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Title: **Neurocognitive benefits of physiotherapy for spinal cord injury**

Running title: **Neurocognitive Recovery after Deafferentation**

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Abstract

Spinal cord injury (SCI) interrupts the brain-body input-output exchange and modifies the mental representation of disconnected body parts, with decreased reliance on sensorimotor aspects of body representation and increased weighting of visuospatial ones. We hypothesized that physiotherapy-related benefits might extend to the re-establishment of the typical interplay between these two types of strategies. To test this hypothesis, we asked 42 participants (21 individuals pre- and post-physiotherapy, plus 21 controls) to perform mental rotation of corporal images (a cognitive task than can activate one or the other strategy). Results showed that only after physiotherapy the individuals with SCI showed the sensorimotor "bio-mechanical effect" (orientation-dependent modulation of response times) for the mental rotation of foot images (absent in pre-physiotherapy). This highlights that body representation is adaptable to contingent conditions, in that the reliance on sensorimotor or visuospatial strategies can be altered and, at least partially, restored as a function of physiotherapy.

Keywords: Neurorehabilitation; Motor Cognition; Nervous System; Perceptual Motor Coordination; Human

Introduction

Each year about 200.000 people worldwide must face the consequences of spinal cord injury (SCI), including direct sensorimotor impairments as well as indirect cognitive effects, i.e. aberrant mental representation/simulation of body movements: motor cognition[1-4]. Typically, the SCI-related deficits, as well as the benefits of associated rehabilitation, are assessed at the level of body periphery (limbs), in terms of motricity and/or sensitivity. However, the effects of rehabilitation at the cognitive level raise striking importance. Indeed recent neuroengineering solutions can let the nervous signals travel between brain and body[5, 6], so physically bypassing the spinal lesion. Thus, as SCI impacts motor cognition, it is likely that aberrant neural signals originating in the brain will render such technological solutions unusable. Based on recent evidence that rehabilitation helps maintaining cognitive functions[7], the present study assessed the benefits of rehabilitation on motor cognition after SCI.

To this aim we used a motor cognition task able to activate mental sensorimotor strategies without actual execution of movements: mental rotation of bodily images - participants are presented with rotated images of body parts (e.g. a hand or a foot) and judge their laterality (left, right) while Reaction Times (RTs) are measured. To perform this task, people tend to simulate the rotation of their own correspondent body part towards the position of the image. This is demonstrated by the influence of image orientation on the RTs[8]. Indeed, the RTs required to align series of gradually more rotated images to the vertical, constitute the so-called "Bio-Mechanical Effect" (BME): increased RTs for the mental rotation of images presented at 180° with respect to images at 0°[9]. Despite the BME has been consistently reported, it is also modulated by the characteristics of the image itself. BME is, in fact, large for images of body parts[10] and small for images of a full human body[11]. Such modulation is a sign of the use of sensorimotor (large BME) or visuo-spatial strategies (small BME)during mental rotation[12, 13]. Within this framework, SCI affects mental rotation in a very specific manner, producing a progressive switch from sensorimotor to visuo-spatial strategies in the mental rotation of images depicting the affected limbs[1, 14]. Therefore, BME seems the ideal tool to assess the state of motor cognition as well as the effects of rehabilitation.

On this basis, it can be hypothesized that mental rotation of foot images (the affected limbs) (i) is affected before rehabilitation and (ii) will improve after rehabilitation. No differences are expected for images representing healthy limbs. To test this hypothesis, we performed two comparisons. First, between-subject, we assessed the impact of SCI on mental rotation of different images by comparing the performance of individuals with and without SCI. Second, within-subject, we compared the characteristics of mental rotation in the same individuals with SCI before and after rehabilitation.

Materials and Methods

Participants - Taking into account the risks of large samples[15], to identify the appropriate sample size we performed a power analysis[16] on a previous dataset from individuals with SCI who performed an experiment in a setup similar to the present one[1]. This approach showed that with 20 participants the experimental protocol was effective to get at least 80% power and type-1 error (p=0.05). Therefore, 42 participants (all male and adults) were enrolled in the study (21 individuals with SCI and 21 age-matched controls). Controls participated only once and their performance was used as reference to assess the group-level differences with respect to SCI individuals in the pre-rehabilitation session. Individuals with SCI underwent two experimental sessions (pre- and post-rehabilitation), allowing within-subject comparisons to avoid the risks of inter-subject variability. All participants were informed of the study procedures and signed a written informed consent. Individuals with SCI were selected according to the following inclusion and exclusion criteria. Inclusion: (i) clinically established SCI; (ii) no rehabilitation for the last 3 months. Exclusion: (i) presence of other neurological and/or psychiatric disorders; (ii) global cognitive impairment; (iii) head trauma; (iv) drug abuse. The experimental procedure was approved by the local Ethics Committee and the study was carried out in accordance with the Declaration of Helsinki 2013.

Clinical assessments - Prior to the experiment, the sensorimotor impairments of individuals with SCI (neurological level and severity) were clinically assessed with the American Spinal Injury Association Impairment Scale (AIS)[17]. Based on the sensorimotor functions below SCI, individuals with SCI were assigned to one of the following classifications: "A" = No sensory or motor function is preserved in the sacral segments S4-5; "B" = Sensory but not motor function is preserved below the neurological level and includes S4-5; "C" = Motor function is preserved at S4-5 for voluntary anal contraction OR the sensory function is preserved at S4-S5 and more than half of key muscle functions below the single neurological level of injury having a muscle grade < 3; "D" = Motor incomplete status as defined above, with at least half (half or more) of key muscle functions below the single neurological level of injury having a muscle grade ≥ 3; "E" = Sensation and motor function are graded as normal in all segments and the patient had prior deficits.

SCIs were distributed along the cervical, thoracic, and lumbar regions of the spinal cord, ranging between C3 to L4 (Table 1). This was reflected in sensorimotor troubles of the lower limbs in all the individuals with SCI. Due to the absence of sensory and motor functions in the sacral regions all the SCIs classified as AIS A were diagnosed as "complete" (N=5). Complete SCIs were at or below the 6th thoracic vertebra, therefore the hand functions were preserved. All other individuals with SCI were classified as AIS B, C, or D (incomplete SCI) with at least partially preserved sensorimotor functions of the hands. Thus, despite the structural heterogeneity, at the functional level none of the individuals with SCI suffered from complete sensory-motor deficits at the hands.

Table 1 - SCI Classification

Stimuli (Mental Rotation Images) - Sets of naturalistic pictures of a foot, hand, or human body[1] were presented one at a time on a computer screen, oriented in one out of four clockwise orientations from the upright (0°, 90°, 180°, 270°) (Figure 1). The body images represented a front-facing standing person with the arms flexed upwards at the level of the elbows. One hand of the body image was darker. To avoid task habituation and response repetition, all images varied in terms of view (dorsum or palm) and laterality (left or right). The overall configuration (gender, age, ethnicity, etc.) and visual features (shape, size, luminosity, etc.) of the two views for each image were very similar. All images covered a visual angle comprised between 11° and 13° at a distance of 60cm.

Figure 1 - Stimuli

Procedure - Response times (RTs) were recorded automatically with a microphone. Participants' responses (left, right) were manually entered during the experiment. RTs and accuracy were analyzed offline. The pre-*Physiotherapy* session took place only if individuals with SCI did not undergo any rehabilitation program for at least three months. At the beginning of each experimental session (pre- and post-*Physiotherapy*), all participants practiced the task using a set of images different from the ones included in the actual experiment (different orientations). Each session comprised six blocks, two blocks for each image type (foot, hand, body). Each block contained 48 images (24 left-lateralized and 24 right-lateralized) randomly presented in one of the four orientations (0°, 90°, 180°, 270°). Participants sat in front of a computer screen positioned at 60cm from their eyes. Image presentation was controlled by the E-Prime software (Psychology Software Tools Inc., Pittsburgh USA). Each trial began with a fixation cross (1000ms). Subsequently, an image appeared on the screen and remained visible until a response was given. Participants provided vocal responses to judge the laterality (left or right) of each image, as quickly and accurately as possible. For the body images, participants identified the laterality of the darker hand.

Rehabilitation Program - The rehabilitation procedure, hereafter defined as "*Physiotherapy*", took place between the two experimental sessions (pre- and post-physiotherapy). During *Physiotherapy* all individuals with SCI underwent personalized and intensive rehabilitation protocols for a 3- to 10-week long period. As a function of the individual clinical conditions, in general, *Physiotherapy* comprised sections of stretching and joint mobilization, manual therapy, and training for postural changes and wheelchair driving. *Physiotherapy* exercises aimed to recovery muscle strengthening were administered for the upper body parts and when possible (incomplete lesions) for lower limbs. For patients with AIS C and D a walking training was carried out whenever it was possible. Interventions to contrast pain and electrotherapy were used when necessary.

Data Analysis - Objective endpoint measures (RTs) were defined as the time between the image onset and the onset of the participant’s verbal response. Trials with incorrect responses and/or artifacts (unexpected noise, coughing, etc) were excluded from the analysis (9.8%). To analyze the *Overall Magnitude of BME* (the RTs difference between 0° and 180°) for each image type and in each session (controls, SCI-pre, SCI-post), we subtracted the RT values obtained specifically by each participant with images at 0° from the RT value obtained with images at 180°. Then, separately for each image type, we used 9 two-sample t-tests (3 for each image type) to directly compare the BME score of each sample (controls, SCI pre-*Physiotherapy*, SCI post-*Physiotherapy*) to each other ($p<0.05$).

Furthermore, RTs were analyzed according to two main research questions. First, to assess the *Specific Impact of SCI on BME*, we compared the performance of individuals with SCI in the pre-*Physiotherapy* session versus controls. To this aim we performed a 2x3x4 mixed-model ANOVA with the between-subject factor Group (SCI, controls), and repeated measures for the factors Image (body, hand, foot) and Orientation (0°, 90°, 180°, 270°). Second, to assess the *Neurocognitive Effects of Physiotherapy*, we compared the performance of the same individuals with SCI in the pre- and post-*Physiotherapy* sessions. To this aim we performed a 2x3x4 within-subject repeated-measure ANOVA with Period (pre, post), Image (body, hand, foot), and Orientation (0°, 90°, 180°, 270°) as main factors. In both analyses, the post-hoc comparisons were Newman-Keuls corrected to account for multiple comparisons. Partial η^2 ($p\eta^2$) were used as effect sizes. The laterality and view of images varied only to avoid habituation, their influence falls out of the scopes of the present study, and has been anyways already documented elsewhere[1, 18]. For these reasons, they were not included as factors in either analyses, resulting in a greater statistical power.

Finally, to investigate the relationship between RTs in the mental rotation task and the impact of clinical aspects related to SCI, we performed an ANCOVA between RTs and the temporal gap from the onset of lesion to the pre-physiotherapy session, the time passed between the pre- and post-*Physiotherapy* sessions, AIS, and neurological level of injury scores. Covariance analyses were conducted by means of R statistical software (R Core Team, 2017) with the *afex* package[19]. Post-hoc comparisons among covariance scores were computed through the package *emmeans*[20] Tukey corrected for multiple comparisons.

Results

Overall Magnitude of BME

For the foot images the planned t-tests showed the significantly smaller BME for individuals with SCI pre-*Physiotherapy* [(Mean(M)=185ms, Standard Error(SE)=60.7ms, Effect Size (d) = -0.96] with respect to controls (407.4ms, 40ms) (p<0.002), as well as the significantly larger BME for individuals with SCI post-*Physiotherapy* (M=427.4ms,SE=105.9ms, d=0.63) with respect to pre-*Physiotherapy* (M=185ms, SE=60.7) (p<0.026). Remarkably, the BME difference between individuals with SCI in the post-*Physiotherapy* session and controls was not significant. In addition, for the hand images, individuals with SCI had a larger BME in the post-*Physiotherapy* (M=642.7ms,SE=113.6ms, d=0.63) with respect to the pre- *Physiotherapy* session (M=435.1ms, SE=102.9ms) (p<0.014), although the SCI vs. control comparison was not significant before and after *Physiotherapy*. Finally, the BME for the body images was not significantly different in any of the three comparisons (Figure 2).

Figure 2 - BME

Specific Impact of SCI on BME

The between-subject analysis of RTs in individuals with SCI pre-Physiotherapy versus controls showed the significant interaction between Group, Image, and Orientation [F(6, 240)=2.26; p<0.038; pη^2=0.05]. The post-hoc tests indicated that this interaction was explained by the longest RTs obtained by both individuals with SCI (M=1819.3ms,SE=154.5ms) and controls (M=1749.8ms,SE=78.7ms) for the hand images presented at 180° with respect to all the other images (all p<0.032; Figure 3). Importantly, for the foot images the RTs of individuals with SCI were not significantly modulated by Orientation (all p>0.1), while controls showed a significant increase of RTs between foot images presented at 90° (M=1208ms, SE=79.8ms) and 180° (M=1550ms, SE=97ms, d=0.84; p<0.001) and a decrease between images at 180° and 270° (M=1201ms, SE=80.3ms, d=0.85; p<0.001). Conversely, for the hand and the body images both individuals with SCI and controls showed similar RTs profiles, with large BME for the hand images and a small BME for body images. In fact, for the hand images both groups showed progressively increasing RTs for images at 0° (SCI: M=1384.2ms, SE=80.3ms; controls: M=1218.6ms, SE=51.3ms), 90° (SCI: M=1607.3ms, SE=144.7ms; controls: M=1308.4ms, SE=62.7ms), and 180° (SCI: M=1819.3ms, SE=154.5ms; controls: M=1749.8ms, SE=78.7ms), as well as decreased RTs for images at 270° (SCI: M=1520.1ms, SE=149.9ms; controls: M=1286.1, SE=56.5ms) (all d>±0.31 ; all p<0.001). For the body images neither group showed significant modulations of RTs as a function of Orientation (all p>0.19). Further group-related effects showed that Orientation had a weaker influence on individuals with SCI than controls [interaction Group by Orientation: F(3,120)=3.75, p<0.012; $p\eta^2$=0.08] and that individuals with SCI were generally slower than controls [main effect of Group: F(1,40)=4.14, p<0.048; $p\eta^2$=0.09].

Figure 3 :Orientation

Neurocognitive Effects of Physiotherapy

The within-subject analysis of RTs of the same individuals with SCI in the pre-*Physiotherapy* versus post-*Physiotherapy* sessions showed the significant 3-way interaction between Period, Image, and Orientation [F(6, 120)=2.28; p<0.040; $p\eta^2$=0.10]. The post-hoc tests of this interaction showed that only for the foot images the RTs profile of the individuals with SCI varied between pre- and post-*Physiotherapy* (Figure 3). In particular, in the post-*Physiotherapy* session the RT for foot images oriented at 180° (M=2025.8ms, SE=201.5ms) was significantly longer with respect to images oriented at 0° (M=1598.4ms, SE=123.6ms), 90° (M=1577.2ms, SE=139.1ms), and 270° (M=1642.7ms, SE=171ms) (all d>±0.4 ;all p<0.001). Such difference was not present in the pre-*Physiotherapy* session, where the RTs for each orientation were not significantly different among each other (all p>0.05). Conversely, the RT profile for the mental rotation of hand and body images remained unchanged, showing the expected trend of responses (presence and absence of orientation-dependent modulation of RTs, respectively). In particular, both in the pre- and post-*Physiotherapy* sessions, the RTs for hand images increased non-monotonically as a function of Orientation [pre-*Physiotherapy*: 0°(M=1384.2ms, SE=80.3ms), 90°(M=1607.3ms, SE=144.7ms), 180°(M=1819.3ms, SE=154.5ms), 270°(M=1520.1ms, SE=149.9ms); post-*Physiotherapy:* 0°(M=1377.8ms, SE=94.8ms), 90°(M=1670.9ms, SE=156.8ms), 180°(M=2020.4ms, SE=182.8ms), 270°(M=1670ms, SE=168.8ms) (all d>±0.3 ; all p<0.020)]. Similarly, both in the pre- and post--*Physiotherapy* sessions, the RTs for body images were not significantly modulated as a function of Orientation (all p>0.05). The significant 2-way interaction between Period and Orientation [$F(3,60)=5.80$; $p<0.015$; $p\eta^2=0.23$] indicated that the longest RTs were recorded in the post-*Physiotherapy* session for images oriented at 180° (M=1883ms, SE=180.7ms; all d>±0.4 ; all p<0.001), while the shortest RTs corresponded to images at 0° in the pre-*Physiotherapy* session (M=1358.6ms, SE=93.3ms; all d>±0.3 ; all p<0.001). The significant main effect of Period [$F(1,20)=5.01$; $p<0.039$; $p\eta^2=0.20$] indicated that RTs were longer in the post-*Physiotherapy* (M=1636.6ms, SE=154.9ms) than the pre-*Physiotherapy* session (M=1477.5ms, SE=118.4ms, d=0.3).

Other effects

Other Image- and Orientation-related effects generally confirmed previous work. In particular, the significant main effect of Image [$F(2,40)=8.04$; $p<0.001$; $p\eta^2=0.29$] showed that RTs were shorter for the body images (1417.8ms) with respect to hand (1633.8ms) and foot images (1617.3ms) (all p<0.002). The significant main effect of Orientation [$F(3,60)=19.9$; $p<0.001$; $p\eta^2=0.50$] indicated that RTs for images oriented at 180° (1747.2ms) were the longest (all p<0.001), while RTs for images at 0° were the shortest (1420.1ms) (all p<0.028). The difference between RTs for images at 90°(1526.5ms) and 270°(1531.3ms) was not significant. The significant interaction between Image and Orientation [$F(6,120)=6.75$; $p<0.001$; $p\eta^2=0.25$] indicated that RTs for hand and foot images were more modulated by Orientation than the body images. In particular, for body images the differences of RT among the different orientations were never significant; for hand images such difference was always significant (all p<0.01); for foot images the RTs for images at 180° had the longest RTs (all p<0.001).

Correlation between SCI completeness and mental rotation

The significant effects of RTs-AIS covariance analysis are graphically represented in Figure 4. The analysis of the potential influence of clinical variables in the BME confirmed the significant effects observed for the *Specific Impact of SCI on BME* as well as for the *Neurocognitive Effects of Physiotherapy* (all p<0.05 and all pη2>0.10). In addition, two interactions involving AIS were statistically significant: the 3-way interaction among AIS, Image and Orientation [F(6, 114)=2.26; p<0.05; pη2=0.11] and the 2-way interaction between AIS and Image [F(2,38)=7.83; p<0.01; pη2=0.29]. Post-hoc tests for the AIS, Image and Orientation interaction showed that the difference in the RTs-AIS covariance between hand versus foot images at 180° was significant (hands: β=50.76; 95%CI=-203.06;304.57; foot: β=-193.27; 95%CI=-447.08;60.54; p<0.01). This difference shows that the performance with hand images practically remains constant across the AIS levels. Conversely, for the foot images, participants with less deficit were advantaged (faster) only when foot images were not in a canonical position (i.e. 180°, see also the interaction between AIS and Image).

The RTs-AIS covariance as a function of Image showed the significant difference between hand versus body images at 270° (hands: β=-136.63; 95%CI=-390.45;117.18;body: β=36.17; 95%CI=-217.64;289.99; p<0.05). Higher AIS levels were linked with larger RTs in hand images than in body images only at 270°, where fingers are pointing away from the body's midsagittal plane and motor mental rotation is more difficult[21]. These effects were not significant when images were at 0° (all p>0.07). In the other orientations, the differences between body images and foot images at the same orientations were significant (all p<0.01; body: 90°: β=14.01; 95%CI=-216.59;291.04; 180°: β=57.39; 95%CI=-196.43;311.21; 270°: β=36.18; 95%CI=-217.64;289.99; foot: 90°: β=-202.42; 95%CI=-456.23;51.40; 180°: β=-193.27; 95%CI=-447.09;60.54; 270°: β=-164.13; 95%CI=-417.95;89.68).

Post-hoc analyses of the interaction between AIS and Image showed a difference in the covariance between RTs and AIS in the body vs. the foot images (p<0.001), indicating that worse AIS scores corresponded to slower RTs for foot images (β=-167.38; 95%CI=-412.52;77.77). The trend for body images was essentially linear (i.e. the RTs did not change with AIS, β=36.20; 95%CI=-208.94;281.35). Together with the significant difference in the RTs-AIS covariance between hand versus foot images at 270°, this suggests that individuals with a milder SCI (less sensorimotor deficits) tended to have better performance in mental rotation of foot images with respect to individuals with a more severe SCI (severe deficits).

The ANCOVAs on the level of lesion and the interval between the pre- and post-*Physiotherapy* sessions confirmed the significant results found in the main analyses of the mental rotation task (all p<0.05, pη2>0.10). There were not main effects nor interactions with the covariates of lesion level and the interval between sessions. These results indicate that the participants' performance in the mental rotation task were not biased by these clinical variables.

Figure 4 - Correlations

Discussion

Neurocognitive Effects of Physiotherapy

We continuously calibrate movements as a function of the available sensory information[22]. SCI reduces or even stops the brain-body information exchange and affects the mental representations of deafferented body parts[7, 23, 24], including a modification of the interplay between sensorimotor and visuo-spatial strategies for body representation[1]. Our results indicate that such modification (i) concerns the mental representation of deafferented body parts, and (ii) can be reversed as a function of physiotherapy.

The disadvantage for upside-down images (large BME) suggests the activation of a sensorimotor strategy for mental rotation, while its absence (small BME) indicates the involvement of a visuo-spatial strategy[25]. Thus, the magnitude of BME can be interpreted as the translation of the properties of physical joint constraints (the available somatosensory input) in mental representation of body segments[18]. In the present study, in pre-physiotherapy session, individuals with SCI did not show a BME in the mental rotation of feet, while in the post-physiotherapy session the BME was re-established. In addition, both in pre- and post-physiotherapy the RTs profiles of individuals with SCI for the mental rotation of hand (hands' sensorimotor functions are at least partially preserved) and body images(visuospatial strategy) were not significantly different with respect to controls. This is in line with previous evidence on the somato-topographically organized impact of SCI on motor cognition, with tetraplegics impaired in upper and lower limbs' representations, and paraplegics only in the lower limbs' ones[24]. As in both sessions we presented exactly the same images, any bias due to visual aspects can be excluded. Also, as the BME's difference between pre- and post-*Physiotherapy* concerned only some orientations (0° and 180°), and a 3- to 10-week long interval separated the two experimental sessions, any learning bias can be excluded. Thus, we propose that the difference in pre- vs. post-*Physiotherapy* BME for the mental rotation of foot images isdue to the physiotherapy itself, regardless the training duration, as also supported by the absence of correlation between BME and duration of training.

Typically, different strategies can be used in mental rotation and people can switch between them[26]. On this basis, we propose that the larger BME in the post-*Physiotherapy* session indicates a switch from a visuo-spatial (smaller pre-*Physiotherapy* BME) to a sensorimotor strategy in mental rotation of feet. This interpretation is based on the theoretical differentiation between the body schema and the body image. As body *schema* we refer to the online representation of the somatosensory information about one's own body[27], referring to previous sensorimotor experience[28]. Conversely, the body *image* refers to the pictorial aspects of body representation[29], strongly relying on previous visual experience[30]. Typically, body schema and body image coherently coexist and interact, but SCI is often associated with disorders in body schema[31, 32], and not in body image[33]. We propose that, being unable to access somatosensory input, in the pre-physiotherapy session individuals with SCI used visuospatial strategies (body image) for the mental rotation of foot images. Conversely, in the post-physiotherapy session they showed the typical BME in mental rotation of foot images, suggesting that physiotherapy promoted the relying on sensorimotor strategies (body schema).This interpretation is in line with evidence that, after SCI, motor cognition can improve in association with physiotherapeutic interventions[7] and that completeness and level of SCI covary with motor cognition abilities[24]. This is confirmed in the present study by the covariance results with the completeness of the lesion. In fact, less motor deficits (assessed by the AIS scores) lead to better performances in mental rotation of foot images, as also supported by the correlation between AIS scores and patients' BME in responses regarding foot images.

Specific Impact of SCI on BME

Considering that all individuals with SCI had at least partly preserved sensorimotor functions of the hands, it is not surprising that the BME for hand images was similar to controls in both the pre- and post-*Physiotherapy* sessions. However it was larger in the post- than pre-physiotherapy session. This supports that, after *Physiotherapy*, individuals with SCI relied more on sensorimotor aspects of their hands' representation (not only feet). On this basis, the present results support that physiotherapy impacts the representation of a below-lesion body part (foot) leaving relatively preserved the representation of an unaffected body part (hand). This further highlights the importance of the residual brain-periphery exchange in the activation of sensorimotor aspects of body representation.

For both individuals with SCI (pre- and post-*Physiotherapy*) and controls, the BME for the mental rotation of body images was very small. Such absence of BME is in accordance with previous evidence that mental rotation of bodies is weakly affected by biomechanical constraints both at the behavioral[12] and neural level[34]. On this basis, we propose that, independently of physiotherapy, the full-body mental representation is preserved in SCI as it is based on visuo-spatial mechanisms. This is supported by brain imaging evidence that vision and mental rotation of body images recruit similar occipito-temporal (visual) brain regions[35-37].

Conclusions

In typical conditions, a large BME is considered a sign of the activation of sensorimotor strategies, while a small BME suggests the recruitment of visuo-spatial strategies[13]. Here we directly compared the pre- and post-*Physiotherapy* BME of SCI individuals' mental rotation of foot, hand, and body images. This approach provided insights into the plastic modifications of the relative weight of sensorimotor and visual strategies in body representation. Before physiotherapy the BME was large for hand, but not foot, images. After physiotherapy the BME for foot images increased and resembled that of controls. Individuals with SCI (like controls) did not show BME for the mental rotation of body images, supporting the specificity for the foot images. On this basis, we suggest that physiotherapy improved the use of sensorimotor strategies in body representation. This indicates that even if the body is affected by deafferentation/deefferantation, focused physiotherapy can ameliorate the relationship between sensorimotor and visual aspects of body representation. Based on the effectiveness of mental movement simulation in a wide range of neurological disorders[38], and given its ability to re-activate otherwise silent sensorimotor representations, we propose that mental rotation is a more direct, less strenuous, and more controllable method to assess the effect of rehabilitation on the properties of sensorimotor bodily representations.

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Table 1 - SCI Classification

#	Level	Type	AIS
1	C3	Inc	C
2	C4	Inc	C
3	C4	Inc	B
4	C7	Inc	D
5	L1	Inc	D
6	L1	Inc	C
7	L4	Inc	D
8	L4	Inc	D
9	T10	Inc	D
10	T11	Com	A
11	T11	Inc	D
12	T12	Inc	B
13	T4	Inc	D
14	T4	Inc	B
15	T6	Com	A
16	T6	Com	A
17	T7	Com	A
18	T7	Com	A
19	T8	Inc	D
20	T8	Inc	D
21	T9	Inc	D

Legends

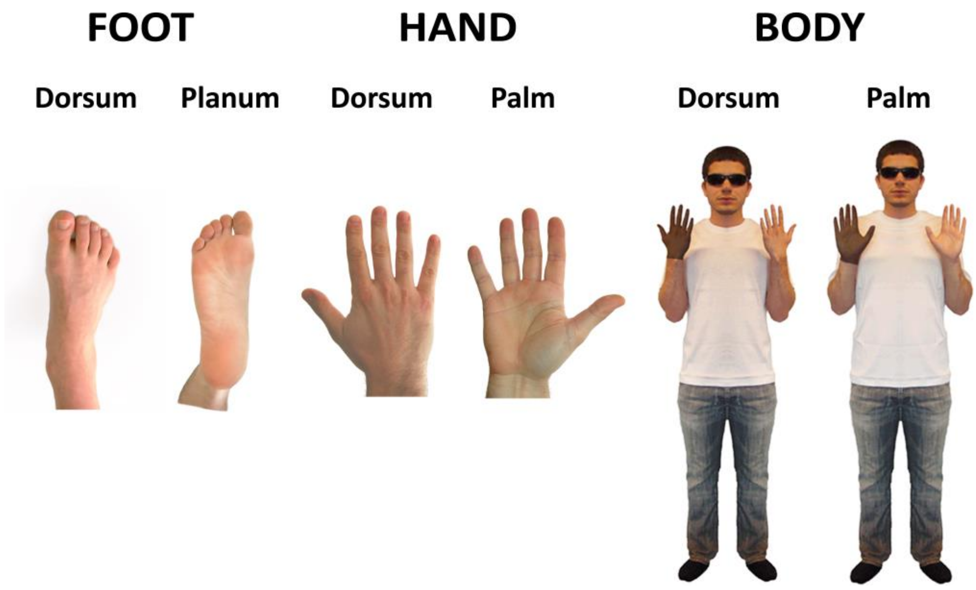

Figure 1 - Mental Rotation Images. Three classes of bodily images were included in the protocol (Body, Hand, Foot). All stimuli were presented for both right and left side (laterality), either from a dorsum or a palm/planum view and rotated in one out of four clockwise orientations (0°, 90°, 180°, 270°).

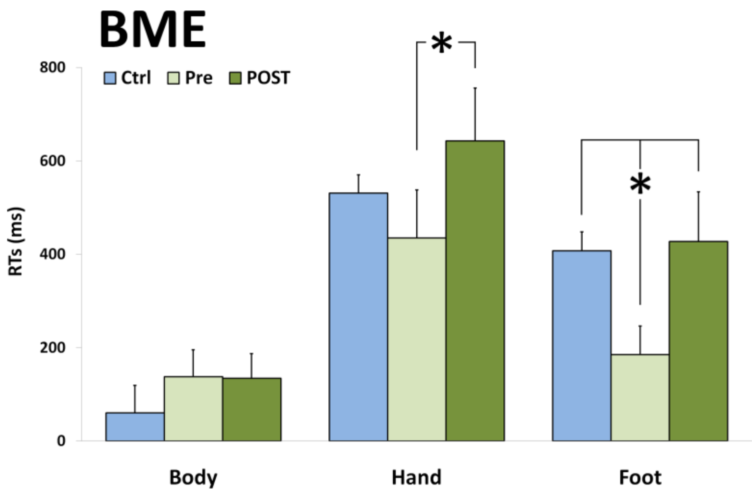

Figure 2 - Overall Magnitude of BME for the mental rotation of all type of images (Foot, Hand, Body) in controls and Individuals with SCI (pre- and post-physiotherapy). In the post-physiotherapy session the BME increased for the mental rotation of foot and hand images, but not for the body images. Error bars represent standard error. Asterisks represent significant differences.

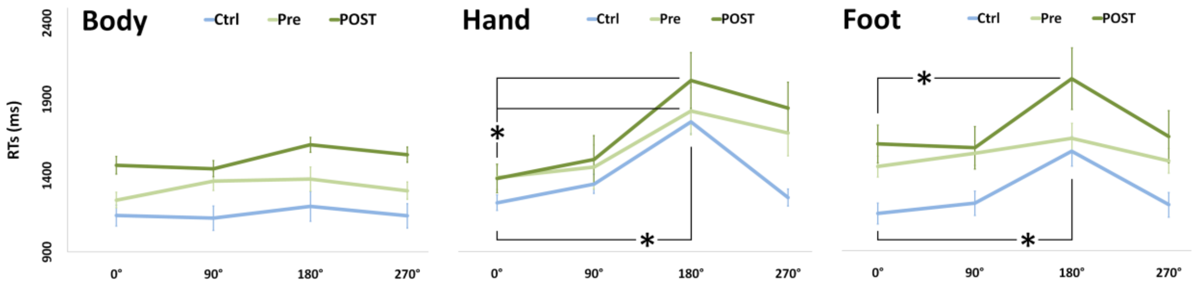

Figure 3 - Orientation-dependent mental rotation. RTs are plotted as a function of Group (controls, pre-Physiotherapy SCI, post-Physiotherapy SCI), Image (Body, Foot, Hand), and Orientation (0°, 90°, 180°, 270°). The analysis Specific Impact of SCI on BME (light green vs. blue lines) showed that mental rotation of foot images was specifically impaired (small variations of RTs as a function of Orientation) in individuals with SCI with respect to controls. Conversely, the RTs profiles for the mental rotation of body and hand images were very similar between individuals with SCI and controls. The analysis Neurocognitive Effects of Physiotherapy (dark green vs. light green lines) showed that mental rotation of foot images was more influenced by Orientation in the post- than the pre-Physiotherapy session (being the RTs profile similar to those of controls). Error bars represent standard error. Asterisks represent only the BME-related significant comparisons (180°-0°). Other post-hoc significant differences are embedded in the results section.

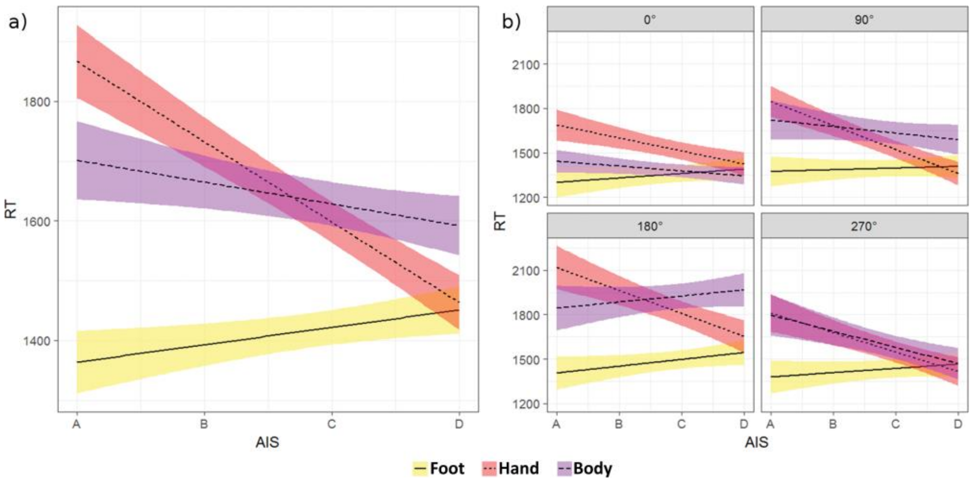

Figure 4 - Correlation between SCI completeness and mental rotation task. **A)** Regression lines and standard deviation between AIS scores and mental rotation RTs divided by Image (foot, hand, body). A clear inverse tendency between AIS and RTs is observable in foot images. **B)** Regression lines and their standard deviation between AIS and RTs divided by Image and Orientation.