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Motor imagery in spinal cord injured people is modulated by somato-topic coding, perspective taking and post-lesional chronic pain.

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Running head: *Motor imagery in spinal cord injury*

Motor imagery in spinal cord injured people is modulated by somato-topic coding, perspective taking and post-lesional chronic pain.

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ABSTRACT

Motor Imagery (MI) allows one to mentally represent an action without necessarily performing it. Importantly, however, MI is profoundly influenced by the ability to actually execute actions, as demonstrated by the impairment of this ability as a consequence of lesions in motor cortices, limb amputations, movement limiting chronic pain and spinal cord injury. Understanding MI and its deficits in patients with motor limitations is fundamentally important since development of some brain-computer interfaces and daily-life strategies for coping with motor disorders are based on this ability. We explored MI in a large sample of patients with spinal cord injury (SCI) using a comprehensive battery of questionnaires to assess the ability to imagine actions from a first-person or a third-person perspective and also imagine the proprioceptive components of actions. Moreover, we correlated MI skills with personality measures and clinical variables such as the level and completeness of the lesion and the presence of chronic pain. We found that the MI deficits: i) concerned the body parts affected by deafferentation and deefferentation; ii) were present in first but not in third-person perspectives and iii) were more altered in the presence of chronic pain. MI is thus closely related to bodily perceptions and representations. Every attempt to devise tools and trainings aimed at improving autonomy needs to consider the cognitive changes due to the body-brain disconnection.

1. Introduction

Motor imagery (MI) is defined as the process of internally representing a motor command without an effective overt movement as the outcome (Jackson, Lafleur, Malouin, Richards, & Doyon, 2001). However, MI is closely connected to action execution, as demonstrated by neuroimaging results showing that MI involves neural structures largely overlapping with those involved in actually performing the imagined movements, in particular the premotor areas, the left intraparietal sulcus and subcortical structures such as basal ganglia and cerebellum (Bonda, Petrides, Frey, & Evans, 1995; Corradi-Dell'Acqua, Tomasino, & Fink, 2009; Decety, 1996; Gerardin, Sirigu, Lehéricy, Poline, Gaymard, Marsault, … Le Bihan, 2000). Since during MI actions are not actually carried out, the motor cortex shows much less activation for imagined compared to real movements (Glidden, Rizzuto, & Andersen, 2005). For these reasons MI is considered in an intermediate position along the continuum within motor preparation and motor execution (Nikulin, Hohlefeld, Jacobs, & Curio, 2008; Stephan & Frackowiak, 1996; Stephan, Fink, Passingham, Silbersweig, Ceballos-Baumann, Frith, & Frackowiak, 1995). The inherent link between motor imagery and action execution has been confirmed in studies showing that MI is altered in a number of pathological conditions characterized by an impairment of the ability to actually perform actions such as Locked-in Syndrome (Conson, Sacco, Sarà, Pistoia, Grossi, & Trojano, 2008), Amiotrophic Lateralis Sclerosis (Fiori, Sedda, Ferrè, Toraldo, Querzola, Pasotti, … Bottini, 2013), dystonia (Fiorio, Tinazzi, & Aglioti, 2006) and in chronic pain conditions (Coslett, Medina, Kliot, & Burkey, 2010; Schwoebel, Friedman, Duda, & Coslett, 2001). Another clinical condition that could make the execution of some movements extremely difficult or even impossible is spinal cord injury. Sufferers cannot move body parts below the lesion level due to a massive disconnection between the brain and the body. Thus, SCI constitutes an important model for exploring the relationship

between MI and the execution of specific movements. While initial research and recent behavioural results suggest that MI abilities are spared after SCI (Decety & Boisson, 1990; Fiori, Sedda, Ferrè, Toraldo, Querzola, Pasotti, … Bottini, 2014; Hotz-Boendermaker Funk, Summers, Brugger, Hepp-Reymond, Curt, & Kollias, 2008), neuro-functional anomalies in the dynamics of event-related potentials (Lacourse, Cohen, Lawrence, & Romero, 1999) and altered cortical activation during MI tasks have been found (Alkadhi, Brugger, Boendermaker, Crelier, Curt, Hepp-Reymond, & Kollias, 2005; Cramer, Orr, Cohen, & Lacourse, 2007; Hotz-Boendermaker et al., 2008). However, whether SCI people maintain their MI ability over time and they implement new post-lesional cognitive strategies is still unclear (Fiori et al., 2014; Hotz-Boendermaker et al., 2008). Despite the increasing interest in this topic (Di Rienzo, Collet, Hoyek, & Guillot, 2014), no systematic studies on the effects of level and completeness of the lesion on different types of MI in SCI have been done. Moreover, little is known about whether MI defects specifically involve the body parts that cannot be voluntarily moved and how MI deficits in SCI may be influenced by clinical variables such as the interval of time since the lesion, the degree of autonomy and the presence of pain.

To explore these issues we used a self-reporting measure of MI (originally introduced by Isaac, Marks, & Russell, 1986) in the modified version of Roberts and colleagues (VMIQ-2, Roberts, Callow, Hardy, Markland, & Bringer, 2008). The questionnaire consists of three subscales: i) motor imagery from a first-person perspective (Internal Visual Imagery, IVI), ii) motor imagery from a third-person perspective (External Visual Imagery, EVI) and iii) the somatosensory components of action imagery (kinaesthetic imagery, KIN). Each subscale supposedly explores different MI-related cognitive processes that, although interacting a great deal in daily life circumstances, may be selectively altered by the changes in brain and body representations that occur after SCI.

In contrast to the original VMIQ-2 version (Isaac et al., 1986), the items in the revised scale (Roberts et al., 2008) all require participants to imagine themselves (and not other people) while they perform actions (Roberts et al., 2008). In the scale that we adopted therefore, MI was from both the first- and third-person perspectives. More specifically, the EVI subscale necessitates imagining oneself performing actions from a third–person perspective, ("as if you were watching yourself from an external position"). This is a process that has been shown to involve cognitive processes other than those involved in first-person perspective imagery (Ionta, Fourkas, & Aglioti, 2010; Ionta, Fourkas, Fiorio, & Aglioti, 2007; Moro, Pernigo, Zapparoli, Cordioli, & Aglioti, 2011). For the IVI and KIN subscales, participants were asked to imagine themselves performing actions from a first-person perspective. IVI explores individuals' ability to judge an action while "looking out through their own eyes", and for the KIN participants must "imagine feeling themselves doing the movement". IVI and kinaesthetic imagery have been identified as separate modalities (Fourkas, Ionta, & Aglioti, 2006), with the latter probably being the most sensitive measure of MI.

Note that actual motor deficits in SCI depend on the lesion level with cervical lesions typically inducing tetraplegia (deficits involving both upper and lower limbs) and dorso-lumbar lesions inducing paraplegia (deficits involving only lower limbs). Thus, to explore the issue of whether MI deficits are associated with action execution deficits, we made an important change to the VMIQ-2 consisting of the addition of questions specifically assessing the imagery of actions performed with upper limbs, lower limbs or both, in order to have somato-topographic MI assessments. More specifically, we asked participants to imagine actions involving the full body (FB), only the upper limbs (UL) or only the head and shoulders (HS). Healthy participants would be able to perform all of the actions, patients with paraplegia only UL and HS, and patients with tetraplegia only HS. As a result of these changes, it was not possible to compare the SCI scores with the normative data

(Roberts et al., 2008) and for this reason a control group of neurologically healthy subjects was used. In addition, in order to exclude the effects of personality variables, these were carefully controlled. Scores in our version of the VMIQ-2 were correlated with a number of important clinical variables including the level and completeness of the lesion, the time since lesion, the degree of independence in daily life and the presence of pain.

2. Materials and methods

2.1 Participants

Forty-nine subjects suffering from SCI in the chronic phase (> 1 year) and 24 neurologically healthy controls (age, gender and education-matched) agreed to participate in the study. The neurological level of injury (NLI) and completeness of lesion were measured by means of the American Spinal Injury Association scale (ASIA, Kirshblum, Burns, Biering-Sorensen, Donovan, Graves, Jha, … Waring, 2011). The SCIM-3 scale (Invernizzi, Carda, Milani, Mattana, Fletzer, Iolascon, … Cisari, 2010) was used to quantify the degree of autonomy in daily life activities. Patients with: i) developmental deficits; ii) a history of head injury, vascular brain lesion or psychiatric disorders and/or iii) mental deterioration or deficits in general cognitive abilities were not included in the study. Clinical and demographic data are reported in Table 1.

Table 1 near here

The study was approved by the local Ethics committee (CEP Prot. N. 40378) and was conducted in accordance with the ethical standards of the Declaration of Helsinki (2013).

2.2 Materials and Procedure

Data regarding the MI abilities of the participants were collected at their homes or in a quiet room at a Department of Rehabilitation in one 60-minute session. Other clinical variables and personality traits were assessed with specific scales. The order of the questionnaires was randomized between subjects. Participants responded verbally to the questions and the examiners manually recorded the responses.

2.2.1 Motor Imagery

Three different somato-topographic action types were investigated by means of the modified VMIQ-2 (see Supplementary Materials): a) movements involving the head, mouth and shoulders or that consisted of maintaining assisted positions (Head and Shoulders actions -HS, n. 6, all new items) - the SCI patients were able to execute all of these movements; b) actions involving trunk and upper limbs (Upper Limbs actions -UL, n.3, 2 new items) - the execution of these movements was impaired in tetraplegic but not in paraplegic subjects; c) actions involving the full body and/or the lower limbs (Full Body actions -FB, n. 11, no new items) - the execution of these movements was impaired in all of the SCI subjects. As in the original version, the vividness of each action-image was assessed on a 5-point Likert scale (Table 2, higher value = greater difficulty in MI) and the EVI, IVI and KIN subscales were used.

2.2.2. Pain

In order to ascertain the presence of pain, a new scale inspired by the McGill Pain Questionnaire was employed (Melzack, 1987). To the best of our knowledge this is the first scale devised to measure neuropathic, neuromuscular and visceral pain (Supplementary Materials). The validation process is currently underway but the preliminary results here collected confirm its high correlation with both the *Brief Pain Inventory* (BFI, Caraceni, Mendoza, Mencaglia, Baratella, Edwards, Forjaz, …

Cleeland, 1996) and the *Douleur Neuropathique 4 Questions Scale* (Bouhassira, Attal, Alchaar, Boureau, Brochet, Bruxelle, … Vicaut, 2005) (Spearman's ρ = .46 and .74, respectively).

2.2.3. Personality variables

In order to check the potential effects of variables linked to personality traits, the 10 item-version of the Big Five Inventory Scale (BFI 10, Rammstedt & John, 2007) was proposed. In addition, potential influences of a subjective disposition towards episodes of suggestibility or absorption were assessed (Tellegen Absorption Scale - TAS, Tellegen & Atkinson, 1974). Finally, a measure of an individual disposition to accept changes in body form and surface was recorded by means of the Trinity Assessment of Body Plasticity (BodyTAP, Desmond, Horgan, & MacLachlan, 2001). As an Italian version of these instruments is not available, a back-translation was used.

2.3. Data Handling and Statistical Analyses

The VMIQ-2 responses relating to each condition (IVI, EVI and KIN) and somato-topographic action type (FB, UL and HS) were summed. Data from our pain subscales (visceral, neuropathic and neuromuscular pain) were treated as categorical factors indicating the presence or absence of pain. For each interview regarding personality traits, the specific methodology of scoring according to their original version was followed.

Completeness of lesions was considered a categorical factor (Absence/Presence), and an integer from 1 to 30 (corresponding to intervals from the C1 to the S5 segments) was calculated for the Neurological Level of Injury (NLI). The time from lesion onset referred to the number of years, which had passed since the injury (range: 1 - 44).

The analyses were all computed via the R framework for statistical analyses (R Development Core Team, 2015). We used the *ggplot2* package (Wickham, 2009) for graphical representations

and the *coin* package (Hothorn, Hornik, van de Wiel, & Zeileis, 2006) to compute the *r* effect sizes for the Mann-Whitney and Wilcoxon tests.

Comparisons between the Control and SCI groups were carried out for motor imagery, personality traits (Mann-Whitney tests, with the *r* index as effect size- small: $0.1 \leq |r| < 0.3$, medium: $0.3 \leq |r| < 0.5$, large: $|r| \geq 0.5$) and clinical data (t-test, using the Cohen's *d* as effect size= small: $0.2 \leq d < 0.5$, medium: $0.5 \leq d < 0.8$, large: $d \geq 0.8$; and χ^2 tests, using odds ratio -OR - as effect size - small: $1.5 \leq OR < 3.5$ or $0.29 < OR \leq 0.67$, medium: $OR \geq 3.5 \leq OR < 9$ or $0.11 < OR \leq 0.29$, large: $OR \geq 9$ or $OR \leq 0.11$).

In order to further investigate specific aspects of imagery (EVI, IVI and KIN) and topography (UL, FB and HS) within each group, 3 Friedman ANOVAs on MI questionnaire scores (Bonferroni corrected) were used for each group. Where necessary, post-hoc testing was carried out by means of Wilcoxon tests (Bonferroni corrected).

Moreover, the presence of any correlative link between motor imagery and clinical SCI-related variables, pain and personality traits were verified by means of ANCOVA tests executed on the scores of the VMIQ-2 subscales (IVI, EVI and KIN) for each action category (FB, HS and UL). For main and interaction effects the η^2 was used as effect size (small: $0.13 > \eta^2 \geq 0.02$, medium: $0.26 > \eta^2 \geq 0.13$, large: $\eta^2 \geq 0.26$; Miles & Shevlin, 2001). Post-hoc analyses were computed by means of t-tests or additional regression analyses (Bonferroni corrected).

3. Results

3.1 The Comparison between Healthy Control (C) and SCI groups

The two groups did not differ in age (C: 40.9 ± 14.7; SCI: 43.04 ± 12.5; $t_{(70)}$ = .647, p = .52, d = 0.16), education (W = 471.5, p = 0.236, *r* = .14) and gender ($\chi^2_{(1)}$= 2.84, p = .09, OR = .31).

3.1.1 Vividness of Motor Imagery

MI of FB action, as assessed by the VMIQ-2, was worse in SCI than C in the two first-person perception subscales: IVI-FB (W = 798.5, p = 0.0039, *r* = .34) and KIN-FB (W = 833, p = 0.001, *r* = .39). By dividing the SCI group into patients with paraplegia and patients with tetraplegia we found that the former but not the latter group significantly differed from the Controls (IVI-FB: W = 121.5, p = .0016, Bonferroni corrected, *r* = -.50; KIN-FB: W = 123.5, p = .0018, Bonferroni corrected, *r* = -.50).

Figure 1 near here

In contrast, in the EVI-FB subscale the difference between SCI and C was not significant (W = 700.5, p = 0.0928, *r* = .20).

The two groups showed similar scores in the upper-body and head/shoulders related questions. Mean and SD in the VMIQ-2 scores are reported in Table 2.

Table 2 near here

3.1.1.1 Differences in imagining movements of different body parts

The scores related to the three body part-related questions in the modified VMIQ-2 have different ranges (FB: from 55 to 11; UL: from 30 to 6; HS: from 15 to 3). Therefore, to allow comparisons between body parts, these scores were scaled from 0 to 1 (see Equation below).

$$scaled\ score = \frac{score - min}{max - min}$$

The Control group scores did not differ for body part (all ps > .11), confirming that the three body part questions are of equal difficulty.

In the *IVI subscale*, paraplegics showed differences between FB (.26 ± .32), UL (.08 ± .14) and HS (.05 ± .09) (Friedman $\chi^2_{(2)} = 11.18$, p = .011, Bonferroni corrected). Post-hoc tests indicate that the difference is significant between IVI-FB and IVI-HS (U = 2, p = .01 Bonferroni corrected, *r* = -.57).

There was also a difference for Tetraplegics due to action topography (Friedman $\chi^2_{(2)}= 24.33$, p < .001, Bonferroni corrected). Nevertheless, the tetraplegic patients had more difficulties imagining full body motor actions from their internal visual perspective, (IVI-FB:.41 ± 31) with respect to both IVI-UL (.18 ± .21, U = 8, p = .001, Bonferroni corrected, *r* = -.77) and IVI-HS (.10 ± .20, U = 205, p = .0178, Bonferroni corrected, *r* = -.77).

In the *EVI subscale*, the scores for the three types of action were significantly different both in Paraplegics (Friedman $\chi^2_{(2)} = 11.15$, p = .012, Bonferroni corrected) and Tetraplegics (Friedman $\chi^2_{(2)} = 22.44$, p < .001, Bonferroni corrected). Again, for patients with paraplegia, EVI-FB actions (.21 ± .26) were more difficult to imagine than HS ones (.05 ± .09) (U = 9, p = .037, Bonferroni corrected, *r* = -.48). For tetraplegics, the FB (.26 ± .37) actions were harder than both EVI-UL (.11 ± .16, U = 176, p = .011, *r* = -.50) and EVI-HS (.09 ± .13, U = 14, p = .006, *r* =-.57).

Finally, in the KIN subscale the results indicate the same trend. There were differences in the patients with paraplegia scores depending on the bodily area (Friedman $\chi^2_{(2)} = 15.08$, p = .0002 Bonferroni corrected). In particular, FB scores (.27 ± .29) were worse than UL scores (.05 ± .11, U = 156, p = .02 Bonferroni corrected, *r* = -.76). For tetraplegics, KIN scores differed (Friedman $\chi^2_{(2)} = 26.05$, p < .001 Bonferroni corrected) and the KIN-FB scores (.42 ± .33) were worse than KIN-UL (.18 ± .25, U = 208, p = .012, *r* = -.58) and KIN-HS scores (.08 ± .18, U = 7, p = .001, *r* =-.80) (Figure 2).

Figure 2 near here

3.1.2 Personality traits

The scores of the SCI and C groups did not differ either in the Tellegen Absorption Scale (Tellegen & Atkinson, 1974) (C: 40.3 ± 15.87; SCI: 33.02 ± 16.3; W = 419, p > .08, *r* = .2) or the Trinity Assessment of Body Plasticity (Desmond et al., 2001) (C: 66.6 ± 9.28; SCI: 68.8 ± 13; W = 559, p = .67, *r* = .05). In the Big Five Inventory (Rammstedt & John, 2007), only the Extraversion subscale showed a difference between the groups, with SCI showing greater extroversion than controls (W = 779.5, p < .01, *r* = .31, SCI group =7.49 ± 1.76; Control group = 6.13 ± 1.98). By further dividing the SCI group into Tetraplegia (T, 7.72 ±1.88) and Paraplegia (P, 7.25 ±1.62), only the T group showed to be more extrovert than the C (W = 163.5, p = .029, Bonferroni corrected, *r* = -.38).

3.1.3 Pain

The two subgroups of SCI subjects more frequently reported neuropathic pain than the Controls (C = 4.35%; SCI = 57.14 %, $\chi^2_{(1)} = 16.01$, p < .001, OR = 29.33;Tetraplegics: 52%, $\chi^2_{(1)} = 10.96$, p < .001

Bonferroni corrected, OR = 23.83; Paraplegics 62.5%, $\chi^2_{(1)} = 15.19$, $p < .001$ Bonferroni corrected, OR = 36.67). The number of people reporting musculoskeletal pain did not differ across the groups (C=47.82%, SCI= 40.81 %, $\chi^2_{(1)} = 0.09$, $p = .76$, OR = 0.75).

Moreover, in the Control group nobody reported visceral pain, while 10 participants in the SCI group reported this type of pain (C = 0 %, SCI =20 %, $\chi^2_{(1)} = 3.88$, $p < .05$). There was no statistically significant difference between the Tetraplegics and Paraplegics subgroups for the frequency of visceral pain (Paraplegics 25%, Tetraplegics 16%).

3.2Effects of Clinical variables

A significant effect of the NLI was found in the IVI-FB subscale ($F_{(1,26)} = 6.67$, $p = .037$, $\eta^2 = .16$) indicating that lesions at higher levels were associated with worse performance. (Figure 3).

Figure 3 near here

The interaction between musculoskeletal pain and the interval from the lesion onset was significant in EVI-FB ($F_{(1,26)} = 4.91$, $p = .036$, $\eta^2 = .16$) and in KIN-FB ($F_{(1,26)} = 6.411$, $p = .018$, $\eta^2 = .20$). By separately analysing EVI-FB data from participants with and without musculoskeletal pain, linear models did not reach statistical significance ($ps \geq .15$) and effect sizes were small ($.02 \leq \eta^2 \leq .10$). Nevertheless, as shown in Figure 4, the EVI-FB imagery was more difficult with longer time since

injury for the patients with muscular pain, while for the patients without muscular pain it showed to be easier with longer time since injury.

Figure 4 near here

Musculoskeletal pain was correlated with a decline in KIN-FB imagery over time ($F_{(1,18)} = 14.971$, $p = .001$, $\eta^2 = .45$) (Figure 5).

Figure 5 near here

The lesion completeness only significantly impacted the scores relating to HS actions (IVI-HS: $F_{(1,26)} = 7.343$, $p = .012$, $\eta^2 = .22$; EVI-HS:$F_{(1,26)} = 6.365$, $p = .018$, $\eta^2 = .20$, KIN-HS: $F_{(1,26)} = 6.778$, $p = .015$, $\eta^2 = .21$). In all these cases, patients with complete lesions had less vivid imagery (IVI-HS: 9.38 ± 4.86; EVI-HS: 9.83 ± 5.94; KIN-HS: 9.25 ± 4.77) than those with incomplete lesions (IVI-HS: 6.30 ± 0.74; EVI-HS: 6.44 ± 1.16; KIN-HS: 6.28 ± .74).

In order to better understand the influence of lesion completeness on MI of HS actions, we further divided the SCI group into Tetraplegics and Paraplegics. We then analysed the differences between T-complete, T-incomplete, P-complete and P-incomplete groups by means of Bonferroni corrected pairwise t-tests. The T-complete group (10.58 ± 6.17) showed worse IVI-HS than the two groups with incomplete lesions (T-incomplete: 6.5 ± .96, $p = .026$; P-incomplete: 6.08 ± .29, $p =$

.013). Similarly, for EVI-HS, the T-complete group (11.5 ± 7.75) had higher scores than the T-incomplete (p = .04, 6.77 ± 1.54) and P-incomplete groups (p = .015, 6.08 ± .29). In contrast, Bonferroni corrected comparisons relating to the KIN-HS scores only showed a worsening, non-significant trend for the T-complete group (9.75 ± 5.8) compared to P-incomplete group (6.08 ± .29, p = .072). Finally, in all cases, clinical aspects did not influence UL scores.

No statistically significant correlation between SCIM-III or Extraversion subscale and the Motor Imagery subscales was found (all ps > .12, Spearman's correlations Bonferroni corrected).

4. Discussion

In this study, the presence of MI deficits after SCI was investigated with a particular focus on the potential effects of the subjects' clinical variables and personality traits. The main result shows a somato-topographical distribution of MI deficits that specifically involves full body actions (that are impossible to perform) but spares the actions relating to upper body parts. Lesion level and completeness, time interval from lesion onset and pain do influence MI. In contrast, no effects due to autonomy in daily life activities and personality traits were found.

4.1 Topographic deficits of MI in SCI

Previous evidence concerning MI after SCI has indicated a dichotomy between behavioural results and neuro-functional data. In fact, behavioural experiments failed to find any connections between motor deficits and MI (Fuentes, Pazzaglia, Longo, Scivoletto, & Haggard, 2013; Hotz-Boendermaker et al., 2008), hinting at the possible absence of links between alterations in efferent and afferent information and MI (Hotz-Boendermaker et al., 2008). However, this result contrasts with neuro-functional data indicating that MI in SCI still engages the central movements networks. In fact,

when asked to imagine moving their paralyzed feet, paraplegic patients strongly activate brain areas corresponding to both the action execution and action imagery network in healthy subjects (Alkadhi et al., 2005). This seeming discrepancy may be explained by hypothesizing that people after SCI (Fiori et al., 2014) use non-standard MI strategies, possibly recruiting additional memory and attention systems. We found some evidence of this when we analysed the interviews we carried out, as some patients reported, for example: "Yes, I *remember* this very well", " I *can see* when I did this action" or "Sometimes, I try *to recall* how I ran". The increased activation found in SCI subjects during MI tasks in prefrontal and parietal areas and the additional recruitment of thalamus, putamen/pallidum and cerebellum (Alkadhi et al., 2005; Hotz-Boendermaker et al., 2008) which are all involved in motor learning and memory also support this hypothesis. Our data also indicate that, when asked about their subjective, aware experience of MI, SCI subjects show a reduction in MI with respect to healthy controls in terms of score at the MI questionnaire. Crucially, however, the difference between SCI subjects and controls does not appear in the third person perspective condition, but exists exclusively in the first person perspective condition. This confirms that poor performance does not reflect a generic reduction in mental imagery, but rather a possible SCI disorder affecting body and actions imagery. Moreover, the differences in MI relating to different body parts indicate that both paraplegic and tetraplegic participants performed worse for actions involving the full body imagery as compared to upper body parts imagery, with a significant effect of the level of lesion, in particular for IVI. Thus, MI disorders in SCI seem to be topographically consistent with the localization of sensorimotor deficits. This novel result indicates that deafferentation and deefferentation play a specific role in MI and supports the notion of an inherent link between action imagination and action execution. Interestingly, the possibility that plastic rearrangements of body representations may follow topographic rules has also been suggested in studies describing how synchronous tactile stimulation of the face and fake hand

induces the rubber hand illusion in SCI (Scandola et al., 2014; Tidoni, Grisoni, Liuzza, & Aglioti, 2014) a result that is compatible with the fact that face and the hand are mapped contiguously in the somatosensory and motor cortices. The finding that paraplegic people exhibit deficits in the visual discrimination of static and dynamic lower limbs is also in accordance with the hypothesis that topographic remapping may occur across sensory modalities and body parts (Pernigo, Moro, Avesani, Miatello, Urgesi, & Aglioti, 2012). Significantly, the lower limb deficit involved both body form and action hinting at a pervasive influence of ongoing body signals on the brain network dedicated to visual body processing (Pernigo et al., 2012). Similarly, impairments in locomotion have been found to affect the capacity to visually perceive point-light-displays of human locomotion (Arrighi, Cartocci, & Burr, 2011). Finally, topographic effects were found in a task involving perceptual judgments. In this task SCI participants observed a series of videos with movement of hands. After the vision participants had to report via keyboard the shortest time in which they and a young adult could accurately perform these movements. The SCI responses were consistent with their actual performance, with worse judgments in participants with cervical lesions as compared to those with below-cervical SCI (Manson, Sayenko, Masani, Goodman, Wong, Popovic, … Welsh, 2014).

To sum up, convergent evidence indicates that the brain networks involved in body-related perception and higher-order cognitive processing of body-related information, such as action recognition, peripersonal space perception (Canzoneri, Marzolla, Amoresano, Verni, & Serino, 2013; Serino, Bassolino, Farnè, & Làdavas, 2007) and motor imagery depend on a continuous, bi-directional flow of information between the brain and the body, and in particular on the integration of motor commands and somatosensory feedback.

4.2 Influence of clinical variables on MI deficits in SCI

Although in self-reported interviews the variability resulting from personality traits and mood might be important, we can exclude these factors in terms of any influence they may have on our main results. In particular, we did not find any SCI vs control differences for suggestibility and absorption (Tellegen Scale) or for the individual disposition to accept changes in one's own body form and surface (BodyTAP). In addition, there were no correlations between the scores in these scales and MI performance.

As for the lesion level, we found that the higher the lesion the worse the MI performance (particularly the IVI subscale). This result confirms the role of deafferentation and deefferentation in MI.

In addition, the completeness of the lesion influences MI of actions involving the head and shoulders in all three subscales (i.e. patients with complete lesions perform worse than those with incomplete lesions), while no difference was found for FB and UL actions. The significance of this distinction between complete and incomplete lesions is difficult to assess due to the great variety of clinical characteristics especially in incomplete lesions: residual functions below the lesion lesion may range from only sensory input to some motor output. A more useful distinction concerning the severity of the lesion is offered by the ASIA Impairment Scale (AIS, Ditunno, Young, Donovan, & Creasey, 1994), according to which the completeness of the lesion is scored along 5 clinical levels, depending on sparing of below lesion-level functions (A: lesion complete; B: spared sensory functions; C and D: increasing spared sensory and motor functions; E: apparently no motor and sensorial consequences). However the AIS scores in our groups of T-incomplete and P-incomplete were very similar (number of AIS<A in P-incomplete: B: 8, C: 1, D: 3; in T-incomplete: B: 7, C: 3, D: 3). We therefore consider the two groups comparable.

The effect of the completeness of the lesion on the MI–HS scores is evident particularly in patients with tetraplegia, where complete lesions are associated with worse MI and in fact tetraplegics affected by complete lesion may be the only ones who are unable to move their head and shoulders. In contrast, patients with incomplete lesions become particularly expert at performing daily life activities using the residual activity of muscles innervated by the spinal accessory nerve (XI cranial nerve), the *plexus cervicalis* (C1-C4) and the plexus brachialis (C4-C8). Residual potential movements are 'hyper-used' in these people a condition that may in some way explain why people with incomplete damage are better at MI than those with complete lesions.

Opposite to our predictions, we did not find any effects of the degree of autonomy in daily life activities to MI performance. We hypothesized that regularly using a body part in everyday activities would be an important factor in terms of maintaining the ability to imagine performing an action with the body part. In contrast, our results suggest that the preservation of afferent/efferent connections between the body parts and the brain is enough to maintain the mental imagery of motor actions.

In fact, in this case, no differences between afferented and deafferented body parts were present.

Another interesting result concerns the effects of pain on MI. As a whole, the frequency of neuropathic pain in our sample is higher than that reported in previous studies (57.14% versus 40%, Vuckovic, Hasan, Fraser, Conway, Nasseroleslami, & Allan, 2014). In addition, the subjects with paraplegia complained more about pain than the participants with tetraplegia. We found visceral pain (20%) to be less frequent than neuropathic pain, without any differences linked to the lesion level. Finally, SCI subjects did not complain about musculoskeletal pain any more frequently than the controls.

Patients with chronic lesions and pain tend to report in our interview less MI (in particular KIN), while no influence of pain is observable in patients without chronic pain. Similarly, in EVI-MI a general detrimental effect of pain over time was recorded, though this trend is not as accentuated as the decline in KIN-MI. In addition, there is an opposite pattern in patients without chronic pain in EVI-MI. This might suggest that, while in the presence of pain MI decreases over time, in the absence of pain people change their MI strategies moving from the first-person towards a third-person perspective.

A reciprocal influence between MI and pain has already been demonstrated (although with different trajectories) in motor imagery tasks based on Brain Computer Interface (Vuckovic et al., 2014). Paraplegic patients with central neuropathic pain achieved higher accuracy and had stronger event related desynchronization than subjects with no pain during a MI task related to hand and feet movements, although there were no statistical differences between body parts (Vuckovic et al., 2014). Unfortunately, in this study the MI perspective was not controlled and we cannot rule out that some compensatory strategies were used. In contrast with this apparent improvement, it has been shown that MI can exacerbate pain and induce dysesthesia in patients without pain sensations (Gustin, Wrigley, Gandevia, Middleton, Henderson, & Siddall, 2008; Bowering, O'Connell, Tabor, Catley, Leake, Moseley, & Stanton, 2013). Neuropathic pain is associated with electrophysiological changes (Boord, Siddall, Tran, Herbert, Middleton, & Craig, 2008; Jensen, Sherlin, Gertz, Braden, Kupper, Gianas, … Hakimian, 2013) and processes of cortical and subcortical reorganization. This involves the primary somatosensory cortex (Henderson, Gustin, Macey, Wrigley, & Siddall, 2011; Wrigley, Press, Gustin, Macefield, Gandevia, Cousins, … Siddall, 2009), as well as the orbitofrontal, dorsolateral prefrontal and parietal cortices, the nucleus accumbens (Gustin, Wrigley, Siddall, & Henderson, 2010) and the thalamus (Gustin et al., 2010).

The widespread nature of these plastic changes may thus explain the contradictory results concerning the effects of pain on MI and at the same time the use of cognitive strategies in order to execute behavioural tasks. Our results indicate that a general reduction in MI is related to pain, while in the absence of pain people spontaneously reduce internal, first-person MI strategies and enhance external, third person perspective strategies. In order to deal with the maladaptive effects of SCI symptoms, people spontaneously move towards new strategies in order to execute MI tasks, which are differently influenced by some clinical variables (Fiori et al., 2014; Hotz-Boendermaker et al., 2008).

5. Conclusions

Our clinical investigation shows that MI in SCI is a very complex function possibly underpinned by multiple cognitive systems and influenced by several clinical variables. We observed that MI in IVI and KIN perspectives might be influenced by the subject's actual body motor control abilities, somato-topically organized. Since IVI and KIN indices are embodied forms of MI (Lorey, Bischoff, Pilgramm, Stark, Munzert, & Zentgraf, 2009), we suggest that our results indicate specific, topographic changes in corporeal awareness in SCI patients (Lenggenhager, Pazzaglia, Scivoletto, Molinari, & Aglioti, 2012; Scandola et al., 2014; Tidoni et al., 2014). This is supported by results regarding the effects of pain, also involving corporeal awareness (Schwoebel et al., 2001). All the changes in the behaviour of SCI patients reflect complex processes of neural cortical and subcortical reorganization. However, this issue requires further investigation in order to achieve a better understanding of how the body can modify the brain and to provide useful information for the design of devices to assist SCI patients and the development of specific programs for MI rehabilitation.

References:

Alkadhi, H., Brugger, P., Boendermaker, S. H., Crelier, G., Curt, A., Hepp-Reymond, M.-C., & Kollias, S. S. (2005). What Disconnection Tells about Motor Imagery: Evidence from Paraplegic Patients. *Cereb. Cortex*, *15*(2), 131–140. doi:10.1093/cercor

Arrighi, R., Cartocci, G., &Burr, D. (2011). Reduced perceptual sensitivity for biological motion in paraplegia patients. *Current Biology*, *21*(22), R910–911. doi:10.1016/j.cub.2011.09.048

Bonda, E., Petrides, M., Frey, S., & Evans, A. (1995). Neural correlates of mental transformations of the body-in-space. *Proceedings of the National Academy of Sciences of the United States of America*, *92*(24), 11180–11184.

Boord, P., Siddall, P. J., Tran, Y., Herbert, D., Middleton, J., & Craig, A. (2008). Electroencephalographic slowing and reduced reactivity in neuropathic pain following spinal cord injury. *Spinal Cord*, *46*(2), 118–123. doi:10.1038/sj.sc.3102077

Bouhassira, D., Attal, N., Alchaar, H., Boureau, F., Brochet, B., Bruxelle, J., … Vicaut, E. (2005). Comparison of pain syndromes associated with nervous or somatic lesions and development of a new neuropathic pain diagnostic questionnaire (DN4). *Pain*, *114*(1-2), 29–36. doi:10.1016/j.pain.2004.12.010

Bowering, K. J., O'Connell, N. E., Tabor, A., Catley, M. J., Leake, H. B., Moseley, G. L., & Stanton, T. R. (2013). The effects of graded motor imagery and its components on chronic pain: a systematic

review and meta-analysis. *The Journal of Pain: Official Journal of the American Pain Society*, *14*(1), 3–13. doi:10.1016/j.jpain.2012.09.007

Canzoneri, E., Marzolla, M., Amoresano, A., Verni, G., & Serino, A. (2013). Amputation and prosthesis implantation shape body and peripersonal space representations. *Scientific Reports*, *3*, 2844. doi:10.1038/srep02844

Caraceni, A., Mendoza, T. R., Mencaglia, E., Baratella, C., Edwards, K., Forjaz, M. J., … Cleeland, C. S. (1996). A validationstudy of an Italianversion of the Brief Pain Inventory (Breve Questionario per la Valutazione del Dolore). *Pain*, *65*(1), 87–92.

Conson, M., Sacco, S., Sarà, M., Pistoia, F., Grossi, D., &Trojano, L. (2008). Selective motor imagery defect in patients with locked-in syndrome. *Neuropsychologia*, *46*(11), 2622–2628. doi:10.1016/j.neuropsychologia.2008.04.015

Corradi-Dell'Acqua, C., Tomasino, B., &Fink, G. R. (2009). What Is the Position of an Arm Relative to the Body? Neural Correlates of Body Schema and Body Structural Description. *Journal of Neuroscience*, *29*(13), 4162–4171. doi:10.1523/JNEUROSCI.4861-08.2009

Coslett, H. B., Medina, J., Kliot, D., &Burkey, A. R. (2010). Mental motor imagery indexes pain: The hand laterality task. *European Journal of Pain*, *14*(10), 1007–1013. doi:10.1016/j.ejpain.2010.04.001

Cramer, S. C., Orr, E. L. R., Cohen, M. J., &Lacourse, M. G. (2007). Effects of motor imagery training after chronic, complete spinal cord injury. *Experimental Brain Research*, *177*(2), 233–242. doi:10.1007/s00221-006-0662-9

Decety, J. (1996). Neural representations for action. *Reviews in the Neurosciences*, *7*(4), 285–97.

Decety, J., & Boisson, D. (1990). Effect of brain and spinal cord injuries on motor imagery. *European Archives of Psychiatry and Clinical Neuroscience*, *240*(1), 39–43. doi:10.1007/BF02190091

Desmond, D., Horgan, O., & MacLachlan, M. (2001). Body boundary appraisals and the measurement of plasticity: development of the Trinity Assessment of Body Plasticity (TABP). In *10th World Congress of the International Society for Prosthetics and Orthotics, Glasgow*.

Di Rienzo, F., Collet, C., Hoyek, N., & Guillot, A. (2014). Impact of Neurologic Deficits on Motor Imagery: A Systematic Review of Clinical Evaluations. *Neuropsychology Review*, *24*(2), 116–147. doi:10.1007/s11065-014-9257-6

Ditunno, J. F., Young, W., Donovan, W. H., & Creasey, G. (1994). The International Standards Booklet for Neurological and Functional Classification of Spinal Cord Injury. *Paraplegia*, *32*(2), 70–80. doi:10.1038/sc.1994.13

Fiori, F., Sedda, A., Ferrè, E. R., Toraldo, A., Querzola, M., Pasotti, F., … Bottini, G. (2013). Exploring motor and visual imagery in Amyotrophic Lateral Sclerosis. *Experimental Brain Research*, *226*(4), 537–47. doi:10.1007/s00221-013-3465-9

Fiori, F., Sedda, A., Ferrè, E. R., Toraldo, A., Querzola, M., Pasotti, F., … Bottini, G. (2014). Motor imagery in spinal cord injury patients: moving makes the difference. *Journal of Neuropsychology*, *8*(2), 199–215. doi:10.1111/jnp.12020

Fiorio, M., Tinazzi, M., & Aglioti, S. M. (2006). Selective impairment of hand mental rotation in patients with focal hand dystonia. *Brain: A Journal of Neurology*, *129*(1), 47–54. doi:10.1093/brain

Fourkas, A. D., Ionta, S., & Aglioti, S. M. (2006). Influence of imagined posture and imagery modality on corticospinal excitability. *Behavioural Brain Research*, *168*(2), 190–6. doi:10.1016/j.bbr.2005.10.015

Fuentes, C. T., Pazzaglia, M., Longo, M. R., Scivoletto, G., & Haggard, P. (2013). Body image distortions following spinal cord injury. *Journal of Neurology, Neurosurgery & Psychiatry*, *84*(2), 201–207. doi:10.1136/jnnp-2012-304001

Gerardin, E., Sirigu, A., Lehéricy, S., Poline, J. B., Gaymard, B., Marsault, C., … Le Bihan, D. (2000). Partially overlapping neural networks for real and imagined hand movements. *Cerebral Cortex (New York, N.Y.: 1991)*, *10*(11), 1093–104.

Glidden, H., Rizzuto, D., & Andersen, R. (2005). Localizing neuroprosthetic implant targets with fMRI: premotor, supplementary motor, and parietal regions. In *Annual Meeting of the Society of Neuroscience*.

Gustin, S. M., Wrigley, P. J., Gandevia, S. C., Middleton, J. W., Henderson, L. A., & Siddall, P. J. (2008). Movement imagery increases pain in people with neuropathic pain following complete thoracic spinal cord injury. *Pain*, *137*(2), 237–244. doi:10.1016/j.pain.2007.08.032

Gustin, S. M., Wrigley, P. J., Siddall, P. J., & Henderson, L. A. (2010). Brain anatomy changes associated with persistent neuropathic pain following spinal cord injury. *Cerebral Cortex (New York, N.Y.: 1991)*, *20*(6), 1409–19. doi:10.1093/cercor/bhp205

Henderson, L. A., Gustin, S. M., Macey, P. M., Wrigley, P. J., & Siddall, P. J. (2011). Functional Reorganization of the Brain in Humans Following Spinal Cord Injury: Evidence for Underlying

Changes in Cortical Anatomy. *The Journal of Neuroscience*, *31*(7), 2630 –2637. doi:10.1523/JNEUROSCI.2717-10.2011

Hothorn, T., Hornik, K., van de Wiel, M. A., & Zeileis, A. (2006). A Lego System for Conditional Inference. *The American Statistician*, *60*(3), 257–263.

Hotz-Boendermaker, S., Funk, M., Summers, P., Brugger, P., Hepp-Reymond, M.-C., Curt, A., & Kollias, S. S. (2008). Preservation of motor programs in paraplegics as demonstrated by attempted and imagined foot movements. *NeuroImage*, *39*(1), 383–394. doi:10.1016/j.neuroimage.2007.07.065

Invernizzi, M., Carda, S., Milani, P., Mattana, F., Fletzer, D., Iolascon, G., … Cisari, C. (2010). Development and validation of the Italian version of the Spinal Cord Independence Measure III. *Disability and Rehabilitation*, *32*(14), 1194–203. doi:10.3109/09638280903437246

Ionta, S., Fourkas, A. D., & Aglioti, S. M. (2010). Egocentric and object-based transformations in the laterality judgement of human and animal faces and of non-corporeal objects. *Behavioural Brain Research*, *207*(2), 452–457. doi:10.1016/j.bbr.2009.10.037

Ionta, S., Fourkas, A. D., Fiorio, M., & Aglioti, S. M. (2007). The influence of hands posture on mental rotation of hands and feet. *Experimental Brain Research*, *183*(1), 1–7. doi:10.1007/s00221-007-1020-2

Isaac, A., Marks, D. F., & Russell, D. G. (1986). An instrument for assessing imagery of movement: The Vividness of Movement Imagery Questionnaire (VMIQ). *Journal of Mental Imagery*, *10*(4), 23–30.

Jackson, P. L., Lafleur, M. F., Malouin, F., Richards, C., & Doyon, J. (2001). Potential role of mental practice using motor imagery in neurologic rehabilitation. *Archives of Physical Medicine and Rehabilitation*, *82*(8), 1133–1141. doi:10.1053/apmr.2001.24286

Jensen, M. P., Sherlin, L. H., Gertz, K. J., Braden, A. L., Kupper, A. E., Gianas, A., … Hakimian, S. (2013). Brain EEG activity correlates of chronic pain in persons with spinal cord injury: clinical implications. *Spinal Cord*, *51*(1), 55–58. doi:10.1038/sc.2012.84

Kirshblum, S. C., Burns, S. P., Biering-Sorensen, F., Donovan, W., Graves, D. E., Jha, A., … Waring, W. (2011). International standards for neurological classification of spinal cord injury (Revised 2011). *Journal of Spinal Cord Medicine*, *34*(6), 535–546. doi:10.1179/204577211X13207446293695

Lacourse, M. G., Cohen, M. J., Lawrence, K. E., & Romero, D. H. (1999). Cortical potentials during imagined movements in individuals with chronic spinal cord injuries. *Behavioural Brain Research*, *104*(1-2), 73–88.

Lenggenhager, B., Pazzaglia, M., Scivoletto, G., Molinari, M., & Aglioti, S. M. (2012). The sense of the body in individuals with spinal cord injury. *PloS One*, *7*(11), e50757. doi:10.1371/journal.pone.0050757

Lorey, B., Bischoff, M., Pilgramm, S., Stark, R., Munzert, J., & Zentgraf, K. (2009). The embodied nature of motor imagery: the influence of posture and perspective. *Experimental Brain Research*, *194*(2), 233–243. doi:10.1007/s00221-008-1693-1

Manson, G. A., Sayenko, D. G., Masani, K., Goodman, R., Wong, L., Popovic, M. R., … Welsh, T. N. (2014). Action possibility judgments of people with varying motor abilities due to spinal cord injury. *PloS One*, *9*(10), e110250. doi:10.1371/journal.pone.0110250

Melzack, R. (1987). The short-form McGill pain questionnaire. *Pain*, *30*(2), 191–197. doi:10.1016/0304-3959(87)91074-8

Miles, J., & Shevlin, M. (2001). *Applying Regression and Correlation: A Guide for Students and Researchers*. (J. Miles & M. Shevlin, Eds.) (p. 272). London: SAGE Publications.

Moro, V., Pernigo, S., Zapparoli, P., Cordioli, Z., & Aglioti, S. M. (2011). Phenomenology and neural correlates of implicit and emergent motor awareness in patients with anosognosia for hemiplegia. *Behavioural Brain Research*, *225*(1), 259–269. doi:10.1016/j.bbr.2011.07.010

Nikulin, V. V, Hohlefeld, F. U., Jacobs, A. M., & Curio, G. (2008). Quasi-movements: a novel motor-cognitive phenomenon. *Neuropsychologia*, *46*(2), 727–742. doi:10.1016/j.neuropsychologia.2007.10.008

Pernigo, S., Moro, V., Avesani, R., Miatello, C., Urgesi, C., & Aglioti, S. M. (2012). Massive somatic deafferentation and motor deefferentation of the lower part of the body impair its visual recognition: a psychophysical study of patients with spinal cord injury. *The European Journal of Neuroscience*. doi:10.1111/j.1460-9568.2012.08266.x

R Development Core Team. (2015). R: A Language and Environment for Statistical Computing. Vienna, Austria.

Rammstedt, B., & John, O. P. (2007). Measuring personality in one minute or less: A 10-item short version of the Big Five Inventory in English and German. *Journal of Research in Personality*, *41*(1), 203–212. doi:10.1016/j.jrp.2006.02.001

Roberts, R., Callow, N., Hardy, L., Markland, D., & Bringer, J. (2008). Movement imagery ability: development and assessment of a revised version of the vividness of movement imagery questionnaire. *Journal of Sport & Exercise Psychology*, *30*(2), 200–221.

Scandola, M., Tidoni, E., Avesani, R., Brunelli, G., Aglioti, S. M., & Moro, V. (2014). Rubber hand illusion induced by touching the face ipsilaterally to a deprived hand: evidence for plastic "somatotopic" remapping in tetraplegics. *Frontiers in Human Neuroscience*, *8*, 404. doi:10.3389/fnhum.2014.00404

Schwoebel, J., Friedman, R., Duda, N., & Coslett, H. B. (2001). Pain and the body schema: evidence for peripheral effects on mental representations of movement. *Brain: A Journal of Neurology*, *124*(10), 2098–2104. doi:10.1093/brain/124.10.2098

Serino, A., Bassolino, M., Farnè, A., & Làdavas, E. (2007). Extended multisensory space in blind cane users. *Psychological Science*, *18*(7), 642–648. doi:10.1111/j.1467-9280.2007.01952.x

Stephan, K. M., Fink, G. R., Passingham, R. E., Silbersweig, D., Ceballos-Baumann, A. O., Frith, C. D., & Frackowiak, R. S. (1995). Functional anatomy of the mental representation of upper extremity movements in healthy subjects. *Journal of Neurophysiology*, *73*(1), 373–386.

Stephan, K. M., & Frackowiak, R. S. (1996). Motor imagery-anatomical representation and electrophysiological characteristics. *Neurochemical Research*, *21*(9), 1105–1116.

Tellegen, A., & Atkinson, G. (1974). Openess to absorbing and self-altering experiences ("absorption"), a trait related to hypnotic susceptibility. *Journal of Abnormal Psychology*, *83*(3), 268–277.

Tidoni, E., Grisoni, L., Liuzza, M. T., & Aglioti, S. M. (2014). Rubber hand illusion highlights massive visual capture and sensorimotor face-hand remapping in a tetraplegic man. *Restorative Neurology and Neuroscience*, *32*(5), 611–622.

Vuckovic, A., Hasan, M. A., Fraser, M., Conway, B. A., Nasseroleslami, B., & Allan, D. B. (2014). Dynamic Oscillatory Signatures of Central Neuropathic Pain in Spinal Cord Injury. *The Journal of Pain: Official Journal of the American Pain Society*, *15*(6), 645–655. doi:10.1016/j.jpain.2014.02.005

Wickham, H. (2009). ggplot2: elegant graphics for data analysis. Springer New York.

Wrigley, P. J., Press, S. R., Gustin, S. M., Macefield, V. G., Gandevia, S. C., Cousins, M. J., … Siddall, P. J. (2009). Neuropathic pain and primary somatosensory cortex reorganization following spinal cord injury. *Pain*, *141*(1-2), 52–59. doi:10.1016/j.pain.2008.10.007

Figures:

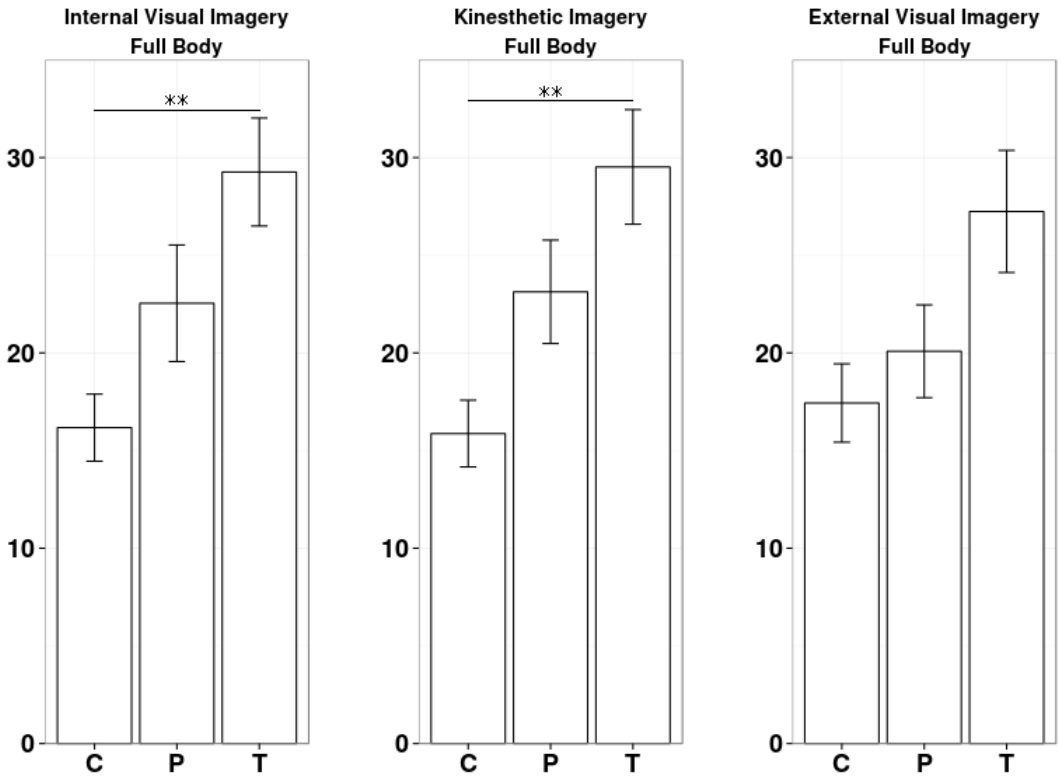


Figure 1: Full-body actions imagery. The mean and standard errors for VMIQ-2 scores relating to IVI-FB, KIN-FB and EVI-FB scores are reported for each group. Higher values mean greater difficulty in MI. Points represent the individual scores. ** = $p < .01$; C: Control group, P: Paraplegic subgroup, T: Tetraplegic subgroup.

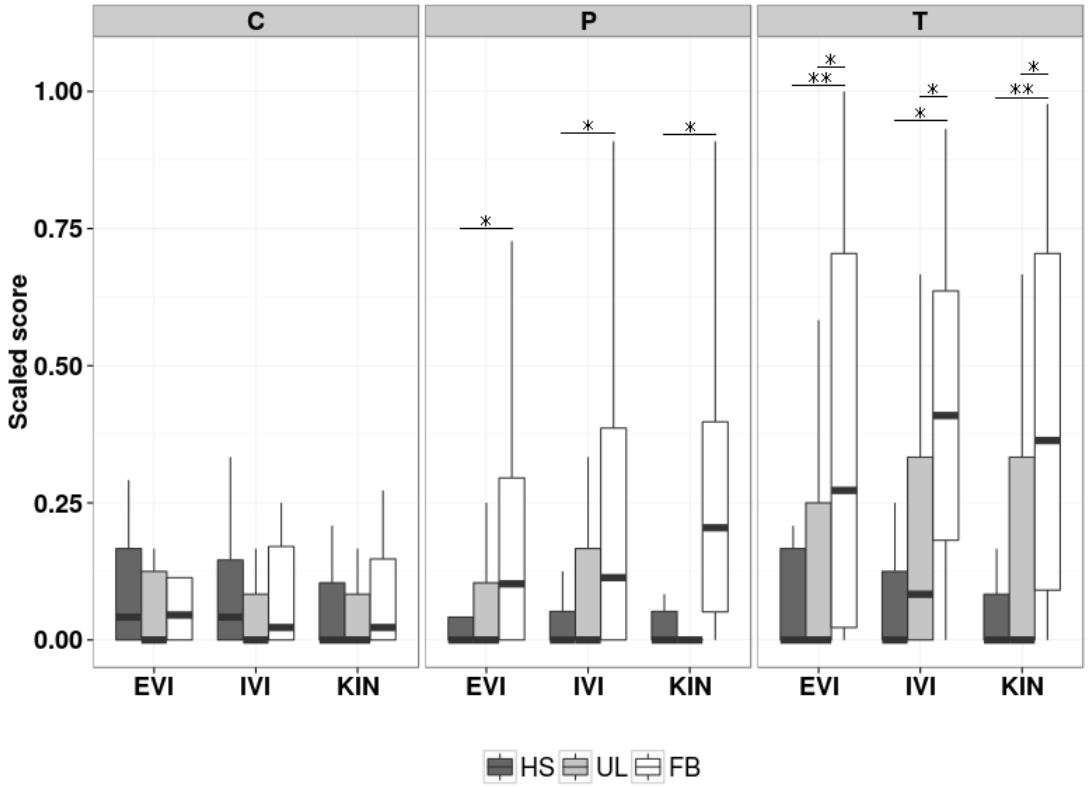


Figure 2: Scaled scores in the modified VMIQ-2. Scores are divided for groups (C: Control group, P: Paraplegic subgroup, T: Tetraplegic subgroup), subscales (EVI: External Visual Imagery, IVI: Internal Visual Imagery, KIN: Kinaesthetic Imagery), and body parts (HS: mouth, head, shoulders, UL: trunk and upper limbs, FB: lower limbs and full-body). . The central line represents the median, the top and the bottom of the box are the first and third quartiles, and the whiskers are the Inter Quartile Range of the lower and of the upper quartile multiplied by 1.5. * = $p < .05$, ** = $p < .01$.

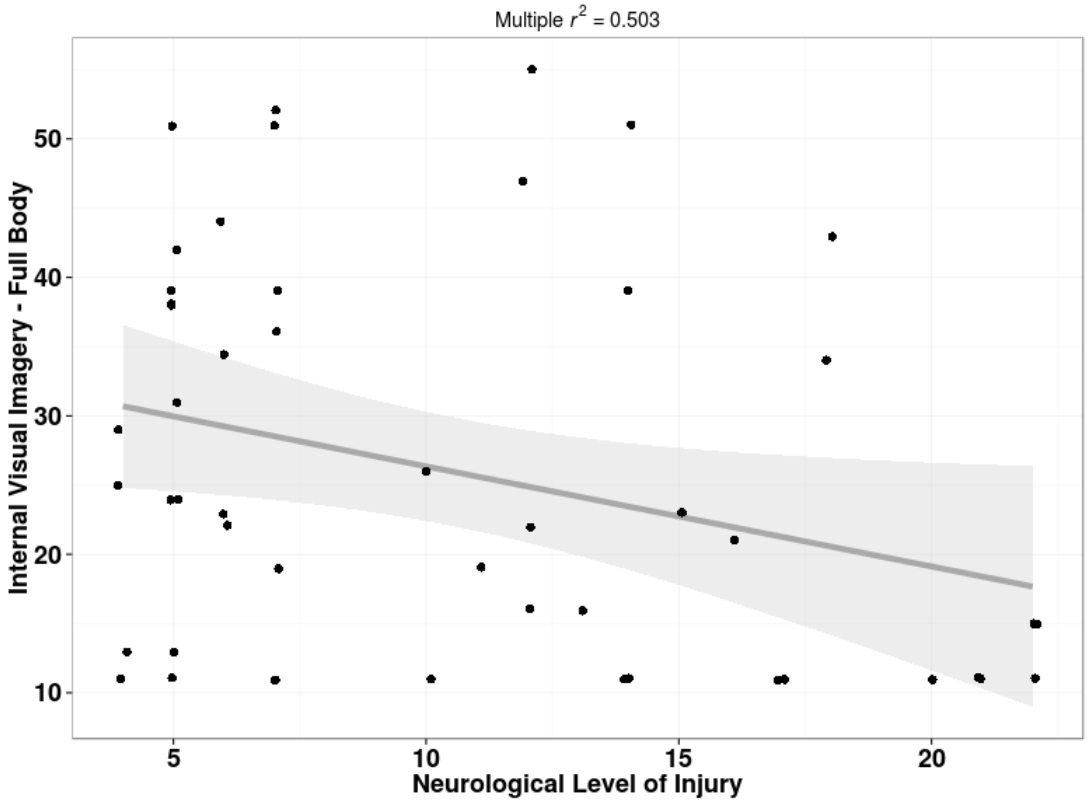


Figure 3: Neurological level of lesion and MI. SCI participants with more caudal NLI show worse "Internal Visual Imagery" (higher scores in IVI correspond to worse performance). Points represent the individual scores. NLI: C1-C8: 1-8, T1-T12: 9-20, L1-L5: 21-25, S1-S5: 26-30. Multiple r2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit)

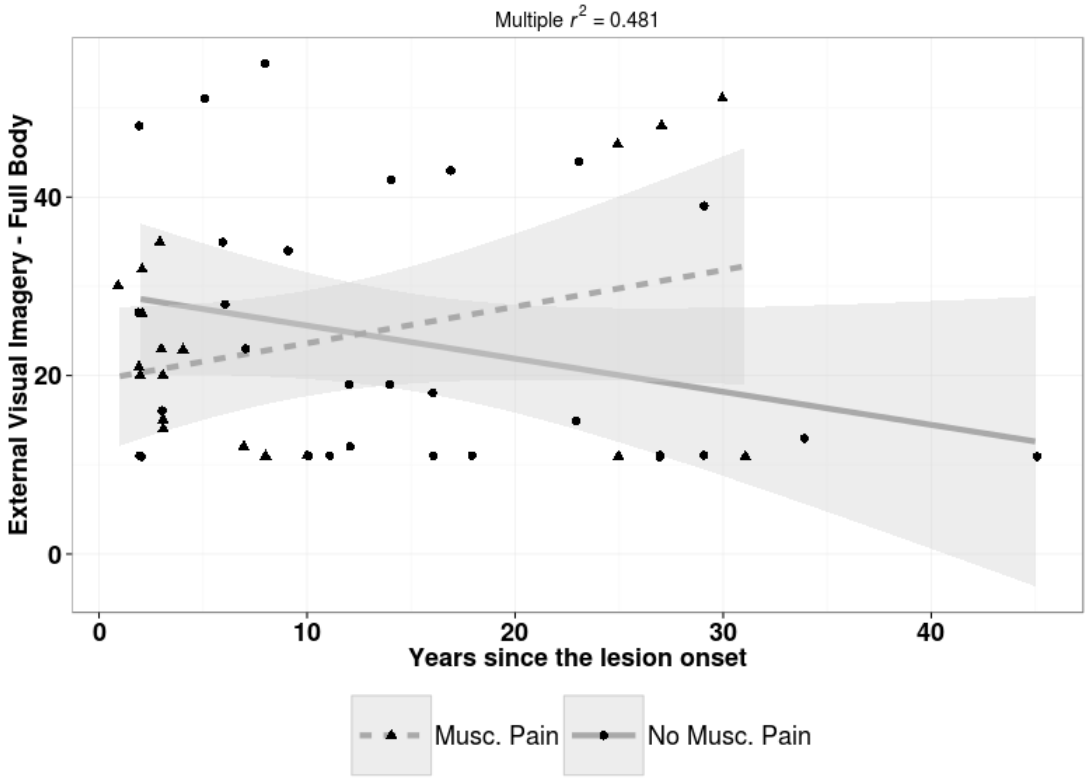


Figure 4: Pain and EVI. Regressions on VMIQ-2 scores relating to “External Visual Imagery” for full-body actions show an opposite pattern over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit)

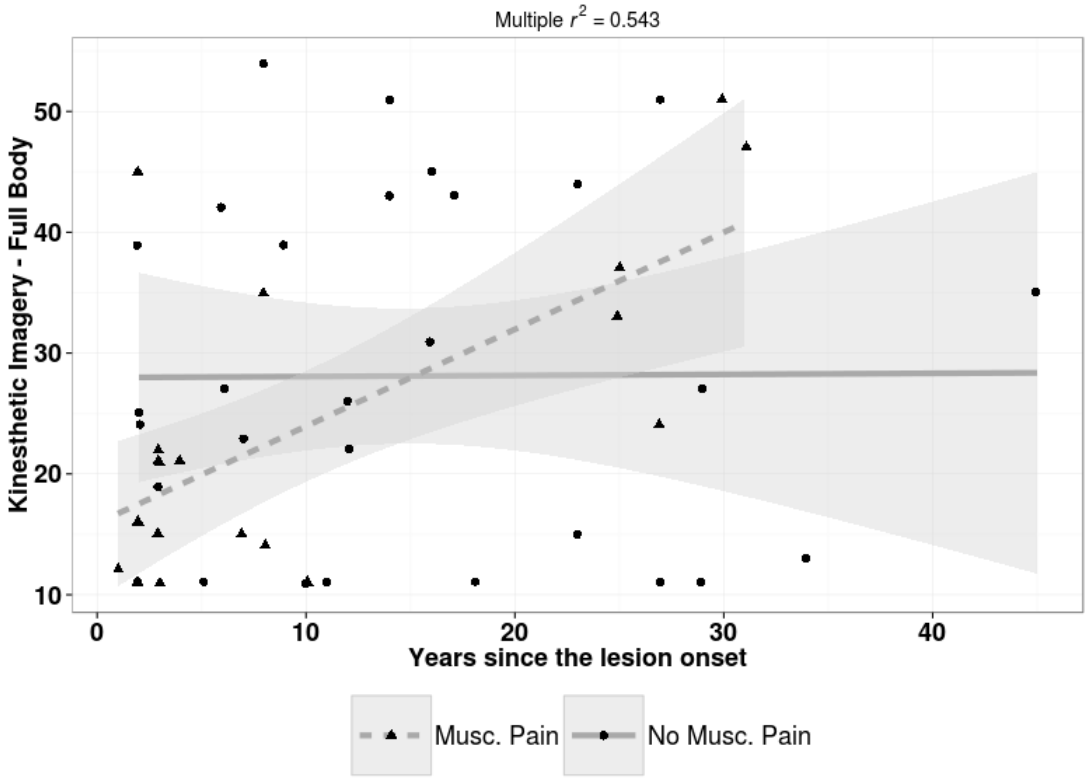


Figure 5: Pain and KIN. Regressions on VMIQ-2 scores relating to “Kinaesthetic Imagery” for full-body actions show a flat trend over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit)

Captions

Figure 1: Full-body actions imagery. The mean and standard errors for VMIQ-2 scores relating to IVI-FB, KIN-FB and EVI-FB scores are reported for each group. Higher values mean greater difficulty in MI. Points represent the individual scores. ** = $p < .01$; C: Control group, P: Paraplegic subgroup, T: Tetraplegic subgroup

Figure 2: Scaled scores in the modified VMIQ-2. Scores are divided for groups (C: Control group, P: Paraplegic subgroup, T: Tetraplegic subgroup), subscales (EVI: External Visual Imagery, IVI: Internal Visual Imagery, KIN: Kinaesthetic Imagery), and body parts (HS: mouth, head, shoulders, UL: trunk and upper limbs, FB: lower limbs and full-body). . The central line represents the median, the top and the bottom of the box are the first and third quartiles, and the whiskers are the Inter Quartile Range of the lower and of the upper quartile multiplied by 1.5. * = $p < .05$, ** = $p < .01$.

Figure 3: Neurological level of lesion and MI. SCI participants with more caudal NLI show worse "Internal Visual Imagery" (higher scores in IVI correspond to worse performance). Points represent the individual scores. NLI: C1-C8: 1-8, T1-T12: 9-20, L1-L5: 21-25, S1-S5: 26-30. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit)

Figure 4: Pain and EVI. Regressions on VMIQ-2 scores relating to "External Visual Imagery" for full-body actions show an opposite pattern over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, that stands for perfect fit)

Figure 5: Pain and KIN. Regressions on VMIQ-2 scores relating to “Kinaesthetic Imagery” for full-body actions show a flat trend over time, due to the presence or absence of musculoskeletal pain. Points represent the individual score. Multiple r^2 values are reported as index of goodness of fit of the model (from 0 to 1, 1 stands for perfect fit)

Tables

Subject	AIS	NLI	G	age	Ed	Hd	Job	Int	D	SCIM-3
Pc 1	A	T8	M	44	8	R	6	1		54
Pc 2	A	T7	M	48	13	R	3	4	T	75
Pc 3	A	T6	M	29	8	R	-	7	T	75
Pc 4	A	T4	M	72	5	R	6	3	T	35
Pc 5	A	T10	M	44	8	R	1	3	T	74
Pc 6	A	T9	M	43	8	R	-	3	T	71
Pc 7	A	T5	M	28	8	R	4	4	T	68
Pc 8	A	T5	M	48	8	R	-	25	T	75
Pc 9	A	T10	F	54	13	R	4	31	T	72
Pc 10	A	T3	M	34	13	R	3	2	T	71
Pc 11	A	T11	M	48	13	R	6	29	T	72
Pc 12	A	T7	M	34	8	R	-	2	T	72
Pi 1	B	T7	M	41	17	R	9	2	T	36
Pi 2	B	T3	M	25	13	R	3	10	T	76
Pi 3	B	T5	M	61	17	R	4	2	p Sur	72
Pi 4	B	T7	F	64	8	R	R	2	p Sur	39
Pi 5	B	T5	M	24	8	R	4	2	T	73
Pi 6	B	T11	M	39	17	R	2	17	T	73
Pi 7	C	L2	M	50	13	R	3	27	T	73
Pi 8	D	L3	M	26	8	R	-	2	T	89
Pi 9	D	L3	M	34	8	R	6	9	T	100

Pi 10	B	L2	M	46	8	R	4	29	T	75
Pi 11	B	L1	M	42	8	R	-	8	T	60
Pi 12	D	L3	F	42	13	R	3	23	T	100
Tc 1	A	C5	F	30	8	R	4	15	T	15
Tc 2	A	C4	M	72	5	R	R	3	T	15
Tc 3	A	C5	M	46	8	R	6	1	T	24
Tc 4	A	C5	M	30	17	R	3	12	T	48
Tc 5	A	C7	M	44	13	R	4	27	T	54
Tc 6	A	C7	M	37	17	R	3	12	T	64
Tc 7	A	C5	M	63	13	R	1	44	T	63
Tc 8	A	C7	M	39	8	R	6	8	T	67
Tc 9	A	C4	M	51	8	R	-	33	T	19
Tc 10	A	C7	M	45	8	R	4	27	T	67
Tc 11	A	C7	M	39	17	R	4	8	T	50
Tc 12	A	C4	M	43	17	R	2	16	T	15
Ti 1	B	C6	M	29	13	R	-	7	T	47
Ti 2	B	C5	M	48	8	R	-	1	T	61
Ti 3	D	C5	M	41	8	R	-	3	T	85
Ti 4	D	C4	M	21	13	R	-	6	T	99
Ti 5	B	C7	M	37	13	R	-	18	T	74
Ti 6	C	C6	M	20	13	R	S	6	T	66
Ti 7	D	C6	M	57	8	R	8	6	T	99
Ti 8	B	C5	F	54	13	R	R	14	T	31
Ti 9	B	C5	M	26	13	R	-	24	T	75
Ti 10	B	C7	M	55	17	R	R	13	T	58

Ti 11	B	C5	M	34	13	R	3	11	T	67
Ti 12	C	C6	F	40	13	R	-	23	T	75
Ti 13	C	C5	F	55	13	R	-	29	T	67

Table 1. **SCI clinical and demographic data**. Pc = complete paraplegia (AIS=A); Pi = incomplete paraplegia; Tc = complete tetraplegia (AIS = A); Ti = incomplete tetraplegia; AIS = Asia Impairment Scale; NLI = neurological level of injury; G = gender; Ed = education; Hd = handedness (R = right); Job = numbers correspond to the job categories of the ISTAT (Italian National Institute of Statistic):1:managers, 2: intellectual and scientific jobs, 3: technical jobs; 4: secretarial jobs, 5: commercial jobs, 6: artisans, specialized workers and farmers;7: industrial workers; 8: unskilled jobs; 9: armed forces; R: retired; - = unemployed; Int = Interval from lesion in years; D = damage; T = traumatic; p-Sur = post-Surgery; SCIM-3 = spinal cord independence measure, ranging from a minimum of 0 (complete dependence) to a maximum of 100 (complete independence).

		SCI	C	P	T
IVI	*FB*	**25.9 ± 14**	16.17 ± 8.05	22.54 ± 14.31	**29.26 ± 13.53**
	UL	4.58 ± 2.22	4.26 ± 2.49	3.96 ± 1.63	5.18 ± 2.57
	HS	7.81 ± 3.74	9.13 ± 5.33	7.12 ± 2.25	8.46 ± 4.72
EVI	*FB*	23.73 ± 13.87	17.43 ± 9.41	20.08 ± 11.40	27.24 ± 15.31
	UL	4.39 ± 2.41	4.09 ± 1.88	3.79 ± 1.35	4.96 ± 3.03
	HS	8.10 ± 4.53	9.35 ± 5.69	7.12 ± 2.19	9.04 ± 5.88
KIN	*FB*	**26.39 ± 13.8**	15.87 ± 8.01	23.12 ± 12.69	**29.52 ± 14.38**
	UL	4.37 ± 2.45	3.74 ± 1.51	3.58 ± 1.35	5.12 ± 3.02
	HS	7.73 ± 3.66	8.04 ± 4.24	7.42 ± 2.87	8.04 ± 4.32

Table 2. **VMIQ-2 scores**. Mean ± Standard Deviation for the modified VMIQ-2 scale, divided by group (SCI: spinal cord injury, C: control, P: paraplegic, T: tetraplegic), subscale (IVI: Internal Visual Imagery, EVI: External Visual Imagery, KIN: Kinaesthetic Motor Imagery) and body area (FB: lower limbs and full body, range: 55-11; UL: trunk and upper limbs, range: 30-6, HS: mouth, head and shoulders, range: 15-3. Higher values mean greater difficulty in MI. The SCI group is further divided into P and T subgroups. The values, which are significantly different from the C group are shown in bold.

Supplementary Materials

VR-Pain scale

This is a "trait" version of a scale related to pain. The main idea consists of exploring the pain sensations experienced by SCI subjects and the most frequent terms used to report them. Hereafter only the pain sensations identified and the associated descriptive terms will be used in the "state" scale.

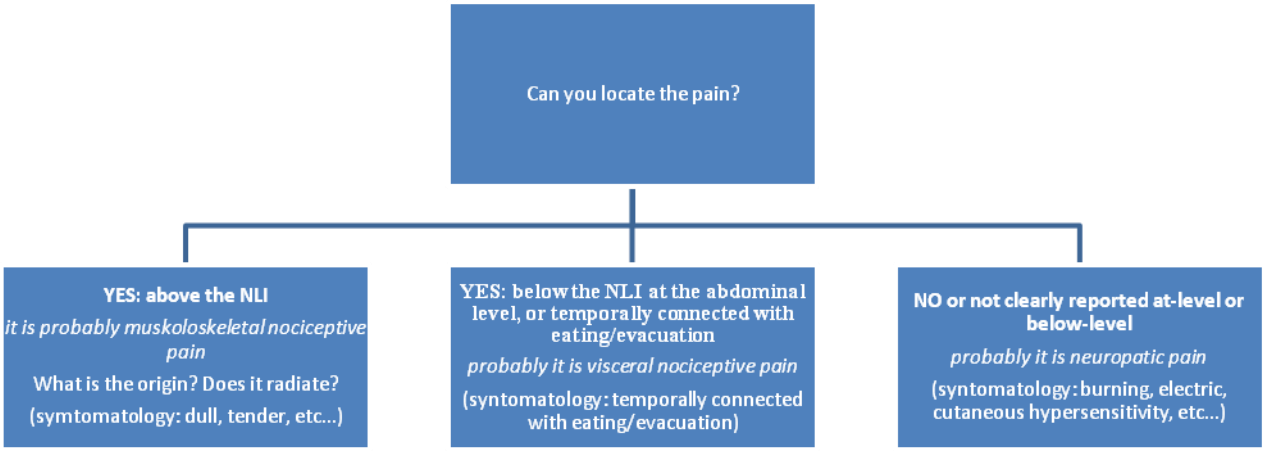
TRAIT:

Now we will ask you some questions concerning any sensations of physical pain that you feel or have felt since your spinal cord injury. The questions not only refer to the present moment, but also to all the sensations of pain that you may feel with greater frequency. We ask you to consider each pain sensation separately.

Neurological Level of Injury (NLI[1]): ____
At-level pain: NLI + three dermatomes below. From ____ to ____
Below-level pain: four dermatomes below NLI. From ____
Above-level pain: above NLI. From ____

[1] With NLI we mean radicular level

For each sensation of pain
ask:



Musculoskeletal nociceptive pain

Origin:

_____

Irradiations:

_____

1. What is the greatest intensity of pain you have ever felt during the worst phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

2. What is the lowest intensity of pain you have ever felt in the best phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

3. What is the frequency of the sensation of pain?

Almost constantly	More than once per day	Once per day	More than once per week	More than once per month	Hardly ever

4. Are there any movements or specific situations that increase, diminish or change the pain sensation?

_____
_____
_____
_____
_____
_____

5. Is it a sharp pain?

0	1	2	3	4	5	6	7	8	9	10

6. Is it dull?

0	1	2	3	4	5	6	7	8	9	10

7. Is it a cramping pain?

0	1	2	3	4	5	6	7	8	9	10

8. Does it tremble?

0 1 2 3 4 5 6 7 8 9 10

9. Does it vibrate?

0 1 2 3 4 5 6 7 8 9 10

10. Does it throb (pulsate)?

0 1 2 3 4 5 6 7 8 9 10

11. Is it a dull beating pain?

0 1 2 3 4 5 6 7 8 9 10

12. Is it a hammering pain?

0 1 2 3 4 5 6 7 8 9 10

1. How long does this pain last?

A few seconds	A few minutes	A few hours	More or less a day	More than a day	More than a week

Visceral nociceptive pain

Origin:

_____

1. What is the greatest intensity of pain you have ever felt during the worst phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

2. What is the lowest intensity of pain you have ever felt in the best phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

3. Which is the frequency of the pain sensation?

Almost constantly	More than once per day	Once per day	More than once per week	More than once per month	Hardly ever

4. Are there any movements or specific situations that increase, diminish or change the pain sensation?

(eating, going to the toilet, etc…)

_____
_____
_____
_____
_____
_____

5. Is it a sharp pain?

0	1	2	3	4	5	6	7	8	9	10

6. Is it dull?

0	1	2	3	4	5	6	7	8	9	10

7. Is it a cramping pain?

0	1	2	3	4	5	6	7	8	9	10

8. Does it tremble?

0 1 2 3 4 5 6 7 8 9 10

9. Does it vibrate?

0 1 2 3 4 5 6 7 8 9 10

10. Does it throb (pulsate)?

0 1 2 3 4 5 6 7 8 9 10

11. Is it a dull beating pain?

0 1 2 3 4 5 6 7 8 9 10

12. Is it a hammering pain?

0 1 2 3 4 5 6 7 8 9 10

1. Is it associated with migraine?

0 1 2 3 4 5 6 7 8 9 10

2. Is it associated with hypertension?

0 1 2 3 4 5 6 7 8 9 10

3. Is it associated with bradycardia?

0 1 2 3 4 5 6 7 8 9 10

4. Is it associated with sweating?

0 1 2 3 4 5 6 7 8 9 10

5. Is it associated with urinary retention?

0 1 2 3 4 5 6 7 8 9 10

1. How long does this pain last?

A few seconds	A few minutes	A few hours	More or less a day	More than a day	More than a week

Neuropathic pain

Origin:

_____

1. What is the greatest intensity of pain you have ever felt during the worst phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

1. What is the lowest intensity of pain you have ever felt in the best phase:

0	1	2	3	4	5	6	7	8	9	10
No pain										Maximum imaginable intensity

2. Which is the frequency of the pain sensation?

Almost constantly	More than once per day	Once per day	More than once per week	More than once per month	Hardly ever

1. Is it sharp?

0	1	2	3	4	5	6	7	8	9	10

2. Does it burn?

0	1	2	3	4	5	6	7	8	9	10

3. Is it dull?

0	1	2	3	4	5	6	7	8	9	10

4. Is it cold?

0	1	2	3	4	5	6	7	8	9	10

5. When you feel this pain, is your skin hypersensitive to light touching and rubbing?

0	1	2	3	4	5	6	7	8	9	10

6. Is it tingly?

0	1	2	3	4	5	6	7	8	9	10

7. Is it similar to an electrical shock?

0	1	2	3	4	5	6	7	8	9	10

1. How long does this pain last?

A few seconds	A few minutes	A few hours	More or less a day	More than a day	More than a week

Psychosocial Assessment (Middleton 2002):

Does the pain affect your ability to take part in daily activities, including sleep?

0	1	2	3	4	5	6	7	8	9	10

Does the pain affect your mood?

0	1	2	3	4	5	6	7	8	9	10

When the pain is bad, what do you try to do? What goes through your mind and what happens to your mood? (Screen for suicidal ideation at such times)

Do you use pain killers (or other substances such as alcohol) or are there other ways that you manage your pain? Do you take more than the recommended dose of medications?

What do you understand to be the cause of your pain? How do you imagine managing your pain in the future?

How do you imagine coping with your pain in the future?

Vividness of Movement Imagery Questionnaire-2 Revised

Instructions:

Motor Imagery refers to the ability to imagine one's own body in motion. The purpose of this questionnaire is to assess your motor imagery. We will ask you to induce mental images and then you will be asked to judge the vividness of these mental images on a 5-point scale. After each question, we will mark the corresponding answer. The first column refers to the mental images produced by thinking of yourself from a third-person perspective (similar to watching yourself on TV or looking at yourself in a mirror (External Visual Image). The second column is for the first-person point of view (Internal Visual Image). The third column is for the sensations felt while imagining the movement (Kinesthetic Image). Try to answer each question separately, independently of the answers given to the other questions. Complete the questions for each point of view separately. The three scores given to each item should not be the same. Please keep your eyes closed for each question.

The questions are divided for bodily area:

FB stands for "Full-Body"

UL stands for "Upper Limbs"

HS stands for "Head and Shoulders"

		Watching yourself from an external position (External Visual Imagery)					Looking out through your own eyes (Internal Visual Imagery)					Imagine feeling yourself doing the movement (Kinesthetic Imagert)				
Bodily area	Item	Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	know that you are thinking of the skill	Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	know that you are thinking of the skill	Perfectly clear and vivid as normal vision	Clear and reasonably vivid	Moderately clear and vivid	Vague and dim	know that you are thinking of the skill
FB	*1.Walking*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	2. Shaking your head sharply	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*3.Running*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	4. Blowing out a candle	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*5. Kicking a stone*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	6. Spitting chewing gum	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*7.Bending to pick up a coin*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
UL	8. Sitting without support	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	9. Running up stairs	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	10. Moving a piece of paper with your mouth	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*11.Jumping sideways*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5

UL	*12. Throwing a stone into water*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*13. Kicking a ball in the air*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
UL	14. moving an object towards yourself	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*15.Running downhill*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	16. Sitting with your back supported	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*17.Riding a bike*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
HS	18. Shrugging	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*19.Swinging on a rope*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
FB	*20.Jumping off a high wall*	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5