *et al*., 2010; Cooper & Shepard, 1975; Jordan *et al*., 2001; Nico *et al*., 2004; Parsons, 1987b; Sekiyama, 1982). The absence of this effect cannot be explained by a recognition deficit, as 0°, not rotated, stimuli are correctly identified by patients. Rather, this result indicates that stimuli have not been mentally rotated by patients.

Secondly, patients do not show the typical *effect of the biomechanical constraints*. In other words, they do not present with a disadvantage in judging hands in positions violating the real limb constraints. In fact, the simulation of the movement of one's own internal body part representation, to fit it with a hand presented in an executable grasping posture ('*simple postures*'), is characterized by faster reaction times and higher accuracy than when the hand is presented in *unusual postures* (Brady *et al*., 2011; Conson *et al*., 2010; Gentilucci *et al*., 1998a,b; Parsons, 1987b, 1994). This effect is considered a specific hallmark of MI. While controls show a significant accuracy decrease between *simple* and *unusual postures* of hands in the HLT, SCI patients do not present this difference. Their accuracy is the same, independently from the hand position conceivableness. Consequently, one could hypothesize that, to judge the hand stimuli, own mental representation of the body part has not been rotated by SCI patients.

This last finding suggests that the second stage of hand laterality recognition, involving a mental movement of one's own hand, is not accessible to SCI patients (Parsons, 1987b, 1994). The interruption of the efferent motor and afferent sensory information flow between the lower body parts and the cortical and subcortical structures may explain the lack of the *effect of biomechanical constraints*, as this disconnection deeply impacts movements mental simulation, in absence of motor feedback (Conson *et al*., 2008, 2010). These results are partly in agreement with studies showing impairments in LIS that demonstrate that a total pontine deafferentation influences MI even when cortical areas are preserved (Conson *et al*., 2008, 2010). However, studies in LIS also show spared VI abilities (Conson *et al*., 2008, 2010). The difference between studies could arise from several factors. First, the 2010 work of Conson and colleagues did not directly explore VI abilities, making it difficult to draw solid conclusions about differences between studies. Secondly, in the 2008 study, a same-different procedure (in other words, a recognition task) has been adopted to investigate VI. This paradigm is easier than tasks requiring the subject to perform an active and demanding cognitive process (Kintsch, 1970). Consequently, a same-different paradigm might be less sensitive to impairments. Finally, LIS patients studies have been performed in smaller samples, including six (Conson *et al.*, 2010) and four (Conson *et al.*, 2008, 2010) patients. In contrast our study involved a larger sample, possibly allowing more sensitivity (Friston, Holmes, & Worsley, 1999).

While it appears clear why MI abilities are compromised in SCI, our results on the lack of the *effect of stimulus orientation* suggest that also VI processes are impaired in these patients. Previous studies on stroke (Vromen, Verbunt, Rasquin, & Wade, 2011), congenital hemiparetic (Steenbergen, van Nimwegen, & Craje, 2007) and upper limb amputee patients (Nico *et al.*, 2004) found that an alteration in the multi-sensory feedback necessary to perform a MI paradigm could determine the use of VI-based strategy. Differently, our results indicate that a traumatic SCI determines a shift in favour not of a VI strategy but of a completely different one, which could be based on memory (or in other words based on the semantic knowledge; Palermo, Piccardi, Nori, Giusberti, & Guariglia, 2010). For instance, in a study on representational neglect, Palermo *et al.* (2010)found that right-brain-damaged patients perform MI and VI tasks adopting an alternative strategy based on the semantic knowledge of the stimuli (Palermo *et al.*, 2010). Even if no mental rotation processes were performed, patients reached a good level of accuracy (Palermo *et al.*, 2010). Similarly, our SCI patients, who did not rotate the visual stimuli, presented nonetheless a good level of accuracy based on a diverse strategy.

This last finding is not intuitive, considering that in our SCI patients there are no cortical lesions that could affect VI abilities. Furthermore, the neuropsychological assessment administered to all patients did not demonstrate any other deficits in the memory domain. However, recent studies started suggesting that mental rotation of objects might rely not only on visuo-spatial abilities but rather it could depend also on visuo-motor processes (Lamm, Windischberger, Moser, & Bauer, 2007). Motor areas, in fact, are also active when subjects experience themselves not to be the agent of the rotation, such as in case of object rotation (Lamm *et al.*, 2007; Richter *et al.*, 2000). This interpretation is compatible with a more parsimonious representation of the objects in the environment that maintain their identity independently from the viewing angle (Gibson, 1966) and irrespectively of the sensory modality involved (Sedda, Monaco, Bottini, & Goodale, 2011). When a SCI occurs, patients start to explore the surrounding in a complete different fashion, forced to rely on a very limited range of viewing angles. Possibly, the absence of movement does not activate anymore motor networks routinely involved in object rotation (Lamm *et al.*, 2007; Richter *et al.*, 2000), including letters, as these stimuli are treated as objects in VI tasks (Jordan *et al.*, 2001). Consequently, we hypothesize that SCI patients approach this VI task by the means of memory, comparing the presented images with an already available representation of a familiar target (Palermo *et al.*, 2010). This alternative strategy allows a good level of accuracy, nullifying the typical rotation effect.

Interestingly enough, it could be argued that the interruption of specific motor and sensory pathways between the lower body parts and the cortical structures might impact MI. In other words, the impairments could be different between paraplegic and quadriplegic patients. On this basis, one could expect that quadriplegic patients would show an impairment on the HLT, with a specific lack of the *effect of biomechanical constraints*, whereas paraplegic patients would not, as they are unimpaired in their upper limbs. This was not the case in our study, failing to support the hypothesis of a selective involvement of efferent and afferent information in MI processes. In agreement with our results, a recent study exploring body image in both quadriplegic and paraplegic SCI patients showed similar results (Fuentes, Pazzaglia, Longo, Scivoletto, & Haggard, 2013). More in detail, the authors developed a quantitative test to explore the perceived distance of body parts in these patients. Quadriplegic and paraplegic patients performed similarly at this task, presenting with the same distortions in body representation independently from the degree of interruption of motor and sensory pathways (Fuentes *et al.*, 2013). Taken together with our results, these findings suggest that body representation and MI, being high cognitive functions, might not be influenced directly by the level of the lesion.

We did not find any significant correlation between age and performance in the MI and VI tasks in controls and SCI patients, although such correlation has been reported in previous studies (Gabbard, Cacola, & Cordova, 2011; Leonard & Tremblay, 2007; Malouin, Richards, & Durand, 2010). This absence could be explained by the small sample size, the small numerousness of subjects in each age class and because the study was not designed to test age-related changes of imagery performance. Indeed, greater samples allowing group comparisons, and most importantly the use of tasks focused on this aspect, might help to detect the effect of age. However, one should expect this effect only in controls, as patients did not seem to operate any mental rotation.

Considering our results from a broader perspective that includes treatment, they suggest caution: not all SCI patients, in fact, might benefit from rehabilitation techniques based on MI as proposed by recent studies (Andersen, Hwang, & Mulliken, 2010; Dickstein & Deutsch, 2007; Malouin & Richards, 2010). Our results, although interesting and new, should nevertheless be considered as preliminary, due to some intrinsic limitations. First, we used accuracy instead of the classical measures such as reaction times. Implementing reaction times recording, maybe with the use of an eye-tracking equipment, could allow to extract different types of indexes such as visual effects and laterality effects (Brady *et al.*, 2011). Secondly, future studies should enlarge the clinical categories of patients taken into account, also involving the type of deafferentation (i.e., complete and incomplete). This comparison could, for instance, disambiguate which kind of information, motor feedback or sensory input, might be predominant to simulate the outcome of a motor act (Helmich, de Lange, Bloem, & Toni, 2007; Schwoebel, Boronat, & Branch Coslett, 2002). Furthermore, even though we did not find significant correlations between time since lesion onset and the MI and VI performance, it could be interesting to explore the same abilities in chronic patients (Kokotilo, Eng, & Curt, 2009; Xerri, 2012).

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