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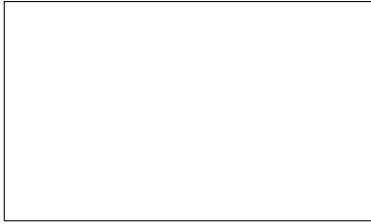


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## Graphical Abstract

### **Implicit and explicit motor imagery ability after SCI: moving the elbow makes the difference**

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## Highlights

### **Implicit and explicit motor imagery ability after SCI: moving the elbow makes the difference**

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- We assessed implicit and explicit MI ability after cervical SCI
- After SCI<sub>C6</sub> implicit MI of elbow movements were impaired
- Implicit MI of elbow movements was preserved after SCI<sub>C7</sub>
- Implicit and explicit MI ability changes after SCI reflect actual motor impairments

# Implicit and explicit motor imagery ability after SCI: moving the elbow makes the difference

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## Abstract

**Background:** Cervical spinal cord injury (SCI) causes dramatic losses of sensorimotor functions and require extensive rehabilitation which can include motor imagery. To date it is unclear whether MI ability is impaired or spared by SCI.

**Aim:** To investigate MI ability after C6 or C7 SCI vs. healthy control.

**Material and method:** 3 groups of individuals with C6 SCI, C7 SCI and aged-gender matched healthy individuals. We performed implicit MI tasks including hand laterality judgment, hand orientation judgment (HOJT), hand-object interaction judgment and explicit MI evaluation of physically possible and impossible (for SCI) including forearm sweep, tenodesis grasp and digital dissociation. Outcomes were responses time (RT) and accuracy (expressed in %) for implicit MI, and task duration for explicit MI.

**Results:** In all but HOJT there was no significant differences in the outcomes across groups with a similar RT and accuracy between participants with C6 and C7 as compared to control. Pattern of response differed for HOJT for individuals with C6 SCI as compared to C7 SCI and controls.

**Conclusion:** These results obtain from an homogeneous population with SCI strongly suggest that MI ability is mainly spared by SCI with selective impairment in implicit MI in case the motor control of the elbow is partially impaired. Use of MI can be recommended with some adaptation for implicit MI of the elbow after C6 tetraplegia.

*Keywords:* reaction time, accuracy, mental chronometry, tetraplegia, rehabilitation

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## 1. Introduction

Spinal cord injury (SCI) of traumatic or non-traumatic origin results in dramatic loss of sensorimotor functions. The severity of SCI varies depending on the neurologic level of injury and the completeness of the lesion. Between 250000 and 500000 cases of cervical SCI are reported yearly around the world (World Health Organization, 2013). The incidence of SCI ranges from 12.1 to 57.8 per million (Van den Berg et al., 2010), and 19.4 per million in France (Albert and Ravaud, 2005). SCI at the cervical level elicits quadriplegia, with prehensile functions being severely damaged due to the paralysis of upper limb muscles. Restoring prehensile strategies is one of the primary focus of rehabilitative interventions (Snoek et al., 2004; Simpson et al., 2012). After cervical SCI, patients can learn a modified type of prehension which taps into the spared sensorimotor functions of the upper limbs. The tenodesis effect, i.e. a wrist extension eliciting a passive lateral or palmar grip through shortening of thumb or finger tendons, is crucial to prehensile strategies after cervical SCI (Mateo et al., 2013). Research showed that rehabilitation improves force of the wrist extensor muscles, hence facilitating the tenodesis grasp after cervical SCI (Ditunno Jr et al., 2000). Interestingly, motor learning of the tenodesis grasp may be enhanced by the adjunct of motor imagery (MI – i.e. the mental representation of an action without physically executing it) (Mateo et al., 2015). MI recruits overlapping cortical and subcortical structures with those controlling the physical performance of the same action, and can be used to leverage experience-dependent neuroplasticity in both healthy and neurologic populations (Di Rienzo et al., 2016; Ruffino et al., 2017). In patients with SCI, motor learning of tenodesis through MI was associated with a reduction of abnormal patterns of cortical activation; cortical patterns during tenodesis prehension became similar to those measured in non-SCI controls participants after 5 weeks of rehabili-

tation including MI (Mateo et al., 2015; Di Rienzo et al., 2014b). Despite these promising results, further research is required to confirm its therapeutic relevance in the neural modulation of experience-based plasticity after SCI (Mateo et al., 2020).

From a fundamental standpoint, the critical question of whether cognitive motor processes are impacted as a result of long-term SCI remains largely unanswered. The integrity of cognitive motor processes represents an eligibility criteria for inclusion in research protocols designed to assess the effectiveness of MI interventions in neurorehabilitation, since it is predictive of the potential of MI to elicit brain motor networks stimulation (Lorey et al., 2011; Van der Meulen et al., 2014). In a systematic review, Di Rienzo et al. (2014a) emphasized that changes in both implicit and explicit MI ability after SCI, stroke, Parkinson’s disease and amputation, frequently reflected the current sensorimotor capabilities and could thus not be interpreted as the incapacity to engage in MI. This is congruent with computational approaches of motor control, particularly the internal models theory of MI which postulates that MI reproduces predictive action states underlying both the build-up and online control of voluntary movements (Wolpert and Ghahramani, 2000; Grush, 2004; Lebon et al., 2013). Although MI does not allow the update of forward models – due to the absence of physical execution – it involves a comparison between intended and predicted action states (Lebon et al., 2013). Disruption in the ongoing flow of sensory inputs to the central nervous system, and absence of inverse models updates due to the incapacity to physically perform the movement, might bias MI ability. This is consistent with reports of reduced lateralization of brain activity during MI in SCI patients who developed central neuropathic pain (Kumari et al., 2023). Among MI processes, *explicit* MI represents the voluntary process of engaging motor simulation (e.g. grasping movement instructed; Mateo et al., 2015). By contrast, *implicit* MI is involved in cognitive tasks where motor simulation is required, but not explicitly instructed (e.g. hand laterality judgement; Nico et al., 2004). Implicit MI ability is classically assessed from the analysis of response times (RTs) and accuracy in mental rotation of body parts paradigms. Behavioral assessments of explicit MI ability rather involve mental chronometry recordings, typically the correspondence between actual and imagined movement durations (i.e., isochrony; Decety and Boisson, 1990; Guillot and Collet, 2005; Fiori et al., 2014).

At this point, it remains unclear whether SCI results in either spared or impaired MI ability, and implicit and explicit MI ability assessments yielded

contradictory findings. First, Decety and Boisson (1990) interpreted the largely preserved explicit MI ability after SCI as the result of the absence of damage to brain structures. In a study focusing on implicit MI ability, Fiori et al. (2014) reported an absence of biomechanical constraints effects on the accuracy of hand laterality judgments. The authors concluded to an impairment of implicit MI ability as a result of long-term de-afferentation and de-efferentation (Fiori et al., 2014). Noteworthy, the study was conducted in an heterogeneous sample and did not account for the level of clinical impairment in the factorial analysis. Overall, scientific investigations of MI ability after SCI remain scarce, and yielded contradictory findings with regards to the preservation of implicit or explicit MI ability.

We sought to address this gap by investigating both implicit and explicit MI ability after SCI. We controlled the influence of the level of motor impairment by distinguishing C6 and C7 levels of neurologic injury. The present study thus sought to expand current knowledge regarding implicit and explicit MI ability in patients with C6 or C7 SCI compared to age- and gender-matched healthy individuals. We included, in addition to the hand laterality judgment task, a series of validated implicit MI ability tasks from previous studies emphasized for their relevance to assess cognitive motor processes in neurologic populations (Johnson, 2000a; Daprati et al., 2010). We hypothesized that, rather than impaired, changes in implicit and explicit MI ability would be a reflection of the actual sensorimotor impairments after SCI. We hypothesized that such selective impairments may be absent for MI tasks involving movements performed in ecological contexts and trained during rehabilitation.

## 2. Material and Methods

### 2.1. Participants

We included individuals aged 18-65 years with normal or corrected-to-normal vision. For individuals with SCI, only participants with a lesion at the C6 (SCI<sub>C6</sub>) or C7 (SCI<sub>C7</sub>) level were included. All lesions were classified grade A or B on the American Spinal Injury Association (ASIA) impairment scale, indicative of a complete loss of motor functions below the neurologic level (Maynard et al., 1997). All SCI participants had reached a chronic stage, i.e.,  $\geq 6$  months post-SCI (Ditunno Jr et al., 2000). All were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971), with unchanged hand dominance after the lesion. We also included a group of indi-

viduals without SCI (CONTROL), age- and gender-matched to participants included in the (SCI<sub>C6</sub>) or (SCI<sub>C7</sub>) groups. As non-inclusion criteria, we considered cognitive impairments (e.g., a traumatic brain injury concomitant to SCI), upper limb orthopedic or pain limitations restricting movements. The study was conducted in accordance with the ethical standards laid out in the declaration of Helsinki (1964) and its later amendments. The study was ethically approved as part of a larger clinical trial (ACTNR12612001030864) and we obtained written informed consent from each participant.

## 2.2. Experimental design

The experimental design consisted in (i) a simple reaction time task followed by (ii) behavioral evaluations of implicit and explicit MI ability. To control for order bias, implicit and explicit MI evaluations were administered in a counterbalanced order. The experiment was performed in a single session lasting  $\approx 1.5$  hour.

### 2.2.1. Simple reaction time task

We first implemented a simple reaction time task to control for a possible between-group differences in response times (RT) due to upper-limb sensorimotor deficits in SCI<sub>C6</sub> and SCI<sub>C7</sub> participants. SCI<sub>C6</sub>, SCI<sub>C7</sub> and CONTROL participants seated on a table, in front of a computer screen placed 30 cm ahead of them. They adopted a standardized upper-body position, with their left and right hands placed on a tape mark on the table, 2 cm in front of a two-buttons response touchpad (HP®Wireless Trackpad Z6500). They were instructed to press the touchpad response button, immediately after imperative stimuli, i.e. a white cross displayed in the middle of a black screen. Imperative stimuli were displayed following a 1-5 s jitter delay, for each trial. RT was the duration between the onset of the imperative stimuli and the response on the touchpad. They completed one block of 10 trials for both the right and left hands. The order of right and left hand blocks was administered randomly for each individual.

### 2.2.2. Implicit motor imagery evaluations

*Hand laterality judgment.* The hand laterality judgment task was adapted from Fiori et al. (2014). Hand picture stimuli were displayed at the center of the computer screen, and participants had to judge whether they represented a right or left hand. Hand picture stimuli were displayed accordingly to 2 laterality/side (left or right), 4 orientations  $\{0^\circ, 90^\circ, 180^\circ,$



270°} and 2 views (back and palmar, see Figure 1A). Participants responded with their right hand on the right touchpad response button to indicate right hand judgements, and with their left hand on the left touchpad response button for left hand judgements. Each block consisted of 32 hand picture stimuli. Within each block, 16 hand pictures corresponding to the  $2 \textit{ Laterality} \times 2 \textit{ Views} \times 4 \textit{ Orientations}$  were presented twice. Hand pictures were shuffled within each block, to ensure a random presentation order. Participants completed 2 blocks of  $16 \times 2$  trials, separated by a 30 seconds rest period.

*Hand orientation judgment.* The hand orientation judgment task was originally proposed by Johnson (2000b). Participants were displayed pictures of a pastry rolling pin with yellow and purple handles (Figure 1, A). It was displayed in  $\{0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ, 315^\circ\}$  orientations (Figure 1, A). For each orientation, participants determined whether their thumb would be on the side of the yellow or purple handle of the pastry rolling pin if they had to grasp it. This enabled to determine whether the implicit MI process yielded prone or supine hand orientation judgments, for each stimuli orientation. Participants performed, 2 blocks of 24 stimuli (i.e. each of the 8 orientation was presented 3 times), separated by a 45 seconds rest period. Stimuli were shuffled within each block to ensure a random presentation order. Participants completed the task for the right and left hand separately, in random order.

*Hand-object interaction judgment.* This task was adapted from the implicit MI paradigm proposed by Daprati et al. (2010). Participants were presented familiar objects which required either a palmar/force grip or a finger/precision grip, i.e. respectively a knife/handled comb or a tippex corrector/key. Both tasks required tenodesis grasp for participants with SCI<sub>C6</sub> and SCI<sub>C7</sub>. Both types of grasping tasks had been the focus of rehabilitative training period after SCI. As underlined by Daprati et al. (2010), implicit MI of grasping required consideration of the object properties, since all of these objects required a specific orientation to be used (Figure 1, A). Contrary to the hand orientation task where any type of grasping strategy would allow grasping of the pastry rolling pin, the present task required participants to incorporate the functionality of the object during their implicit MI processes. After specifying which hand should be used for the task, participants were requested to provide judgments with regards to the orientation of their hand

if they had to grasp the object. They more specifically determined whether their hand would be in pronation or supination. Noteworthy, the object picture was in a congruent (i.e. can be used by the right/left hand) or incongruent (i.e. cannot be used by the right/left hand) display. We expected that congruent orientations would elicit shorter RT. Participants completed 2 blocks of 16 object picture stimuli, where each object requiring a palmar grip (knife, handled comb) or a finger grip (tippex corrector, key) was presented twice according to congruent and incongruent orientations in relation to the specific hand used to perform the grasp. Pictures were preliminary shuffled to ensure a random presentation order. The two blocks were randomly completed for the left and right hands.

### *2.3. Explicit motor imagery evaluations.*

Participants had to perform/attempt to perform physically and mentally a series of motor tasks with their dominant upper limb that were either possible or impossible to perform physically for SCI participants. First, participants had to complete physical practice (PP) and MI of a forearm sweep on a table using active elbow flexion to enclose a 0.5 l empty plastic bottle. The movement started with 60° of shoulder flexion with the elbow extended, and finished 10 cm ahead of participants' breastbone with 120° of elbow flexion (Figure 1B). SCI<sub>C7</sub> and SCI<sub>C6</sub> participants could both perform the forearm sweep physically without compensation. They were trained on this movement as part of their rehabilitation program to bring objects closer from their body before grasping. Second, participants completed PP and MI of lateral grasping and manipulating actions. They had to lift a large pencil laying on a table 4 times in a row. The grasping and subsequent manipulation, i.e. the lift of the object, required compensatory motor strategies in SCI<sub>C7</sub> and SCI<sub>C6</sub> participants, who had to use the tenodesis grasp during which an active wrist extension triggers a passive finger flexion (Mateo et al., 2013). Control participants were also instructed to use their wrist extension, hence mimicking the tenodesis grasp, although they could have used their fingers to perform a normal grasp. Eventually, we administered a movement that controls could perform physically, but not SCI<sub>C7</sub> and SCI<sub>C6</sub> participants due to the lesion. The movement consisted in a digital dissociation task, i.e. pressing 10 consecutive keys on a numeric keyboard. SCI<sub>C7</sub> and SCI<sub>C6</sub> participants could only attempt to perform this movement physically. Participants first observed the experimenter demonstrate the movement (3 trials). Then, they imagined the movement using a combination of first person visual and

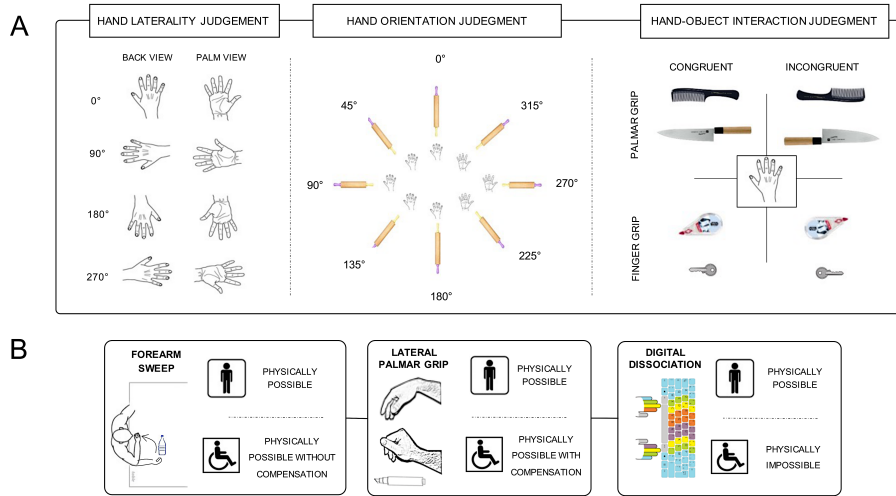


Figure 1: A. Implicit MI tasks administered in randomized order (NB. only right hand stimuli examples are provided for purposes of illustration). Participants underwent a hand laterality judgment task where they provided left/right judgments on hands picture stimuli displayed across 4 orientations and palm/back views (left panel). They also underwent a hand orientation judgement, where they judged whether their thumb would be placed on the side of the yellow or purple handle of a pastry rolling pin displayed in 8 orientations (middle panel). We chose a rolling pin instead of a neutral stick picture since to involve participants in goal-directed implicit MI judgments. The last implicit MI task consisted in a hand-object interaction judgments. Participants judged as fast as possible whether their hand would be in pronation or supination if they had to grasp an object presented in a congruent/incongruent orientation for their use with a pinch or hammer grip (NB. tenodesis grasp for SCI participants). B Explicit MI tasks involving possible movements without compensation, possible movements with compensation and impossible movements for SCI participants.

kinesthetic MI (3 trials). Next, they performed or attempted to perform the movement physically (3 trials), followed by 3 additional MI trials. SCI participants verbally indicated the onset and offset of the attempted movement for the digital dissociation task. All participants indicated verbally the onset and offset of imagined movements during MI trials.

#### 2.4. Statistical analysis

We used R (R Core Team, 2021) and *nlme* (Pinheiro et al., 2021) to run a linear mixed effects analyses of response times/accuracy data collected during the simple reaction time task and implicit/explicit MI evaluations. We

thus built a series of random-coefficient regression models with by-subject random intercepts. Due to the binomial distribution of response accuracy data for implicit MI tasks, we implemented logistic regression models using general linear modeling functions available from the *lme4* package (Bates et al., 2015). For the simple reaction time task, we entered the fixed effects of GROUP (CONTROL, SCI<sub>C6</sub>, SCI<sub>C7</sub>) and HAND LATERALITY (LEFT, RIGHT), with interaction term. To analyze response time and accuracy data on the hand laterality judgment task, we entered the interaction between the GROUP factor and the fixed effects of HAND LATERALITY, HAND VIEW (PALM VIEW, BACK VIEW) and HAND ORIENTATION (0°, 90°, 180°, 270°). For the hand-object interaction task, RT and accuracy data were analysed using the interaction between the fixed effect of GROUP and HAND (LEFT, RIGHT), CONGRUENCY (CONGRUENT, INCONGRUENT) and PREHENSION TYPE (FORCE GRIP, PRECISION GRIP). For PP and MI durations collected during explicit MI evaluations, we built a linear mixed effects model testing the fixed effects of GROUP, TASK (FOREARM SWEEP, LATERAL GRIP, DIGITAL DISSOCIATION) and CONDITION (MOTOR IMAGERY, PHYSICAL PRACTICE), with interaction term. The statistical threshold was set up for a type 1 error rate of 5%. As effect sizes, we reported partial coefficients of determination ( $\eta_p^2$ ) using the ad-hoc procedure for linear mixed-effects models implemented in the *effectsize* package (Ben-Shachar et al., 2020). Post-hoc investigations were carried out using general linear hypotheses testing of planned contrasts from the *multcomp* package (Hothorn et al., 2008). We applied Holm’s sequential corrections to control the false discovery rate (Holm, 1979).

### 3. Results

#### 3.1. Simple reaction time task

Raw RT values measured during the simple reaction time task are shown in Table 1. RT collected during the simple reaction time task were not affected by the two-way *GROUP* × *HAND* interaction, nor by the main effects of *HAND* and *GROUP* (i.e. all  $p > 0.05$ ).

#### 3.2. Hand laterality judgment task

The analysis of accuracy data revealed a *GROUP* × *ANGLE* interaction ( $\chi^2(6) = 15.72$ ,  $p < 0.05$ ,  $\eta_p^2 < 0.01$ ). The difference in accuracy between 0° and 180° orientations in the CONTROL group (0°: 2.67% error rate; 180°:

	CONTROL	SCI <sub>C6</sub>	SCI <sub>C7</sub>
Right	0.50 s ± 0.15	0.64 s ± 0.21	0.62 s ± 0.29
Left	0.49 s ± 0.16	0.53 s ± 0.16	0.60 s ± 0.26

Table 1: Raw RTs for the simple reaction time task across groups ( $M \pm SD$ ).

24% error rate) was greater than that in the SCI<sub>C7</sub> group (0°: 11.61% error rate; 180°: 21.43% error rate) ( $p < 0.01$ ). There was also a main effect of ANGLE ( $\chi^2(3) = 86.55$ ,  $p < 0.001$ ,  $\eta_p^2 < 0.05$ ), due to a higher error rate for 180° stimulus orientation compared to {0°, 90°, 270°} stimuli orientations (all  $p < 0.001$ , Figure 2).

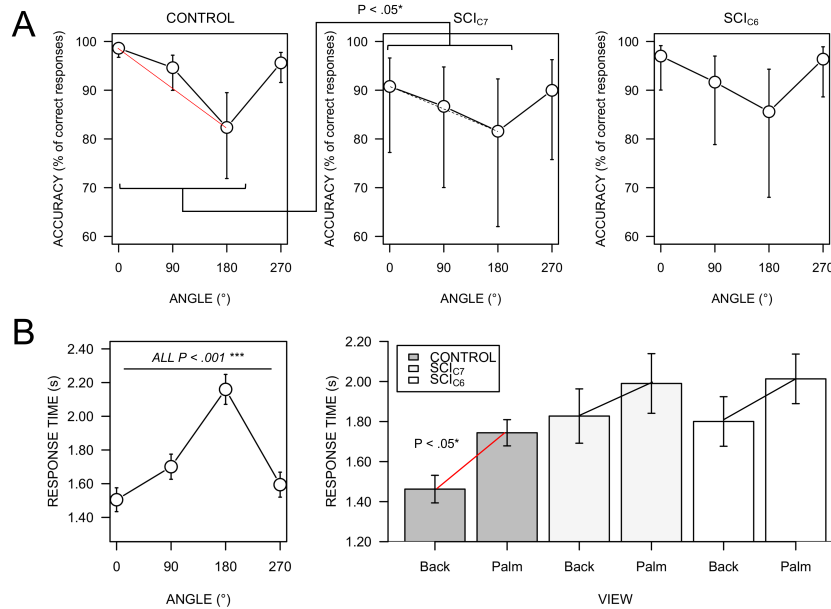


Figure 2: A. Illustration of the  $ANGLE \times GROUP$  interaction found on the accuracy of hand laterality judgments. The slope between 0° and 180° orientations in the CONTROL group was steeper than that in the SCI<sub>C7</sub> group. B. RTs were affected by the main effect of ANGLE in all groups (left panel). By contrast, the main effect of VIEW on response times higher in CONTROLS compared to SCI<sub>C7</sub> and SCI<sub>C6</sub> participants (right panel).

RTs during hand mental rotation were affected by the two-way  $GROUP \times VIEW$  interaction ( $F(2, 1916) = 5.23$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.02$ ). Post-hoc comparisons revealed that the RT difference between BACK VIEW and PALM

VIEW in the CONTROL group (BACK VIEW:  $1.46 \text{ s} \pm 0.81$ ; PALM VIEW:  $1.74 \pm 0.86$ ) was higher than that observed in SCI<sub>C6</sub> (BACK VIEW:  $1.80 \text{ s} \pm 0.88$ ; PALM VIEW:  $2.01 \pm 0.90$ ) and SCI<sub>C7</sub> (BACK VIEW:  $1.83 \text{ s} \pm 0.95$ ; PALM VIEW:  $1.99 \pm 1.02$ ) groups (both  $p < 0.05$ , Figure 2A). There was also a main effect of ANGLE ( $F(3, 1916) = 93.22$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.13$ ). RT differed for all hand orientations (all  $p < 0.001$ , see Figure 2). The main effect of LATERALITY approached the statistical significance threshold ( $F(1, 1916) = 3.23$ ,  $p = 0.08$ ,  $\eta_p^2 = 0.01$ ), with shorter RT for the DOMINANT ( $1.69 \text{ s} \pm 0.87$ ) compared to NON DOMINANT hand pictures ( $1.75 \text{ s} \pm 0.92$ ).

### 3.3. Hand orientation judgment task

Frequencies of pronation/supination judgements were affected by the two-way *GROUP*  $\times$  *ANGLE* interaction ( $\chi^2(14) = 250.85$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.08$ ). Post-hoc analyses showed that ANGLE affected frequencies of pronation/supination judgements similarly in the CONTROL and SCI<sub>C7</sub> groups (Figure 3). CONTROL and SCI<sub>C7</sub> participants reported preferentially pronation judgments for  $\{225^\circ, 270^\circ, 315^\circ\}$  orientations, whereas  $\{45^\circ, 90^\circ, 135^\circ, 180^\circ\}$  orientations yielded primarily supination judgements (Figure 3). By contrast, in SCI<sub>C6</sub> patients all stimuli orientations yielded evenly distributed pronation and supination prospective judgements, i.e. frequencies ranging between 40-60% (Figure 3). Post hoc comparisons showed that the difference between  $0^\circ$  and  $\{45^\circ, 90^\circ, 135^\circ\}$  in prehensile judgment observed in CONTROLS and SCI<sub>C7</sub> was greater than that observed in SCI<sub>C6</sub> patients (all  $p < 0.001$ ). Likewise, the difference between  $\{45^\circ, 90^\circ, 135^\circ, 180^\circ\}$  and  $\{225^\circ, 270^\circ, 315^\circ\}$  orientations was greater in CONTROLS and SCI<sub>C7</sub> than the corresponding differences in SCI<sub>C6</sub> (all  $p < 0.001$ , Figure 3).

RTs on the hand orientation task were only affected by the two-way *GROUP*  $\times$  *ANGLE* interaction ( $F(14, 3114) = 2.31$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.01$ ). The only contrast which survived the corrected statistical significance threshold for post-hoc comparisons was the difference between  $270^\circ$  and  $315^\circ$  stimuli orientations for RT in the CONTROL group ( $270^\circ$ :  $1.04 \text{ s} \pm 0.55$ ;  $315^\circ$ :  $1.23 \text{ s} \pm 0.65$ ), which was greater than the corresponding difference between the two stimuli orientations in the SCI<sub>C6</sub> group ( $270^\circ$ :  $1.42 \text{ s} \pm 0.76$ ;  $315^\circ$ :  $1.28 \text{ s} \pm 0.67$ ) ( $p < 0.05$ ).

### 3.4. Hand-object interaction judgment task

Accuracy data was only affected by the main effect of GRIP ( $\chi^2(6) = 6.07$ ,  $p < 0.01$ ,  $\eta_p^2 = 0.01$ ), with a higher error rate for the PRECISION GRIP

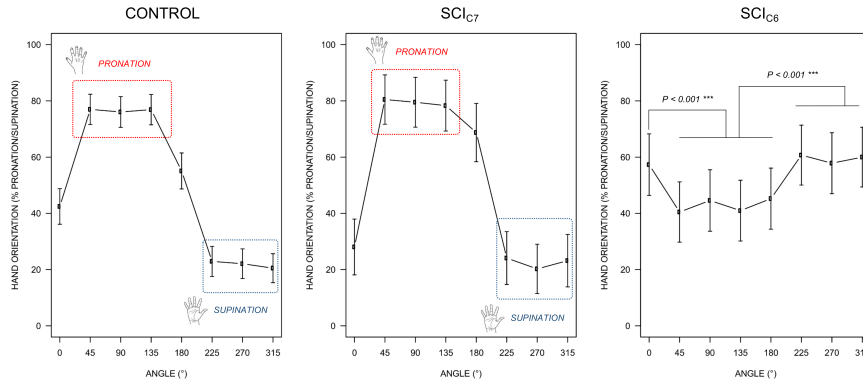


Figure 3: *GROUP*  $\times$  *ANGLE* interaction effect on response accuracy for hand orientation judgments. A similar pattern of pronation/supination preferential hand orientation judgments emerged across the the different stimuli orientations in the CONTROL and SCI<sub>C7</sub> group. However, such pattern of pronation/supination preference was absent in SCI<sub>C6</sub> participants who had physical impairment of pronation/supination movements.

(3.08%) compared to the FORCE GRIP grip (1.48%).

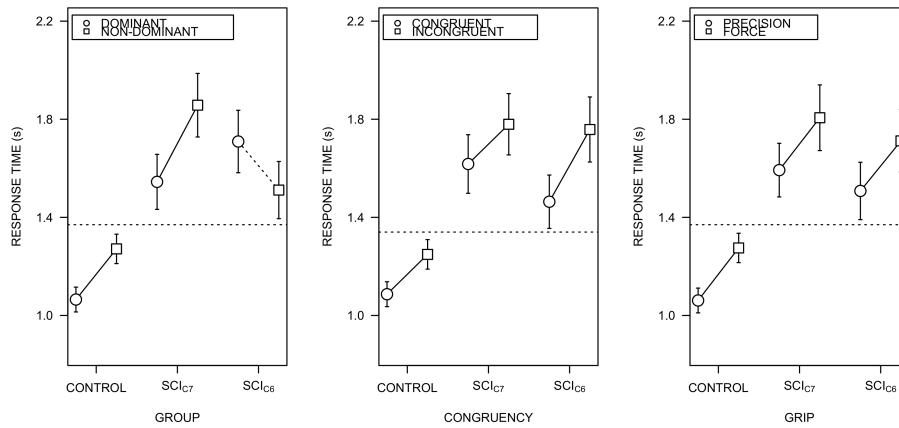


Figure 4: Illustration of the *GROUP*  $\times$  *LATERALITY* interaction effect on RTs for hand-object interaction judgments. SCI<sub>C6</sub> participants did not exhibit the shorter RTs pattern found in CONTROL and SCI<sub>C7</sub> participants for the DOMINANT compared to NON-DOMINANT hand-object interaction stimuli. Interestingly, *LATERALITY* and *GRIP* yielded comparable effects on RTs across groups.

The analysis of RTs revealed a two-way *GROUP*  $\times$  *LATERALITY* interaction effect ( $F(2, 2016) = 19.14, p < 0.001, \eta_p^2 = 0.02$ ). No other two-way interaction was observed (all  $p > 0.05$ ). The RT difference between object stimuli displayed for the DOMINANT and NON-DOMINANT hands was greater in the CONTROLS (DOMINANT:  $1.06 \text{ s} \pm 0.65$ ; NON-DOMINANT:  $1.27 \text{ s} \pm 0.65$ ) and SCI<sub>C7</sub> (DOMINANT:  $1.54 \text{ s} \pm 0.85$ ; NON-DOMINANT:  $1.86 \text{ s} \pm 0.96$ ) than in SCI<sub>C6</sub> participants (DOMINANT:  $1.71 \text{ s} \pm 0.96$ , NON-DOMINANT:  $1.51 \text{ s} \pm 0.88$ ) (both  $p < 0.001$ , Figure 4). The difference between stimuli for the DOMINANT vs. NON-DOMINANT hand was similar in the CONTROL and SCI<sub>C7</sub> groups ( $p > 0.05$ ). We also found a main effect of CONGRUENCY ( $F(1, 2106) = 53.68, p < 0.001, \eta_p^2 = 0.02$ ) and GRIP ( $F(2, 2016) = 65.10, p < 0.001, \eta_p^2 = 0.03$ ). RT were longer during the INCONGRUENT ( $1.46 \text{ s} \pm 0.89$ ) compared to CONGRUENT ( $1.27 \text{ s} \pm 0.78$ ) object orientations. RT were eventually longer for the PRECISION GRIP ( $1.47 \text{ s} \pm 0.89$ ) compared to the FORCE GRIP ( $1.26 \text{ s} \pm 0.78$ ).

### 3.5. Explicit motor imagery evaluations

The ANOVA table for the linear mixed effect model carried on PHYSICAL PRACTICE and MOTOR IMAGERY durations for the FOREARM SWEEP, LATERAL PALMAR GRIP and DIGITAL DISSOCIATION tasks is shown in Table 2.

	Num DF	Den DF	F	p-value	$\eta_p^2$
GROUP	2	31.578	0.90	0.42 NS	0.05
TASK	2	253.45	0.71	0.49 NS	< 0.01
COND	1	252.98	9.77	0.001 **	0.04
TRIAL	1	252.98	0.48	0.49 NS	< 0.01
GROUP:TASK	4	253.397	15.77	< 0.001 ***	0.20
GROUP:CONDITION	2	252.98	0.18	0.83 NS	< 0.01
TASK:CONDITION	2	252.98	5.88	0.003 **	0.04
GROUP:TASK:CONDITION	4	252.98	1.02	0.40 NS	0.02

Table 2: Table 2. ANOVA table computed for the linear mixed effects model fitted to actual and imagined durations collected during explicit MI evaluations.

Post-hoc investigations of the *GROUP*  $\times$  *TASK* interaction showed that the difference between the LATERAL GRIP and the DIGITAL DISSOCIATION durations in the CONTROL group (LATERAL GRIP:  $13.63 \text{ s} \pm 5.64$ ; DIGITAL DISSOCIATION:  $13.66 \text{ s} \pm 3.12$ ) was reduced compared to that in SCI<sub>C7</sub>



(LATERAL GRIP:  $13.06 \text{ s} \pm 5.24$ ; DIGITAL DISSOCIATION:  $16.01 \text{ s} \pm 3.71$ ) and SCI<sub>C6</sub> (LATERAL GRIP:  $14.66 \text{ s} \pm 4.24$ ; DIGITAL DISSOCIATION:  $15.89 \text{ s} \pm 4.39$ ) participants (both  $p < 0.001$ ). Likewise, FOREARM SWEEP durations were longer than the finger pinch duration in the CONTROL group (FOREARM SWEEP:  $17.95 \text{ s} \pm 5.73$ ), whereas an opposite pattern was found in SCI<sub>C6</sub> (FOREARM SWEEP:  $14.10 \text{ s} \pm 3.30$ ) and SCI<sub>C7</sub> (FOREARM SWEEP:  $13.04 \text{ s} \pm 4.12$ ) participants (both  $p < 0.001$ ). For the *TASK*  $\times$  *CONDITION* interaction, post-hoc comparisons showed that MOTOR IMAGERY durations for the FOREARM SWEEP ( $15.19 \text{ s} \pm 5.02$ ) and LATERAL GRIP ( $14.87 \text{ s} \pm 5.57$ ) were shorter than PHYSICAL PRACTICE durations (FOREARM SWEEP:  $18.08 \text{ s} \pm 5.72$ ; LATERAL GRIP:  $16.72 \text{ s} \pm 5.07$ ) ( $p < 0.01$ ), whereas an opposite pattern was observed for the DIGITAL DISSOCIATION task (PHYSICAL PRACTICE:  $13.70 \text{ s} \pm 3.70$ ; MOTOR IMAGERY:  $14.99 \text{ s} \pm 3.61$ ) ( $p > 0.05$ ).

#### 4. Discussion

The present study sought to disentangle whether MI ability was spared or impaired after SCI. We conducted implicit and explicit MI ability tests in two groups of SCI participants and a group of healthy controls. We controlled for the influence of upper limb motor deficits on RTs recorded during implicit MI assessments, using a preliminary simple reaction time task. Our results revealed selective impairments of implicit and explicit MI ability after SCI. Compared to controls, MI ability changes in SCI participants overall reflected the actual motor impairments. This postulate is consistent with the systematic review of MI ability profiles in neurologic populations (Di Rienzo et al., 2014a). Changes in implicit MI ability were superior in SCI<sub>C6</sub> than in SCI<sub>C7</sub> participants, particularly during MI tasks which involved representations of elbow movements that SCI<sub>C6</sub> participants were no longer able to perform physically. Present findings support that MI ability profiles in SCI participants should not be interpreted as degraded MI ability *per se*, but rather as the integration of the chronic state of de-afferentation and de-efferentation in the cognitive processes mediating action representation.

We administered the well-known hand laterality judgement task, with four hand stimuli orientations and two hand views. A pioneering study by Fiori et al. (2014) reported that SCI participants did not exhibit the biomechanical constraint effects of stimuli orientation compared to controls. The authors concluded that body representations were impaired as a result of the chronic state of deafferentation and defferentation. Recently, Vastano and

Widerstrom-Noga (2023) observed increased RT to identify the laterality of both 75° and 150° hand stimuli orientations in SCI compared to control participants, thus confirming the hypothesis that SCI might affect both early processing of the visual stimuli and later components of higher-order cognitive motor processes mediating the mental rotation of body parts. We found here that the different stimuli orientations had a similar effect on RT in SCI<sub>C6</sub>, SCI<sub>C7</sub> and control groups – although the difference between 0° and 180° orientation was superior in controls. This pattern of RT changes in all groups is consistent with the well-established effect of unfamiliar orientations (e.g. 180°), which typically requires more time to be identified than more familiar hand orientations (Nico et al., 2004). The present results contradict past observations of RT patterns reported in hand laterality judgment paradigms in SCI populations (Fiori et al., 2014; Vastano and Widerstrom-Noga, 2023). Such inconsistencies may account for differences in the sample of SCI participants across studies. For instance, both quadriplegic and paraplegic SCI participants were included in Vastano and Widerstrom-Noga (2023)’s study, with ASIA scores ranging A-D. By contrast, our sample exhibited quadriplegia with ASIA A scores. Vastano and Widerstrom-Noga (2023) used 2 hand stimuli orientation in their implicit MI design (75° and 150°), whereas most hand laterality judgment paradigm, including ours, involve more than 4 different hand orientations. This makes comparisons of the results pattern between studies difficult. Admittedly, we found that in the control group palm hand views took more time to be identified than back hand views. This, again, reflects the familiarity of the hand stimuli, back views corresponding to the most frequent hand orientations in daily life (Nico et al., 2004). While our results do indicate that implicit MI ability may be largely preserved after SCI across different stimuli orientations, both SCI participants groups exhibited a reduced effect of the hand view on their RT compared to controls. This corresponds to past observation of reduced biomechanical constraints effects after SCI (Fiori et al., 2014). Switching from palm to back hand views requires elbow rotation, and difficulties/inability to perform such movement physically could account for the attenuation of the hand view effect. Taken together, our results advocate for primarily spared implicit MI ability after SCI. Differences from motor deficits. The cortical mechanisms underlying hand laterality judgments may thus be preserved after SCI, and incorporate changes resulting from the chronic state of deafferentation and deafferentation (Ionta et al., 2016).

Additional results supporting the selective impairment hypothesis of MI

ability after SCI emerged from the hand orientation judgment task. Compared to controls, abnormal patterns of hand orientation judgments were found in SCI<sub>C6</sub> participants only, for whom elbow movements were the most severely impaired. Conversely, we found identical patterns of pronation/supination judgments ratios across the different object orientation in SCI<sub>C7</sub> and control participants. There was a prevalence of pronation judgments for 45°, 90° and 135° orientations and a prevalence of supination judgments for 225°, 270° and 325° orientations. Data attested that controls and SCI<sub>C7</sub> participants had comparable implicit MI of elbow movements across object orientations, but not in the SCI<sub>C6</sub> group who responded at the level of chance for all object orientations. Comparable findings emerged from the analysis of RT. After a C6 SCI, elbow movements are severely impaired due to paralysis of the *supinator* muscle (posterior interosseus nerve, C6-C7). Although some compensation can be achieved by the *biceps brachii* (musculocutaneous nerve, C5-C6), elbow movement in the horizontal plane requires innervation of *pronator teres* (median nerve, C6-C7) and *pronator quadratus* (median nerve, C8 and T1) muscles without possible compensation (Md, 2006; O'Brien, 2023). The hand orientation judgment task clearly shows the deleterious influence of an incapacity to physically perform the movement on implicit MI ability. This is consistent with previous reports of a selective changes in MI ability after SCI, and suggests that MI ability profiles should not be considered independently from the actual sensorimotor deficits (Fiorio et al., 2006; Di Rienzo et al., 2014a). Replicating the implicit MI paradigm from Daprati et al. (2010), however, suggests the potential recovery of implicit MI ability for goal-directed actions, i.e. grasping actions of daily life objects targeted by rehabilitation. RT were not different between groups for hand-object interaction judgements requiring either palmar or precision grips. While RT were shorter for the dominant compared to non-dominant upper-limb actions in controls and SCI<sub>C7</sub>, but not SCI<sub>C6</sub> participants, the effect of the congruency of the object orientation or the type of grasping action required on RT was comparable across groups (Nico et al., 2004; Ionta et al., 2007).

Explicit MI ability of upper limbs movements indexed from mental chronometry were unchanged after SCI, including for physically impossible actions due to SCI (i.e., digital dissociation). Past experiments established that SCI participants were able to differentiate MI from attempted voluntary movement for actions that engaged somatic effectors innervated below the neurologic level (Hotz-Boendermaker et al., 2008). Temporal congruence between the duration of actual and imagined actions was comparable across groups. This

is consistent with previous reports showing no difference in movement times between tetraplegic and healthy individuals during daily life upper limb actions, such as signing and drawing (Decety and Boisson, 1990). Nevertheless, between-group differences in duration were observed between the motor tasks, irrespective of the actual or imagined performance condition. Forearm sweep was both physically and mentally performed faster than the digital dissociation task in SCI participants, whereas both movements had a similar duration in controls. Forearm sweep with the elbow flexed is a familiar action for SCI participants, since it is part of the motor rehabilitation. This movement is used to bring objects closer to the body before grasping, or for its compensatory role during grasping of small objects using the edge of a table. By contrast, forearm sweep with elbow flexion has no specific function in controls. Mental chronometry thus reflected task habituation in both SCI and control groups without distortion of the temporal congruence (Guillot and Collet, 2005). The situation is opposite for the finger dissociation task, which can be performed easily by controls but is impossible after cervical SCI.

## 5. Conclusion

The present study included an homogeneous sample of participants with motor-complete cervical SCI. MI ability was largely preserved compared to age- and gender-matched control individuals. This is consistent with recent functional brain imaging evidence of largely preserved brain activation patterns in SCI patients during MI of lower limb movements (Wang et al., 2023). Although selective impairments in MI ability emerged for implicit MI tasks requiring manipulating elbow movement representations – particularly in the SCI<sub>C6</sub> group — it is suggested that the functional equivalence between actual and imagined action is preserved after cervical SCI and that MI training could be recommended to improve functional outcomes in rehabilitation (Di Rienzo et al., 2014a; Chen et al., 2016; Cramer et al., 2007; Wang et al., 2023). The overall preservation of a congruent pattern of MI ability with regards to the current motor repertoire could be the result of the modified prehensile strategies, with regular use of the tenodesis grasp in daily life contributing to maintain the internal models of upper limb actions by providing sensory feedback to the forward model. A pioneering neuroimaging study revealed that, for lower limb movements that SCI participants could no longer perform physically, MI training restored activation of the putamen

and globus pallidus which are known to play a key role during the early stages of motor learning (Cramer et al., 2007). The preservation of cognitive motor processes involving upper limb motor representations suggests that individuals with C6 or C7 quadriplegia could benefit from MI training to improve tenodesis grasp strategies. MI training focusing upper limb motor functions, with a particular emphasis on the active wrist extension, could potentiate the effects of classical rehabilitation programs targeting tenodesis grasp coordination (Mateo et al., 2015; Di Rienzo et al., 2014b). Future studies should thus further decipher the possibility of counterbalancing selective changes in implicit MI ability, as shown for explicit MI ability in earlier experiments (Mateo et al., 2018; Cramer et al., 2007).

## **6. Author contributions**

FDR, AGU and CC conceptualized the experiment. FDR, SM and SH designed the methodology. Investigations were conducted by SH, FDR and SM, while SM, SH and AGE participated to the data curation. SM and FDR performed the formal analysis. GR, CC and AGU were involved in providing resources, supervision and project administration. SD provided the software. SM and FDR wrote the original draft which was revised edited by all co-authors. All authors approved the final version of the submitted manuscript.

## **7. Declaration of interest**

The authors have nothing to disclose.

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