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Influence of Sports on Cortical Connectivity in Patients with Spinal Cord Injury-A High-Density EEG Study

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Abstract: Background: Minutes after an injury to the spinal cord, structural and functional reorganization of the connected brain areas may be initiated. Exercise enhances this neuroplasticity in the further course of the condition, which might modulate the connectivity patterns in brain regions responsible for movement execution and imagination. However, connectivity patterns have not been analyzed as a correlate for activity effects on neuroplasticity after spinal cord injury (SCI). We hypothesize that wheelchair sport has a modulating effect on the cortical connectivity in patients with SCI, such that distinguished activity patterns can be observed between sportive and non-sportive individuals with SCI and healthy participants. Methods: Sportive (n = 16) and non-sportive (n = 7) patients with SCI as well as sportive (n = 16) and non-sportive (n = 14) healthy participants were instructed to either observe, imagine, or conduct an observed movement while high-density EEG (HD-EEG) was recorded. Functional connectivity was computed from the recorded signals, and the coefficients were compared between groups and conditions using a non-parametric repeated measures analysis. Results: We found that depending on being sportive or not, patients with SCI and controls would react differently to the conditions, but the effects depended on the location in the brain as well as the analyzed frequency range ($p < 0.05$). Further analysis indicates that non-sportive patients showed higher connectivity received by the right posterior parietal cortex and a lower connectivity received by the left M1 compared to sportive patients. These effects were mainly observed during movement imagination, not during movement. Sportive and non-sportive participants in the healthy control group showed smaller differences than the patients. Conclusions: The results suggest a modulative effect of sports on connectivity patterns during movement imagination and to some extent during movement. This effect was predominantly found in patients with SCI, and to a lesser extent in healthy participants with opposing connectivity patterns. We suggest that this might be due to increased cortical excitability and the elevated brain derived neurotrophic factor (BDNF) level in patients with SCI that is enhanced by exercise.

Keywords: spinal cord injury; wheelchair sports; exercise; cortical connectivity; HD-EEG

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1. Introduction

Minutes after an injury to the spinal cord, structural and functional reorganization of the affected brain areas is initiated [1–3]. Deafferentation and lack of proprioception lead to remodeling processes in the brain in the sense of a negative-maladaptive neuroplasticity, and thus to a long-term reorganization of the cortical topography [3].

However, neuroplasticity is a two-way street, and as the disease progresses, there are various possibilities to either strengthen or weaken the utilized pathways. Studies on both animal models and humans indicate that cortical structures are highly adaptable after deafferentation [4–9]. In the chronic state of the disease, exercise enhances neuroplasticity, which might modulate connectivity patterns in brain regions responsible for movement imagination and execution [10]. A transcranial magnetic stimulation (TMS) study by Nardone and colleagues demonstrated that cortical excitability is increased in patients with spinal cord injury (SCI) after passive cycling [10]. A further TMS study on healthy racquet players revealed the impact of specific training on brain activity. Healthy professional racquet players showed increased cortical excitability in the hand muscles that was laterally and medially shifted on the motor cortex as compared to non-professional racquet players [11]. Evidence for plastic changes in the brain due to specification of long-term sports is also given by TMS study results for healthy tennis players [12]. Moreover, motor imagery of tennis, but not golf or table tennis, resulted in increased corticospinal facilitation of the associated muscles in expert tennis players. Notably, this effect of motor imagery was not observed for novice tennis players.

One possibility to intensify and support physical training is the use of motor imagery (movement imagination) that is described as a mental representation of an action without an actual motor output [13]. Also during motor imagery, increased cortical excitability could be observed in patients with SCI. EEG data revealed similar primary motor cortex activation during movement imagination and execution, while in healthy participants the activity was reduced during movement imagery [14]. Lacourse and colleagues revealed that inhibitory processes during imagined movements of an intact limb may be weakened by SCI so that movement and imagery processes yield more similar EEG patterns in patients with SCI in comparison to healthy subjects [15].

There is evidence that movement imagination training improves motor performance, modifies brain function, and reduces pain in patients with SCI [16,17]. Motor imagination training of the right foot resulted in increased functional magnetic resonance image (fMRI) activation of the left putamen and improved speed of movement in non-paralyzed muscles. Athanasiou and colleagues examined patients with incomplete SCI conducting a movement imagination task during high-density electroencephalography (HD-EEG) recording and found a significant decrease in connectivity between subsets of the functional sensorimotor network. The authors also discovered increased local processing, which possibly indicates an adaptive compensatory mechanism of injury-induced neuroplasticity [18]. A review showed that movement imagination of possible non-paralyzed movements was found to improve reach-to-grasp performance by increasing both tenodesis grasp capabilities and muscle strength. Additionally, movement time and trajectory variability decreased, whereas EEG, functional magnet resonance imaging, and magnetoencephalography data analysis revealed a reduction in the abnormally increased brain activity [19].

Searching the literature for EEG studies on movement imagination in patients with SCI mainly resulted in studies on brain–computer interfaces [20–23]. The aim of these studies is the better understanding of EEG patterns and their discriminability between movements in patients with SCI. However, the possible influence of physical training and motor imagination on neurophysiological correlates of neuroplasticity has rarely been considered by previous research, and especially not with respect to networks. Network analysis in the sense of measuring statistical connectivity between regions of interest reveals more subtle patterns of neuroplasticity as compared to analysis of regional volume change or activation patterns. In the present work, we ask the question of whether patients with SCI show differential effects in connectivity patterns in response to movement and imagination of movement depending on being sportive or not. Firstly, this work contributes to a deeper understanding of neuroplasticity in SCI patients, which is of great interest for rehabilitation [24]. Secondly, it provides information on cortical activity during movement imagination. This is relevant, as motor imagination training might be a valuable supplement to existing therapies. Thirdly, we focus on the effect of wheelchair sports on the cortical connectivity measured by HD-EEG in patients with SCI, which has not been done before. We hypothesize that wheelchair sport has a modulating effect on the cortical connectivity within and between motor and sensory areas in patients with SCI during movement imagination and movement execution.

2. Methods

2.1. Ethics

This study was performed in line with the principles of the Declaration of Helsinki and was approved by the local ethics committee (415-E/1890/11-2016). All participants signed an informed consent form.

2.2. Participants

We recruited 25 patients with SCI from the hospital's residential or ambulance station and by contacting wheelchair sports clubs. Patients were categorized into a non-sportive ($n = 9$) and a sportive group ($n = 16$). The sportive patients conducted wheel chair dancing ($n = 9$), wheelchair basketball ($n = 2$), hand-biking ($n = 3$), or drove marathon ($n = 2$), while patients in the non-sportive group did not practice any sports on a regular basis. Thirty healthy participants were recruited and split into a sportive ($n = 16$) and a non-sportive ($n = 14$) group; we defined participants to be sportive if they engaged in exercises more than once a week.

2.3. Paradigm

For the high-density EEG (HD-EEG) recording, patients sat in front of a computer screen in a quiet room. The screen was used to display the experiment. Sound was delivered via the built-in boxes of the presentation computer. The paradigm was programmed in Matlab (The Mathworks) [25] using the Psychophysics toolbox [26,27]. The experiment consisted of six conditions, each of which was repeated in 24 trials. All 6×24 trials were presented in randomized order. In each trial, participants saw a video of a person rhythmically moving their shoulders to a sound, imitating upper-body dance moves. Participants were then either asked to (1) simply watch the video (resting condition), (2) imitate the movement within the rhythm (movement condition) or (3) to imagine performing the movement (movement imagination condition). In order to facilitate rhythmic timing of the participants' movements and imagined movements, we gave them a rhythmic, acoustic cue. Accompanying the video was either a musical song excerpt ("A night like this—instrumental version" by Caro Emerald with 123 beats per minute) or two alternating beeping sounds with 2 Hz frequency. This resulted in 6 conditions: rest-music, rest-beep, movement-music, movement-beep, imagination-music, and imagination-beep. Each condition lasted for 6 s, after which an inter-trial interval of 6.5 s showed the instruction for the following trial. Video and sound material was prepared using Apple Inc.'s iMovie (Apple Distribution International Ltd. Hollyhill Industrial Estate Hollyhill, Cork, Ireland). In the further course of the manuscript, we refer to *condition* as movement or movement imagination and to *sound* as beep or music.

2.4. HD-EEG Data Recording

HD-EEG was recorded with 256-channel HydroCel geodesic sensor nets and a GES 400 amplifier (Koninklijke Philips N.V., Amsterdam, The Netherlands) digitally sampled at 1000 Hz using Philips' NetStation 4.5.6 software. Impedances were kept below 75 kΩ, adhering to proposed guidelines [28,29]. The acquired data were first filtered between 0.1 Hz and 80 Hz using an FIR Bandpass filter with a roll-off of 1 Hz and the passband as well as the stopband gain set to 0.1 dB and 40 dB, respectively. In addition, a 50 Hz notch filter was applied to eliminate line noise.

2.5. HD-EEG Data Preprocessing

Data were segmented for each experimental condition into segments of 6 s length, following the length of the trials (i.e., video and sound duration). A baseline correction was performed for an entire segment based on the average activity of the entire segment. Channels were manually screened for corrupted signals, especially taking into account ocular channels, and in case the overall quality of single channels was poor, individual channels were replaced by average values from neighboring channels. Finally, all EEG segments were exported as .mat files for further analyses.

2.6. HD-EEG Connectivity Analysis

Using the software Matlab (Version 9.5.0) [25], data from EEG channels were averaged according to 10 pre-defined regions over both hemispheres: primary motor cortex (M1), primary somatosensory cortex (S1), premotor cortex (PMC), supplementary motor area (SMA) and posterior parietal cortex (PPC). A figure outlining the channels pertaining to each of these regions of interest is given in the Supplementary Materials (Table S1, Figure S1). Brain regions and respective electrodes were adapted from the recent literature [18,30]. For each segment, autoregressive models were calculated using the mvfreqz.m and mvar.m function implemented within the BioSig toolbox [31]. The multivariate autoregressive models were calculated for all region x region combinations and for the two frequency bands of interest (alpha: 7–13 Hz, and beta: 13–39 Hz). The model order was chosen in adherence with two boundary criterions: first, the maximum model order was set at 200, thus guaranteeing the adherence with a proposed ratio of 3:1 between given samples and the number of estimates [32]. Second, given the aim to estimate measures for 34 frequency components and the spatial sampling of 10 regions, the model order needed to be above 6.8 to ensure valid mapping of respective components [33]. Based on these restrictions, we performed a model optimization procedure, calculating for each subject and trial an autoregressive model with model orders 7 to 200 and deriving the Schwarz Bayesian criterion for each model using the artif2.m function of the tsa toolbox [34]. Following this, we calculated the optimal model order for each participant as an average from the respective trials and performed the final calculation of the multivariate autoregressive models based on this average of optimal model orders (see Table S2 in Supplementary Materials for individual averaged model order). From these coefficients, we derived the full frequency directed transfer function (ffDTF), a directed measure of interaction normalized with respect to all of the frequencies in the predefined frequency interval [35]. For each subject, the mean connectivity matrices over the trials were calculated. In order to remove activation due to the visual and auditory stimulation, we subtracted the connectivity of the resting condition from the movement and movement imagination conditions as follows:

- Watching the movie + beep was subtracted from movement imagination + beep.
- Watching the movie + beep was subtracted from movement + beep.
- Watching the movie + music was subtracted from movement imagination + music.
- Watching the movie + music was subtracted from movement + music.

2.7. Statistics

Statistical data analysis was conducted using the statistical software package R (version 4.2.1) [36]. To test the overall effects according to our hypotheses, we conducted a semi-parametric repeated measures ANOVA that allowed for non-normality and variance heterogeneity [37] using the function RM from the package MANOVA.RM [38]. The ANOVA included the between-subject factors group (healthy control, SCI patients) and sport group (sportive, non-sportive), and the within-subject (repeated measures) factors frequency (alpha, beta), source (M1l, M1r, S1l, S1r, PMCl, PMCr, SMAl, SMAr, PPCl and PPCr), sink (same regions as source), movement condition (imagination, movement), and sound condition (beep, music). We extracted the significant effects and interactions from that model. Next, in order to investigate which regional interactions, condition, sound, and frequency ranges showed significant group x sport group interaction, we conducted tests via nonparametric two-factorial tests provided by the R-package rankFD [39], using group and sport group as between-subject factors. We fitted one model for every combination of frequency, source, sink, movement condition, and sound condition. This resulted in 800 *p*-values, which we adjusted to control the false discovery rate (FDR) using the Benjamini–Yekutieli method [40].

3. Results

3.1. Demographic and Clinical Data

Two of the recruited patients had to be excluded from data analysis, as HD-EEG recording could not be completed due to software problems. We included 23 patients (9 women, 14 men) with an average age of 47.4 years (SD = 13.1). Clinical characteristics of the patients varied between an American Spinal Injury Association (ASIA) score of A to D, complete and incomplete lesions, as well as traumatic and non-traumatic etiologies (Table 1). The 30 healthy participants (17 women, 13 men) had an average age of 44.2 years (SD = 14.3).

Table 1. Overview of individual patients including age, lesion characteristics, ASIA score, and group.

	w/m	Age	Traumatic/Non-t.	ASIA Score	Lesion	Complete/Incomplete	Age of Injury	Group
1	w	62	NT	B	Th10	C	5 m	PNS
2	w	46	T	C	L1	IC	36 y	PNS
3	w	31	T	A	Th5	C	5 y	PNS
4	m	20	NT	A	Th10	C	2 m	PNS
5	m	60	T	D	C4	IC	5 y	PNS
6	m	49	T	D	C6	IC	4 y	PNS
7	m	57	T	A	Th12	C	13 y	PNS
8	w	45	T	B	C7	IC	7 y	PS
9	w	48	T	C	L1	IC	28 y	PS
10	m	70	T	D	L2	IC	5 m	PS
11	m	25	NT	A	T10	C	25 y	PS
12	m	47	T	A	C6	C	18 y	PS
13	w	61	T	A	Th8	C	6 y	PS
14	w	52	T	A	Th12	C	36 y	PS
15	w	32	T	A	Th7	C	17 y	PS
16	m	42	T	A	Th9	C	25 y	PS
17	m	47	T	A	Th5	C	25 y	PS
18	m	54	T	B	C6	IC	37y	PS
19	m	51	T	A	L2	C	33 y	PS
20	m	66	NT	C	L3	IC	7 y	PS
21	m	55	NT	A	L3	C	31 y	PS
22	w	40	T	B	L2	IC	18 y	PS
23	m	30	T	A	L5	C	10 y	PS

T = traumatic injury, NT = non-traumatic injury, C = complete SCI, IC = incomplete SCI, Cx = cervical, Thx = thoracic, Lx = lumbar, PNS = patients who are not practicing sports, PS = patients who practice sports, y = years, m = months.

3.2. Connectivity Analysis

There were several significant interactions between group and sport group (see Table 2), which depended on the location (sink/source) but also the frequency and the condition. These significant interactions indicated that depending on being sportive or not, patients with SCI and controls yielded different activation patterns depending on the conditions, the location in the brain as well as the measured frequency range. Moreover, two of these interactions included the factor sound, indicating that sportive participants reacted differently to music vs. beep sounds as compared to non-sportive participants.

To determine the direction of effect and which frequency range and location were most responsive to this interaction, we tested for a significant interaction between group and sport group for each frequency band (2), each condition (2), both sounds (2), and each regional interaction (100). Since such extensive multiple testing was unlikely to survive any correction for multiple comparisons, we reported both corrected and uncorrected results, but limited ourselves to interpreting results that were significant at $p < 0.01$, uncorrected (Table 3).

Table 2. The table shows all effects of frequency, source, sink, condition, group, and sport group with a *p*-value < 0.05. Statistics were calculated via ANOVA; the table displays F-value, *p*-value and first and second degree of freedom.

	Test Statistic	df1	df2	*p*-Value
frequency	5.383	1	Inf	0.02
source	2.749	4.17	Inf	0.025
frequency × source	3.811	4.27	Inf	0.003
sink	7.752	5.789	Inf	<0.001
frequency × sink	5.726	6.869	Inf	<0.001
source × sink	11.349	9.69	Inf	<0.001
condition	4.451	1	Inf	0.035
frequency × source × condition	2.534	4.099	Inf	0.037
source × condition	3.225	3.756	Inf	0.014
sink × sound	2.083	6.312	Inf	0.048
sink × condition	11.02	4.567	Inf	<0.001
frequency × sink × condition	8.443	5.758	Inf	<0.001
source × sink × condition	11.573	10.718	Inf	<0.001
frequency × source × sink x condition	2.899	10.922	Inf	0.001
group × sport group × frequency × sound	**4.582**	**1**	**Inf**	**0.032**
frequency × condition	13.432	1	Inf	<0.001
group × sport group × sink × condition	**2.872**	**4.567**	**Inf**	**0.017**
group × sport group × frequency × sink × condition	**2.288**	**5.758**	**Inf**	**0.035**
group × sport group × source × condition	**2.454**	**3.756**	**Inf**	**0.047**
group × sport group × source × sink × sound	**1.844**	**12.54**	**Inf**	**0.033**

Df = number of degrees of freedom, Inf = infinite. Effects relevant for the hypotheses of this manuscript are highlighted in bold font.

Table 3. All significant effects (*p* < 0.01, uncorrected) resulting from tests of the interaction between group and sport group.

Source	Sink	Condition	Sound	Frequency	F-Value	df1	df2	*p*-Value	*p* Adj
S1l	PPCr	imagination	beep	alpha	12.53	1	46.64	0.001	0.669
Ml	PPCr	imagination	beep	alpha	12.32	1	37.59	0.001	0.762
S1l	Ml	imagination	beep	alpha	8.75	1	47.64	0.005	1
SMAr	S1l	imagination	beep	alpha	7.88	1	46.54	0.007	1
PMCl	Ml	imagination	beep	alpha	7.62	1	48.07	0.008	1
S1r	S1l	imagination	music	alpha	20.9	1	39.44	<0.001	0.137
S1l	PPCr	imagination	music	alpha	11.4	1	41.97	0.002	0.844
Mr	S1l	imagination	music	alpha	11.56	1	37.98	0.002	0.844
Mr	SMAl	movement	music	alpha	9.33	1	43.05	0.004	1
Ml	S1r	imagination	music	beta	19.09	1	39.96	<0.001	0.167
PMCl	S1r	imagination	music	beta	15.74	1	42.47	<0.001	0.283
S1l	S1r	imagination	music	beta	15.96	1	37.46	<0.001	0.283
S1l	Ml	imagination	music	beta	10.28	1	47.66	0.002	1
PMCl	Ml	imagination	music	beta	10.21	1	39.41	0.003	1
S1l	**Ml**	**imagination**	**beep**	**beta**	**27.94**	**1**	**45.24**	**<0.001**	**0.02**
Ml	Ml	imagination	beep	beta	16.58	1	47.56	<0.001	0.254
PMCl	Ml	imagination	beep	beta	14.59	1	45.59	<0.001	0.334
PMCr	Mr	movement	beep	beta	10.49	1	39.49	0.002	1
S1l	PMCr	movement	beep	beta	8.24	1	45.87	0.006	1

M1 = primary motor cortex, S1 = primary somatosensory cortex, PMC = premotor cortex, SMA = supplementary motor area, PPC = posterior parietal cortex, r = right, l = left, df = number of degrees of freedom, *p* adj = *p*-value adjusted for multiple comparisons.

Due to the high number of comparisons, only one of the corrected *p*-values was significant. Figure 1a shows the significant interaction.

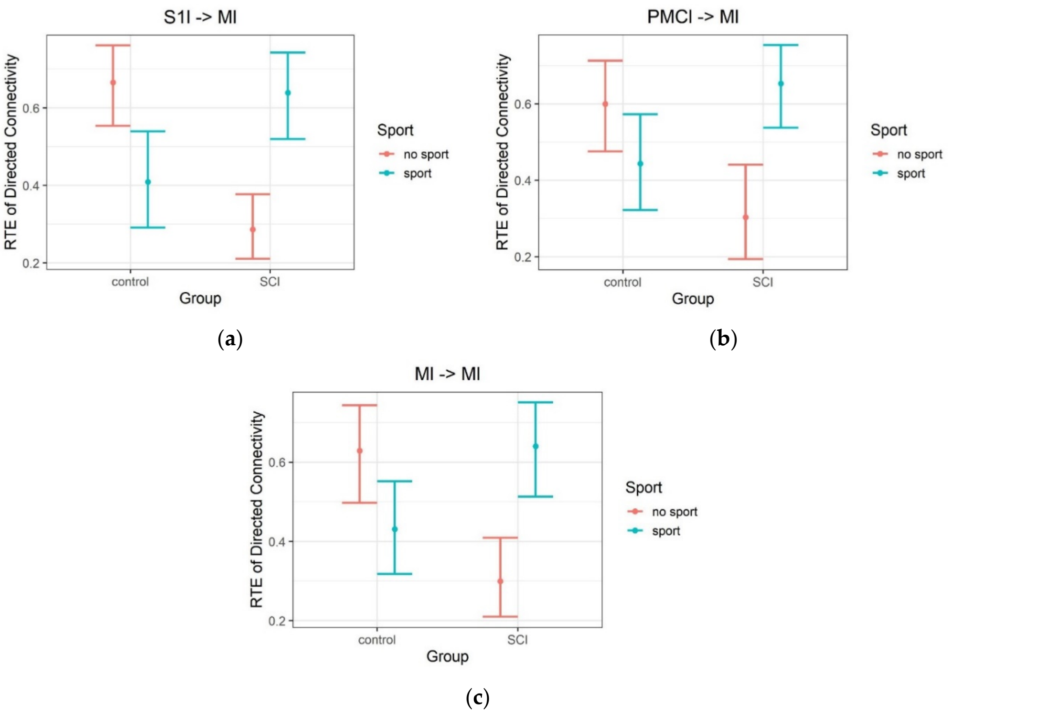


Figure 1. Directed connectivity during the condition imagination, the sound beep, and the frequency beta from (**a**) S1l to M1l, (**b**) PMCl to M1l, and (**c**) M1l to M1l. SCI = spinal cord injury, RTE = relative treatment effect, Ml = left primary motor cortex, S1l = left primary somatosensory cortex, PMCl = left premotor cortex.

In the movement condition, only a few group interactions showed a $p < 0.01$ (uncorrected). In the beta range, the differences became evident during the beep condition and were negligible between sport groups for healthy controls, while in the SCI group the connectivity was stronger in the sportive group as compared to the non-sportive group. These effects were found over the right hemisphere and in interhemispheric connectivity (Figure 2a,b).

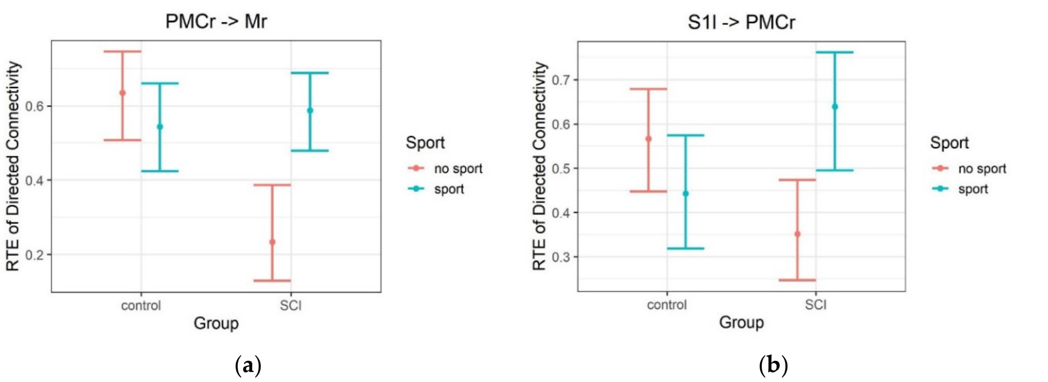


Figure 2. Directed connectivity during the condition movement, the sound beep, and the frequency beta from (**a**) PMCr to M1r, and (**b**) S1l to PMCr. SCI = spinal cord injury, RTE = relative treatment effect, Mr = right primary motor cortex, S1l = left primary somatosensory cortex, PMCr = right premotor cortex.

In the alpha range, there was only one effect $p < 0.01$ (uncorrected), which was evident during music. The alpha connectivity showed the opposite pattern, where there was no difference between sport groups for SCI patients but higher activity in the non-sportive healthy group as compared to the sportive healthy group (Figure 3).

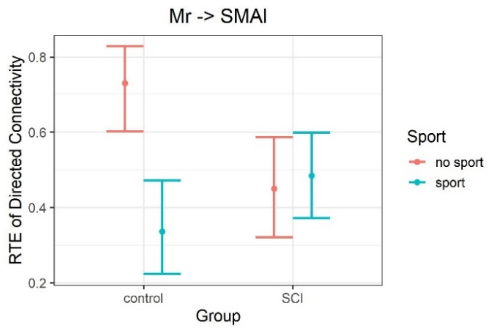


Figure 3. Directed connectivity during the condition movement, the sound music, and the frequency alpha from M1r to SMAl. SCI = spinal cord injury, RTE = relative treatment effect, Mr = right primary motor cortex, SMAl = left supplementary motor area.

In the imagination conditions during beep and music, there were few relevant effects, one of them significant after correction for multiple comparisons (Figure 1a). In the alpha range, there was no difference between sportive and non-sportive controls during the imagination-beep condition (Figure 4a–d) and in the imagination during music condition (Figure 5a–c). Patients showed higher connectivity from left to right hemisphere for the non-sportive group as compared to the sportive group, but higher connectivity from the right to the left and intrahemispheric in the left hemisphere for the sportive group as compared to the non-sportive group.

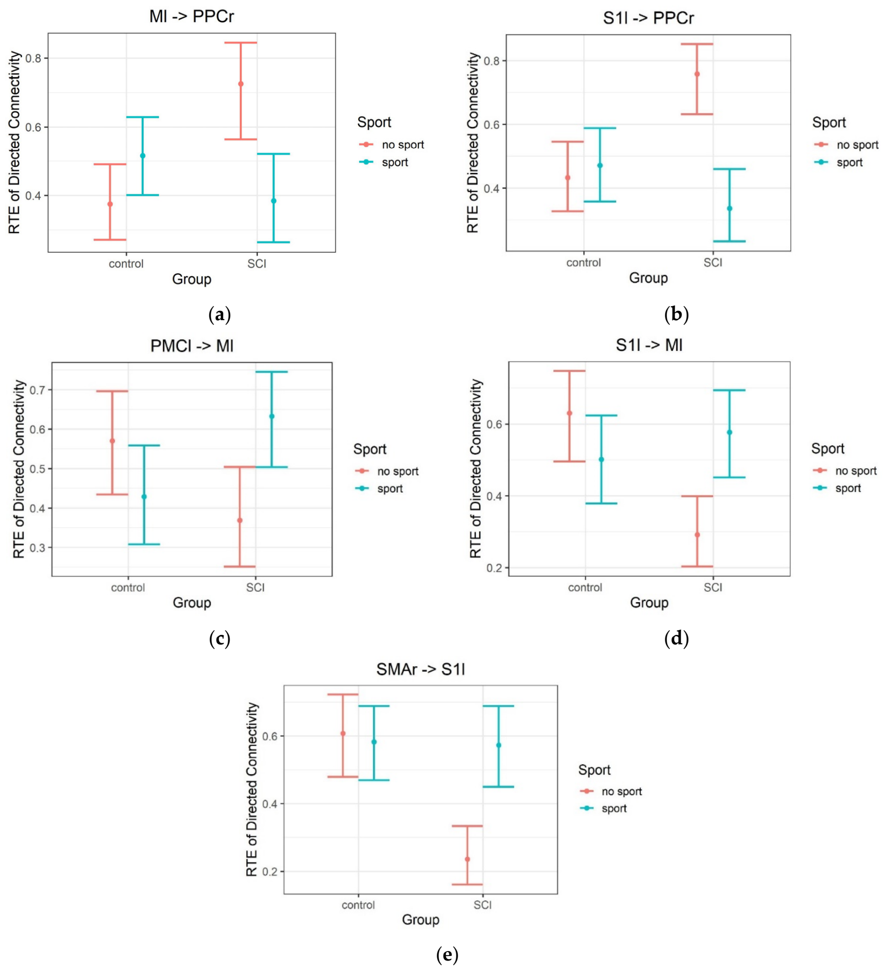
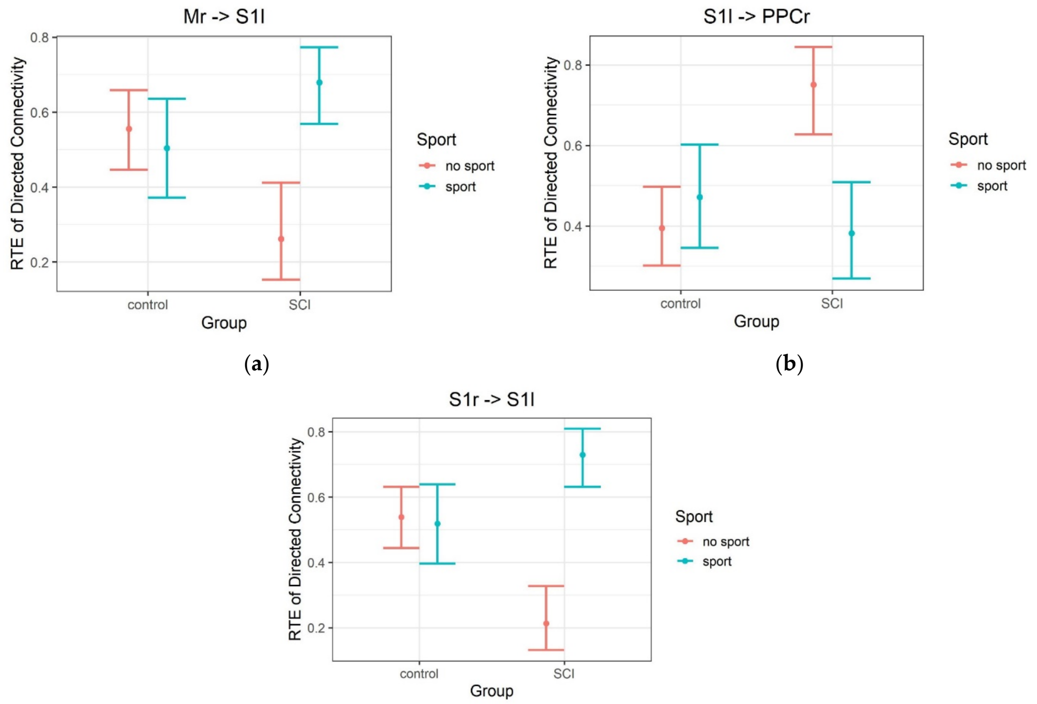


Figure 4. Directed connectivity during the condition imagination, the sound beep, and the frequency alpha from (**a**) M1l to PPCr, (**b**) S1l to PPCr, (**c**) PMCl to M1, (**d**) S1l to M1l, and (**e**) SMAr

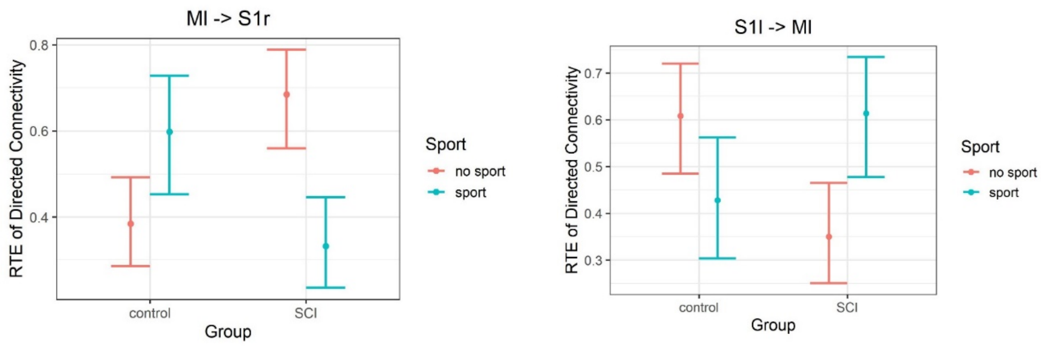
to S1l. SCI = spinal cord injury, RTE = relative treatment effect, PPCr = right posterior parietal cortex, Mr/l = right/left primary motor cortex, S1r/l = right/left primary somatosensory cortex, PMCl = left premotor cortex, SMAr = right supplementary motor area.



(**a**) (**b**) (**c**)

Figure 5. Directed connectivity during the condition imagination, the sound music, and the frequency alpha from (**a**) M1r to S1l, (**b**) S1l to PPCr, and (**c**) S1r to S1l. SCI = spinal cord injury, RTE = relative treatment effect, PPCr = right posterior parietal cortex, Mr/l = right/left primary motor cortex, S1r/l = right/left primary somatosensory cortex.

In the beta range, only intrahemispheric effects in the left hemisphere became evident for imagination during beep condition, with non-sportive controls showing higher activity than sportive controls, and sportive patients showing higher activity than non-sportive patients (Figure 1a–c). These effects were rather strong, with one of them (S1l -> Ml) reaching significance after correction (Figure 1a). The same pattern was observed for imagination during music. In the imagination during music condition, we additionally found connectivity from left to right to be higher for the sportive as compared to the non-sportive controls, but higher for non-sportive as compared to sportive patients (Figure 6a–e).



(**a**) (**b**)

Figure 6. *Cont.*

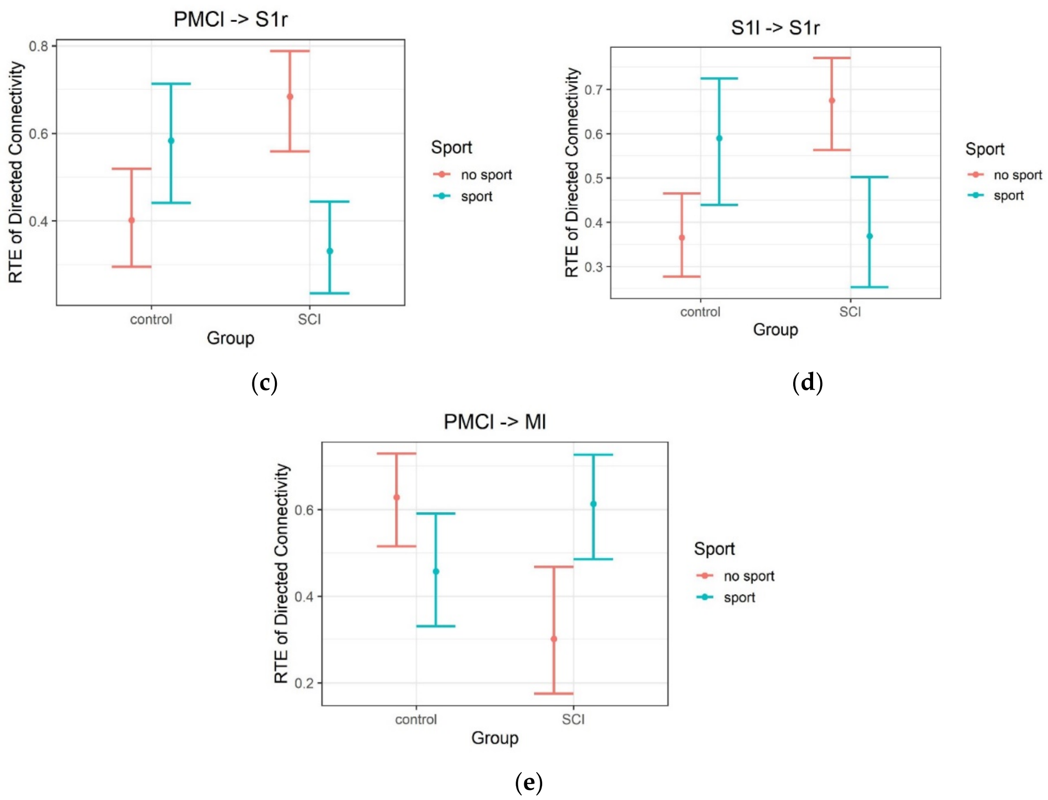


Figure 6. Directed connectivity during the condition imagination, the sound music, and the frequency beta from (**a**) M1l to S1r, (**b**) S1l to M1r, (**c**) PMCl to S1r, (**d**) S1l to S1r, and (**e**) PMCl to M1l. SCI = spinal cord injury, RTE = relative treatment effect, Ml = left primary motor cortex, S1r/l = right/left primary somatosensory cortex, PMCl = left premotor cortex.

4. Discussion

In the present work, we asked the question of whether patients with SCI show differential effects in connectivity patterns in response to movement and imagination of movement depending on whether they are sportive or not. We investigated the effect of sports on cortical connectivity in patients with SCI and healthy participants during movement imagination and movement execution using HD-EEG. We found different patterns in connectivity between the non-sportive groups and sport groups, suggesting a modulative effect of sports on cortical connectivity. We can answer our research question because we found indication for a modulative effect of sportive activity, both in healthy controls and patients, but to a different extent. This was indicated by a different pattern of activation of movement- and imagination-relevant brain networks in healthy controls and patients depending on whether they practiced sports regularly or not.

Exercise plays an important role in rehabilitation of patients with SCI. However, not many EEG studies have been conducted to investigate the influence of sports on the cortical activity in SCI patients. Searching Pubmed in January 2023 with the terms "spinal cord injury + EEG + sports", "spinal cord injury + EEG + exercise", and "spinal cord injury + EEG + physical activity" yielded a clear gap in knowledge in this area. Thirty-three out of the 38 retrieved studies did not concern sports, but gait training, physiotherapy, or brain–computer interface training. The five studies left tested the acute effect of training conducted during the experiment (see Supplementary Table S3) [41–45]. Hence, the influence of regular exercise on long-lasting changes in cortical connectivity had not been addressed thus far.

Prior research demonstrated that patients with SCI exhibit an increased cortical excitability [46–48] that might enhance neuroplastic changes in the cortex. Neuroplasticity is known to be driven by the brain derived neurotrophic factor (BDNF), which, according to a study by Vega and colleagues, is released during exercise and reaches a level six times higher in athletes with SCI at rest compared to healthy participants [49]. The authors also reported that the BDNF level further increased during light hand-bike training and suggested that exercise boosts neuroplastic changes in patients with SCI. The data of our study support this hypothesis, as the difference in sport groups, i.e., the instance that one group is sportive while the other is not, causes a higher difference in connectivity in patients with SCI compared to the healthy participants in the observed brain areas for the alpha frequency range during the imagination condition. It seems plausible that neuroplasticity is facilitated due to the increased cortical excitability and elevated BDNF levels. We speculate that this is the reason why cortical connectivity is more prone to changes due to regular exercise in patients with SCI compared to healthy participants.

Interestingly, this difference can be observed mainly during movement imagination, not during the actual movement where the pattern of results looked quite different. It is possible that the results in the movement condition are biased by the rhythmic movement artefacts, such that interpretation should be performed only cautiously, if at all. Furthermore, none of the effects in the movement condition were significant after correction for multiple comparisons. Even though movement and movement imagination showed similar patterns in brain activation in prior research [50,51], there were still important differences. While during movement, processes resulting in motor initiation are intended, during movement imagination, these processes need to be inhibited. FMRI studies demonstrated a suppressed connectivity to M1 during movement imagination, while this connectivity was enhanced during movement execution [52,53]. In our study, sportive patients show a higher connectivity to the left M1 in the alpha band compared to the non-sportive patients, aligning their pattern with that found in healthy controls—this might represent an effective suppression of M1. One possible explanation for this might be that sportive patients regularly train their movement imagination skills, especially wheelchair dancers. They have to prepare, memorize and practice a choreography composed of complex movements that need to be arranged with the steps of the dance partner. Hence, imagining complex movements while suppressing their execution might be more present in the sportive patient group than in the other groups. Furthermore, the increased suppression of M1 might compensate the elevated cortical excitability [46–48] to avoid unwanted movements. In the beta band, the data showed a higher connectivity toward the left M1 in the sportive compared to non-sportive patients during movement. The higher frequency indicated an enhancement in M1 activity that might be modulated by sports after SCI, resulting in a physiological level. Furthermore, it is of interest that in our data, the M1 in the role as connectivity sink was located only in the left hemisphere. Functional MRI studies revealed that the left hemisphere possesses greater intrahemispheric local connections than the right one, particularly in brain areas associated with language and fine motor coordination [54]. In contrast, the right hemisphere was reported to show more interhemispheric connections than the left counterpart [55,56]. In our study, intrahemispheric connections over the left hemisphere were stronger in sportive patients as compared to non-sportive patients, while the difference was smaller and of opposite direction in healthy participants; hence, the increased intrahemispheric connectivity might be influenced by the combination of exercise and implications of the SCI. Still, it has to be kept in mind that the role of M1 during movement imagination is not yet clear. Hetu and colleagues reviewed the literature on this topic and reported that out of 122 experiments that were published, only 22 observed activity of M1 during imagination of movement [57]. More research is needed to clarify the role of M1 during imagination and its task as source and sink of information flow in different frequency bands.

In addition to what we observed in M1, the connectivity toward the right PPC showed different patterns between the groups. In the alpha band, the non-sportive patients had a higher connectivity compared to all of the other groups. In former studies, the PPC played an important role in restraining movement imagination [58], the integration of spatial orientation [59], and the concept of the "body schema", i.e., the bodily posture and the position of limbs [60]. It receives input from brain areas including motor, somatosensory, visual, auditory, cingulate, and prefrontal cortices, and integrates proprioceptive and vestibular signals from subcortical areas. Hence, the PPC serves higher-order functions [61]. In an EEG study, Athanasiou and colleagues recorded a lower connectivity in the functional sensorimotor network in patients with SCI [18]. Due to the deafferentation and an impaired exchange of signals between the central and peripheral nervous system, the body schema might be modified in patients with SCI. This could interrelate to the increased suppression of the right PPC as reflected by increased alpha band connectivity in non-sportive patients. Interestingly, the sportive patients showed a lower connectivity, similar to the levels found in healthy controls, suggesting an important role of exercise on the connectivity toward the right PPC during movement imagination in patients with SCI. Increased connectivity in patients with SCI possibly reflects an adaptive compensation mechanism to overcome the impairment caused by the injury [18]. As motor programs controlled via lower motor neurons in the spinal vertebrae might be disturbed, certain brain areas possibly compensate this impairment. Hence, the relevant brain areas are more active during movement imagination compared to healthy individuals. The role of exercise in this construct is still not completely clear, yet the results of this study demonstrate significant differences in connectivity between sportive and non-sportive patients with SCI and healthy participants.

5. Limitations

There are some limitations to this study. We did not exclude patients based on the height of lesion, age of injury, or degree of impairment, as narrow inclusion criteria would have reduced the sample size in this single-centered study and, thus, reduced statistical power. Moreover, brain physiology, and therefore, cortical connectivity, could potentially have been affected by patient age, years and regularity of practiced physical exercise, and type of sport. The sportive patients included in this study practiced wheelchair dancing, as well as hand-biking and marathon driving. We can assume that the latter groups were less familiar with complex movements as compared to dancers who have more practical experience in imagining movements and choreographies. A further limitation is the missing control for menstrual-cycle-dependent changes in the female participants. Several studies demonstrated a correlation between EEG signals and hormonal state in alpha frequency (α peak frequency, α band width, power in the $\alpha 2$ frequency band, and the maximum power in the low-frequency $\alpha 1$ band), as well as in the beta frequency [62,63]. Solis-Ortiz and colleagues found positive correlations between progesterone level and beta 1, while beta2 showed negative correlations [63]. The original plan of the study was to compare wheelchair dancers to other wheelchair athletes, where we wanted to investigate the specific response of dancers to music as a rhythmic cue. We assumed wheelchair dancers, as compared to other wheelchair athletes, would benefit more from music as a rhythmic cue over simple beep sounds. As the sample size of wheelchair dancers was too small to conduct this type of analysis, we had to limit ourselves to an overall comparison of the effect of music vs. beep sounds as conditions. Indeed, there were some differential effects that pointed to different networks activated by music during imagination of movement in the beta range, where sportive controls and non-sportive patients showed higher left-to-right connectivity. Since analysis of sub-groups was not possible, the further interpretation of the effect of music with respect to sports type was limited. Generally, the sample size for the patient groups was small, and effects due to individual outliers cannot be excluded. The observed effects should be tested in further studies with a larger sample size. Another relevant method for recording connectivity during movement imagination is fMRI. With that method, the accuracy in localization of the regions of interest could be improved, and the reaction to imagining different sport activities could be compared. Finally, recording HD-EEG during movement represents a challenge due to strong muscle and movement artefacts, even if no head movements are included in the selected movement patterns. Although we subtracted the connectivity values of the control (resting) condition from the test condition, it is not guaranteed that all activation due to visual and auditory stimulation was excluded.

6. Conclusions

In conclusion, we found differences in cortical connectivity during movement imagination between sportive and non-sportive patients with SCI and healthy participants. The results suggest a modulative effect of sports on connectivity patterns during movement imagination. Effects found during movement conduction were rather small, supporting the idea of similar but still diverging pathways of communicating brain areas during movement imagination and movement execution. We also found that regular exercise seems to have a greater influence on the connectivity of the brain in patients with SCI as compared to healthy participants. This might be due to the increased cortical excitability in affected patients that enforces plastic changes in the cortex. The results of this study highlight the importance of exercise in the rehabilitation of patients with SCI, while further research is needed to uncover the exact underlying mechanisms of this effect.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app13169469/s1, Table S1. Pre-defined regions and the respective electrodes in the HD-EEG. Figure S1. Pre-defined regions and the respective electrodes in the HD-EEG. Table S2. Individual averaged model order of healthy participants and patients with SCI. Table S3. EEG studies on the effects of sports/ exercise /physical activity on brain activity in patients with SCI.

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