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Original article

Assessing spino-cortical proprioceptive processing in childhood unilateral cerebral palsy with corticokinematic coherence

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Running title: Corticokinematic coherence in children with cerebral palsy

Abstract

Objective: To develop an electrophysiological marker of proprioceptive spino-cortical tracts integrity based on corticokinematic coherence (CKC) in young children with unilateral cerebral palsy (UCP), in whom behavioral measures are not applicable.

Methods: Electroencephalography (EEG) signals from 12 children with UCP aged 19 to 57 months were recorded using 128-channel EEG caps while their fingers were moved at 2 Hz by an experimenter, in separate sessions for the affected and non-affected hands. The coherence between movement kinematics and EEG signals (i.e., CKC) was computed at the sensor and source (using a realistic head model) levels. Peaks of CKC obtained for the affected and non-affected hands were compared for location and strength. The relation between CKC strength on the lesion-side, the lesion-type (cortico-subcortical vs. subcortical) and the level of manual ability were studied with 2-way repeated-measures ANOVA.

Results: At the individual level, a significant CKC peak at the central area contralateral to the moved hand was found in all young children with their non-affected hand and in 8 out of 12 children with their affected hand. At the group level, CKC to the affected hand movements was weaker than CKC to the non-affected hand movements. This difference was influenced by the type of lesion, the effect being predominant in the subgroup (n= 5) with cortico-subcortical lesions.

Conclusion: CKC is measurable with EEG in young children with UCP and provides electrophysiological evidence for altered proprioceptive spino-cortical tracts on the lesioned brain hemisphere, particularly in children with cortico-subcortical lesions.

Keywords: cerebral palsy, corticokinematic coherence, electroencephalography, plasticity, proprioception, sensorimotor mapping.

Introduction

Cerebral palsy (CP) is the most common cause of neurological motor disability in childhood and affects between 1.57 to 1.99 out of 1000 live births in Europe [43]. CP results from an early brain lesion that affects the motor system but also potentially other brain systems, such as the somatosensory system [9]. Among CP individuals, approximately 30% have unilateral spastic CP (UCP) [21].

In children with UCP, somatosensory dysfunction is common, as about 90% have some degree of sensory impairment in at least one of the four following somatosensory modalities: tactile perception (sensitivity to simple stimuli, touch detection/vibration), tactile discrimination (static and moving two-point discrimination), stereognosis (discrimination for size/form/shape), and proprioception [4]. The latter is defined as a combination of sense of position and sense of motion (kinesthesia) without the use of vision and is essential to provide accurate feedback for motor decisions [22]. Proprioception is classically measured by passively moving the metacarpophalangeal or interphalangeal joints of the fingers while patients close their eyes. A recent study has shown that kinesthesia can be assessed more objectively in UCP children using a robotic exoskeleton. Kinesthesia was significantly impaired in this population and children with large arterial cortico-subcortical stroke had more severe proprioceptive deficits than children with periventricular venous infarctions [22]. Interestingly, in that study, impaired kinesthesia was not improved by vision restoration and was not correlated with the level of motor deficit [22].

Measuring proprioception is important in CP for several reasons. First, impaired proprioception may impact motor rehabilitation strategies. Indeed, rehabilitation methods are usually designed to improve motor function in acting directly on motor pathways, but other therapeutic approaches using proprioceptive training exist and may improve motor functions [1]. Second, it has been shown that interventions based on bimanual intensive training impact not only motor functions but also somatosensory functions in UCP children [23, 42]. These therapies would modify cortical somatosensory processing, as shown in a recent randomized controlled trial performed in patients with CP and bilateral involvement using somatosensory evoked potentials (SEPs) [26]. Whether they would also impact the proprioceptive processing is unknown.

Behavioral measures of somatosensory functions are not feasible in children before the age of 4 years [4]. Therefore, neurophysiological methods of exploration of the afferent somatosensory pathways are of interest in this age group. The classical neurophysiological method is to record somatosensory evoked potentials (SEPs). Various types of abnormalities concerning the amplitude, latency, morphology and location of SEPs have been reported in

children with CP [31]. Electrical stimulation of peripheral nerves is the conventional method. However, discomfort and stimulation artefacts limit its use in infants and young children [44]. Even if alternative techniques using cutaneous stimuli such as air puffs [25, 26] or elastic membranes [31] may be considered, none of these techniques are specific to the proprioceptive function.

Corticokinematic coherence (CKC) is an electrophysiological method that specifically investigates the cortical processing of proprioceptive somatosensory afferences [7, 37]. CKC quantifies the coupling between oscillatory cortical activity, recorded with electroencephalography (EEG) or magnetoencephalography (MEG), and limb kinematics (i.e., acceleration) during repetitive movements. The coupling peaks at movement frequency (F_0) and its first harmonic (F_1), with cortical sources predominantly located at the primary sensorimotor (SM1) cortex contralateral to the moved limb (for reviews, see [8, 12]).

In typical adults, this coupling akin to a correlation coefficient ranges between 0.2 and 0.8 at F_0 and F_1 and is found in almost all subjects. The movement rate (from 1 Hz to 4 Hz) [27] and the type of movements (active or passive) do not affect the CKC strength and the main source location [36]. Moreover, CKC strength has an excellent inter-session reproducibility for both hands with MEG [37] as well as EEG [38].

One study was performed in newborns hospitalized in a neonatal intensive care unit for birth asphyxia and suspected epileptic seizures. In all of them and for both hands, significant CKC peaks were observed at F_1 on the central region contralateral to the passively moved hand [44]. CKC is thus an electrophysiological marker of the proprioceptive spino-cortical tract integrity, which does not require any behavioral response and has not been investigated so far in typically developing children nor in subjects (children or adults) with CP.

The aim of this study was to use CKC elicited by passive finger movements in a population of children aged between 1 and 4 years with UCP to assess the integrity of spinal proprioceptive afferents to contralateral SM1 cortex. For that purpose, we recorded EEG signals in CP children while an experimenter passively moved their fingers at 2 Hz. We expected that (i) CKC would be elicited contralaterally to the moved limb on the non-lesioned as well as on the lesioned hemisphere [45], (ii) the lesioned hemisphere would show weaker CKC, indicating impaired processing of neocortical proprioceptive somatosensory afferences [28], and (iii) the type of cerebral lesion (cortico-subcortical or subcortical) would affect the CKC strength.

Methods

Participants

Participants were patients recruited from the out-patient clinics of the Department of Pediatric Neurology at CHU of Angers, France ($n = 4$), and from patients participating in an intervention study aiming at evaluating the effects of a rehabilitation method at CHRU of Brest, France (e-HABIT-ILE study, for details, see [2]; $n = 12$). Ethical approvals for this study were obtained for the two sites of inclusion (29BRC19.0050/ N2019-A01173–54 and 2015-A00985-44/2015/20).

Inclusion criteria were (1) clinical diagnosis of UCP, (2) age at inclusion: ≥ 1 year and < 5 years, (3) detection of a cerebral lesion supporting the diagnosis of UCP with a structural magnetic resonance imaging (MRI) that included a good quality 3D-T1 sequence performed in the last 6 months, and (4) written informed consent signed by parents or legal representatives. Exclusion criteria were (1) behavioral disorder that precluded participation in the study, and (2) surgical procedure or botulinum toxin performed in the upper limbs in the past 6 months.

Patients were clinically assessed using the Gross Motor Function Classification System (GMFCS) and the Manual Abilities Classification Scale (MACS) [15] or the mini-MACS [16] according to the age of the child. A score was established before each EEG session by an experimenter (SB, JD or RB).

Each child's brain injury was visually classified by experienced pediatric neurologists (PVB and MD) from the 3D-T1 sequence into one of the three categories corresponding to the patterns of brain abnormalities predominantly associated with CP [20, 30]. These three categories were: exclusive subcortical lesion (cystic periventricular leukomalacia or periventricular hemorrhagic infarctions), cortico-subcortical lesion (watershed ischemic injury, multicystic encephalomalacia, or stroke) or brain malformation (lissencephaly, pachygyria, polymicrogyria, or schizencephaly). In our sample, the child classified in the brain malformation group had polymicrogyria.

Sixteen children were included. Four were excluded from further analysis due to excessive fussiness ($n = 3$) or insufficient number of epochs available due to abundant interictal epileptiform discharges ($n = 1$). The final sample included 12 children with UCP (8 female and 4 male patients, mean age = 41 months, SD = 13 months, range = 19–57 months), with clinical data summarized in table 1.

Experimental paradigm

A 128-channel passive EEG cap (HydroCel Geodesic Sensor Net, Electrical Geodesics, Inc., Eugene, USA) was placed on the participant's head, and a 3-axis accelerometer developed by AR (ADXL335 iMEMS Accelerometer, Analog Devices, Inc, Norwood, MA) was attached to the tip of their index finger with an elastic bandage in order to record finger movements. During the experimental session, participants sat on their caregiver's lap. They were shown a cartoon on a screen to focus their attention and reduce spontaneous movements, except for the resting condition. Recordings were performed under video control using a video camera (M1065-L, AXIS, Inc., Lund, Sweden) synchronized with the EEG signals.

The experimental design comprised five conditions: two passive movement conditions performed for both hands separately and a resting state (see Figure 1). For the passive movement conditions, the mobilized hand was placed palm up on a table, inside a box to block the visual inputs related to passive movements. Passive movements were performed by an experimenter (JD) who flexed and extended the subject's four last fingers. The affected hand was always moved first. The order of passive movement conditions for each hand was chosen at random. A first condition was designed to estimate CKC and consisted of continuous, repetitive movements at 2 Hz for 3 minutes [44]. A second condition was designed to test the reactivity of the mu rhythm and consisted of 85 movements with an inter-stimuli interval (ISI) of 3.5 s [32]. The experimenter paced their movements on a sound cue that was inaudible to the child.

In the resting condition, assessed twice for 5 minutes, the caregivers were instructed not to engage the child in goal-directed activity and to limit movements [39].

Only the data acquired for the CKC will be presented in this article.

Data acquisition

EEG and acceleration signals were amplified (Net Amp GES 400 series, Electrical Geodesics, Inc., Eugene, USA), filtered through 0.1–450 Hz, and recorded synchronously at 1 kHz with a laptop running a dedicated acquisition software (EGI Net Station v5, Electrical Geodesics, Inc., Eugene, USA). Impedances of the electrodes were kept below 50 k Ω and the reference was at Cz.

Structural 3D T1-weighted cerebral MRIs were acquired on a 1.5T MRI scanner at CHRU Brest (Magnetom Avento, Siemens) and on a 3T MRI scanner at CHU Angers (Trio, Siemens).

Data pre-processing

EEG data were exported to Matlab (Mathworks, Natick, MA, USA). After examination of the raw data in all patients, EEG electrodes on the boundary of the cap were removed (1, 8, 14, 17, 21, 25, 32, 48, 49, 56, 63, 68, 73, 81, 88, 94, 99, 107, 113, 119, 125, 126, 127, 128) because they featured high-amplitude artefacts caused by poor or unstable skin-electrode contact. Thus, signals from the 104 remaining electrodes were kept for further analyses.

EEG signals were then processed using the automated PREP pipeline [3]. They were re-referenced to a common average and the signals at electrodes affected by excessive noise level were interpolated based on the signals of the surrounding electrodes [34]. Electrodes were considered noisy when they matched at least one of the three following criteria [3]: 1) too high wide-band amplitude (robust z-score above 5 for the robust standard deviation), 2) too high ratio between high (>40-Hz) and low (<40-Hz) frequency amplitudes (robust z-score over 5 for the ratio of the median absolute deviation) and 3) too low correlation with other channels (percentile 98 of the correlation with other channels in 1-s windows below 0.4 for over 1% of the windows). This pipeline was repeated until no more bad channels were detected, and at most three times. In our sample, the average number of interpolated electrodes was 3.83 ± 2.04 . Video movies were analyzed offline, frame by frame (30 frames/sec for 300s), together with EEG signals and accelerometer data. Periods with excessive voluntary movements or showing passive hand movements at a frequency different from 2 Hz were removed. In addition, an experienced pediatric neurologist (PVB) reviewed the EEG for the presence of interictal epileptiform discharges, and epochs presenting such discharges in the parietal and central electrodes covering the sensorimotor areas were removed.

To further suppress physiological artefacts, 50 independent components were evaluated from the data band-pass filtered at 0.5–45 Hz with Fast ICA [49]. Independent components corresponding to heartbeat, eye-blink, and eye-movement artefacts were visually identified and corresponding signals reconstructed by means of the mixing matrix were removed from the full-rank data.

The three orthogonal acceleration signals were high-pass filtered at 0.5 Hz and combined into a single, orientation-independent acceleration time-course using their Euclidian norm [5]. After, EEG and accelerometer data were divided into overlapping 2 s epochs (leading to a frequency resolution of 0.5 Hz) with 1.6 s epoch overlap. A minimum of 150 good quality EEG epochs of 2 s duration had to be available for the session to be accepted for processing. The number of rejected components and the number of epochs used in the coherence analysis did not differ between the hands (respectively non-affected hand: 4.83 ± 1.19 vs. affected hand: 4.33 ± 0.98 ,

$t = 1.15$, $p = 0.28$ and non-affected hand: 267.67 ± 75.97 vs affected hand: 305.67 ± 86.69 , $t = 1.21$, $p = 0.25$).

Data analysis in the sensor space

Coherence analysis was performed in sensor space to estimate CKC. Coherence is an extension of Pearson correlation coefficient to the frequency domain, which quantifies the degree of coupling between two signals, i.e. the CKC strength, by providing a number between 0 (no linear dependency) and 1 (perfect linear dependency) for each frequency [18]. In practice, all 2-s epochs were Fourier-transformed and combined to derive a spectrum of coherence between the acceleration signal and each EEG signal, following standard methods [18].

For both hands, we identified without *a priori* the frequencies showing consistent CKC across participants. The frequencies identified were then defined as the frequencies of interest for source-level analyses.

Data analysis in the source space

We reconstructed the sources of CKC at the frequencies of interest. For that, individual MRIs were first segmented automatically using the Freesurfer software (Martinos Center for Biomedical Imaging, Massachusetts, USA) [41]. The EEG forward model was then generated from the segmented individual MRI and a template of electrode locations (ICBM152/GSN Hydrocel 128) with Brainstorm [46] using an individual three-layer Boundary Element Method (BEM) and using standard conductivity values (brain= $0.33/ \Omega\text{m}$, skull= $0.006/ \Omega\text{m}$, and scalp= $0.33/ \Omega\text{m}$) [10].

Based on these forward models, we computed a Minimum-Norm-Estimates inverse solution [11], with the regularization parameter fixed assuming a signal-to-noise ratio of 1 [24]. Then this inverse solution was used to generate coherence maps at the frequencies of interest. Of note, the coherence value at each source location was optimized across the three source orientations as done in a previous work [7].

Each individual map was visualized and the highest CKC value (CKC peak) in the contralateral central areas of the moved hand was collected, and statistical analyses were performed on this data. In a second step, a sublobar localization of the peak (central mesial, central lateral, parietal mesial or parietal lateral) was performed [19].

Statistical analyses

A significance threshold of individual coherence levels was computed under the hypothesis of linear independence and compared at corresponding CKC peaks at 2 Hz (F0) and 4 Hz (F1). The significance level was set to $p < 0.05$ Bonferroni corrected for multiple comparisons (i.e., 104 channels) [28].

Statistical analyses were performed using SPSS Statistics software (IBM, Armonk, NY, USA). First, the normality of the distribution was tested by the Shapiro-Wilk test. Paired-samples parametric t-test, or Wilcoxon signed-rank test when the assumption of normality was not met, were used to compare between hands the number of independent components rejected, the number of artefact-free epochs, and the CKC strength at frequencies of interest.

We studied the effects of the moved hand (affected vs non-affected) and the 2 main groups of lesion type (subcortical lesion vs cortico-subcortical lesion) on the CKC strength. Among the three groups of lesion types identified in our sample, the group of malformations of cortical development consisted in a single participant. This subject was therefore excluded for the secondary statistical analyses. In a second step, we assessed the effects of moved hand (affected and non-affected) and the main groups of manual ability on the CKC strength. Only one participant had a MACS III classification. So, for the secondary analyses, we redefined two groups of manual ability limitations: the Mild Manual Ability Limitation group (MiMAL) included children with MACS I, and the Moderate Manual Ability Limitation group (MoMAL) included children with MACS II and MACS III. These effects were computed for the two frequencies of interest with 2-way repeated-measures ANOVA followed by *post hoc* analysis with Bonferroni adjustment for multiple comparisons.

Results were considered statistically significant at $p < 0.05$.

Results

Corticokinematic coherence

Figures 2 and 3 are illustrations of a patient with a subcortical lesion (figure 2) and a patient with a cortico-subcortical lesion (figure 3) that show the 3 main steps (CKC spectra, sensors location of CKC peaks and source location of CKC peaks) of the analyses performed in each child.

In the sensor space, a peak of coherence was visually identified in all subjects for both hands at movement frequency F0 and its first harmonic F1, as shown in Figure 4.

The coherence strength in the non-lesioned hemisphere was statistically significant at F0 in 2 of the 12 patients and at F1 in 11 of the 12 patients. In the lesioned hemisphere, a significant coherence peak was found at F0 in 5 of the 12 patients and at F1 in 8 of the 12 patients (see Table 2). Thus, 4 of the 12 patients did not present any significant CKC peak in the lesioned hemisphere, neither at F0 nor at F1. However, these 4 patients were not excluded from the group analysis.

The analysis in the source space showed that most of the peaks of CKC in the non-lesioned hemisphere as well as in the lesioned hemisphere were located in the central lateral or mesial cortical area contralateral to the moved limb (20 of 24 CKC peaks at F0, and 23 of 24 peaks at F1), the others being located in the parietal lateral region (see Table 2 and Figure 4).

CKC strength at F0 and F1 ranged from 0.02 to 0.31 (mean \pm SD, F0: 0.11 ± 0.06 ; F1: 0.18 ± 0.07).

Non-Affected Hand vs Affected Hand

For the non-affected hand, the CKC strength differed between F0 (0.09 ± 0.06) and F1 (0.21 ± 0.07 , $t = 4.28$, $p = 0.001$). For the affected hand, no difference between the frequencies of interest was found (F0: 0.13 ± 0.07 ; F1: 0.15 ± 0.07 , $W = 22$, $p = 0.35$).

At F0, the CKC strength did not differ between hands (non-affected hand: 0.10 ± 0.06 ; affected hand: 0.13 ± 0.07 , $W = 26.50$, $p = 0.35$). However, at F1, CKC was significantly stronger for the non-affected hand (0.21 ± 0.07) than the affected hand (0.15 ± 0.07), with a 95% confidence interval on the difference between the means of 0.02–0.11 ($t = 3.34$, $p = 0.007$).

Manual ability impairment and lesion type effects

At F0, there was no significant effect or interaction of the moved hand and lesion type on CKC strength ($F_{1,9} < 2.24$, $p > 0.17$). At F1, there was a significant interaction between the moved hand and lesion type ($F_{1,9} = 5.19$, $p = 0.049$). Post-hoc analysis showed that CKC strength was lower for the affected hand than for the non-affected hand in children with a cortico-subcortical lesion ($p = 0.009$) but not in those with a subcortical lesion ($p = 0.95$). There was no significant interaction between the moved hand and manual ability impairment ($F_{1,10} = 1.1$, $p = 0.32$) and no significant main effect of manual ability impairment ($F_{1,10} = 1.07$, $p = 0.35$).

Discussion

This study assessed CKC in infants and young children with UCP. All included children aged 1 to 4 years who had good-quality data had CKC recorded on the non-lesioned hemisphere at F0 or F1 after repetitive passive movements of the non-affected hand. On the lesioned hemisphere, a significant CKC peak was shown in 8 of 12 children after repetitive passive movements of the affected hand. At the group level, the strength of coherence was significantly higher after repetitive passive movements of the non-affected hand.

The majority (90%) of the CKC peaks were recorded over the primary sensorimotor area (SM1) contralateral to the moved hand, whereas they localized in the lateral parietal region for the remaining 10%. This is in agreement with previous studies [28, 36]. The CKC has been proposed as a functional indicator for the mapping of the SM1 hand area [6]. The coupling was found on the central area of the lesioned hemisphere in all patients, even in those where the peak was not significant. Interestingly, the peak of CKC was also present in the central residual grey matter in participants with extensive cortico-subcortical lesion. This result is consistent with the fact that individuals with UCP show preserved projection of thalamocortical somatosensory tracts in the lesional somatosensory areas [45] and that shifting of the sensory function to the contralesional hemisphere is uncommon and ineffective [14].

As hypothesized, CKC strength was reduced on the side of the lesioned hemisphere, but only at the first harmonic. As the affected hand of patients with UCP is also the non-dominant hand, this difference should not be related to the physiological difference between the dominant and the non-dominant hand. Indeed, in young typical adults, CKC was found to be stronger in the non-dominant than the dominant leg [37]. Therefore, our findings evidence that children with UCP have impaired somatosensory afferences on the affected side. This is in line with other neuroimaging studies that support somatosensory reorganization in this population. A reduced number of fibers and a loss of microstructural organization of the white matter of the thalamocortical ascending tract to the lesioned hemisphere were described and these alterations were associated with deficits of somatosensory function [47]. Reduced grey matter volumes in lesional primary (S1) and secondary somatosensory cortices (S2) were also found in conjunction with sensory impairments [33]. Finally, neurophysiological studies using tactile stimulations found a significant difference in cortical processing between affected and non-affected hands [25, 35].

The secondary analysis conducted on the two main groups of brain lesions of our population showed that the difference in the CKC strength between moved hands was mainly present in the cortico-subcortical lesion group compared to the subcortical lesion group. This finding was

expected as individuals with CP and cortico-subcortical lesions show more severe somatosensory impairment than those with a subcortical lesion [22, 50]. We did not investigate the relationship between the somatosensory function and CKC strength because we were unable to assess the degree of functional somatosensory disability in our population due to the young age of the participants. Therefore, we searched for an effect of the level of manual ability impairment on CKC strength, yielding to negative result. This is in line with behavioral studies that have shown an inconstant relationship between proprioception and motor function in CP [4]. As a relationship was found between CKC from ankle movements and a behavioral assessment of balance in typical adults [37], such an assessment could be used in other studies to clarify the effect of the level of motor dysfunction on the CKC level.

The sample size in the current exploratory study was small. Still, it is consistent with previous publications investigating neuroplasticity in children with UCP (for a review, see [40]). It should also be noted that studies of functional activation of the somatosensory system induced by passive hand movements or tactile stimuli using functional MRI did not find either significant difference of cortical activation between the affected hand of children with UCP and the dominant hand of typical children [48], or any specific pattern related to the type of lesion [17]. These data that are divergent from the present CKC study could be related to differences of somatosensory stimuli between studies, or to differences that exist between an indirect method of neural activation imaging based on the neurovascular coupling and a neurophysiological method. Taken together, this suggests that the CKC method could be more sensitive than fMRI to make correlations with the level of functional disability in patients with UCP.

This study was not designed to establish the physiological strength of CKC in young children because it did not include typically developing children. Although the non-lesioned hemisphere of patients with UCP cannot be considered as completely typical [29], coherence strength obtained after passive movements of the non-affected hand may be considered as a good approximation of the values expected in 1–4 years typically developing children. We found a strength of coherence at about 0.2, i.e., higher than the values observed in newborns (<0.1) [44] and close to the typical young adult (0.2) [37]. This early maturation of the CKC parallels the maturation of the mu rhythm that reflects the neural activity of the primary sensorimotor cortex and shows frequency values similar to values obtained in young adults by the end of the first year of life [13]. We also found that the coherence between passive movements of the non-affected hand and the non-lesioned hemisphere was higher at F1 than at F0, as already reported in other studies [36, 44].

Conclusion

This study shows that spino-cortical proprioceptive tract integrity can be assessed in young children with UCP on the lesioned and non-lesioned hemispheres by computing the coupling between passive finger movement kinematics and sensorimotor cortex neurophysiological activity. This coupling is impaired on the side of the lesioned hemisphere in this population. Since CKC is non-invasive, robust, easily and rapidly administered, it appears to be a promising early electrophysiological marker of proprioception in CP.

Disclosure of interest

The authors declare that they have no competing interest.

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Legends of Figures

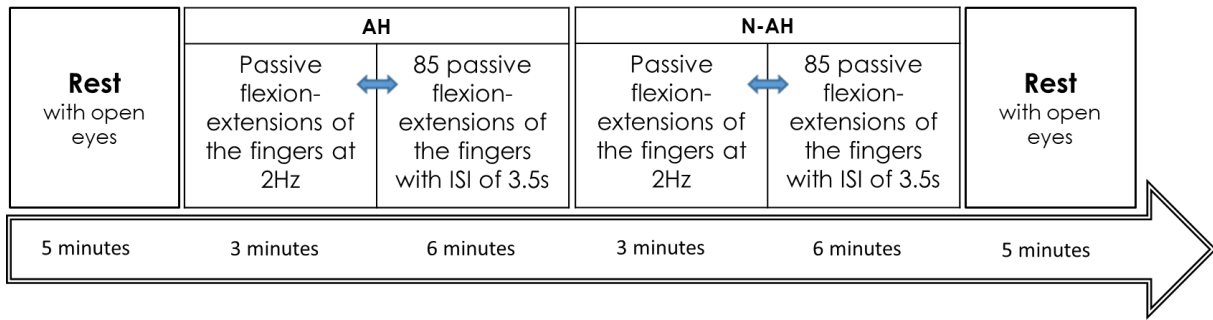
Figure 1. Experimental design. AH = Affected Hand; N-AH = Non Affected Hand; ISI = Inter-Stimuli Interval;  = random order.

Figure 2. Illustration of results obtained in the same child (participant 3) for the affected and non-affected hands. A = Individual corticokinematic coherence (CKC) spectra. B = sensors location of CKC peaks at 4 Hz. C = source location of CKC peaks at 4 Hz, showing that the peak was located in the mesial central cortical area of the non-lesioned hemisphere (blue region), and in the lateral central cortical area of the lesioned hemisphere (red region). MRI shows a subcortical lesion on the right side.

Figure 3. Illustration of results obtained in the same child (participant 11) for the affected and non-affected hands. A = Individual corticokinematic coherence (CKC) spectra. B = sensors location of CKC peaks at 4 Hz. C = source location of CKC peaks at 4 Hz, showing that the peak was located in the lateral central cortical area of the non-lesioned hemisphere (red region), and in the mesial central cortical area of the lesioned hemisphere (blue region). MRI shows an extensive cortico-subcortical lesion on the left side.

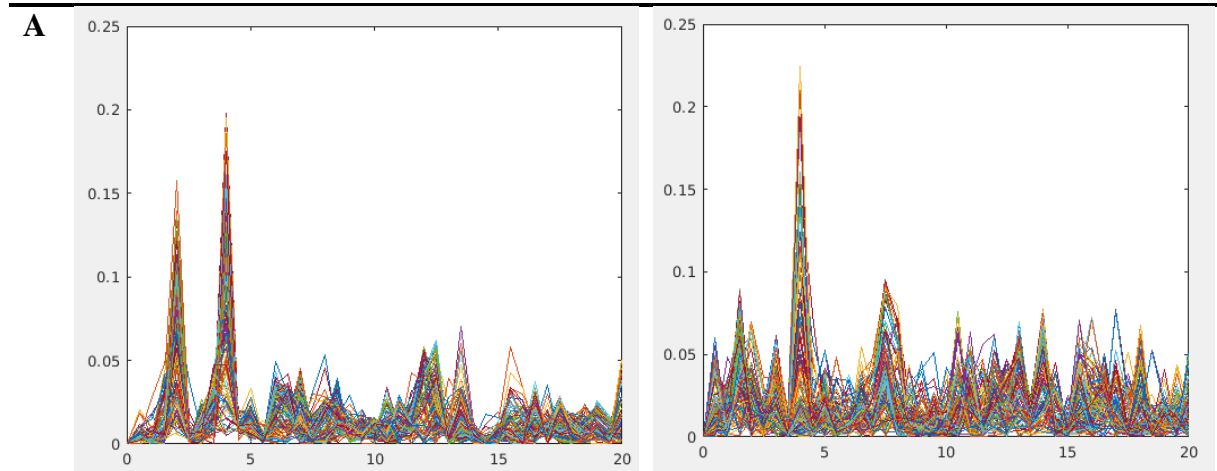
Figure 4. Source location of the highest CKC peak for each hand and each participant. The red cross indicates the source location of the CKC peak. Eleven participants had lesions located on the left side and for the two participants (3 and 10) with lesions located on the right side the images were reversed. Therefore, for each participant, the hemisphere on the left side represents the CKC peak for the affected hand, and the hemisphere on the right side represents the CKC peak for the non-affected hand

Figure 5. Individual coherence spectra for each participant. Each gray trace represents the maximum coherence between the electroencephalography (EEG) and accelerometer signals for a single individual. Black traces are group averages.

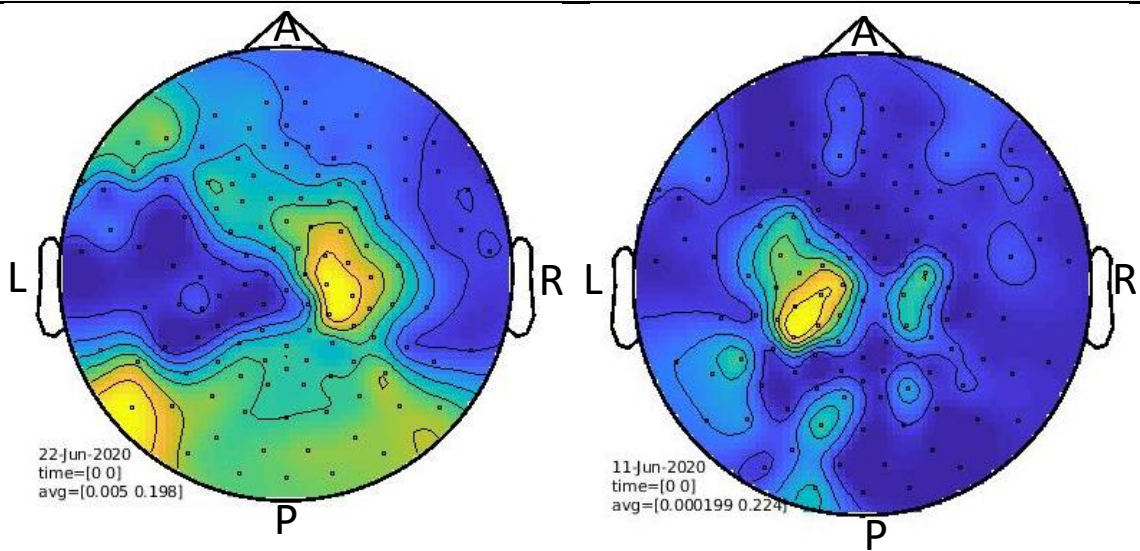


Affected Hand

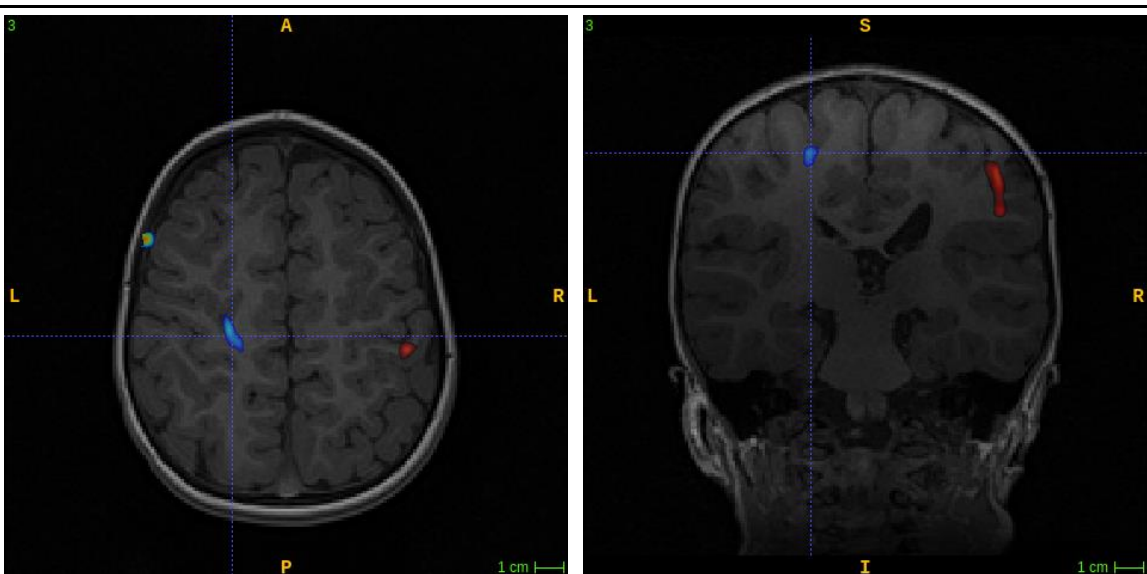
Non-Affected Hand



B



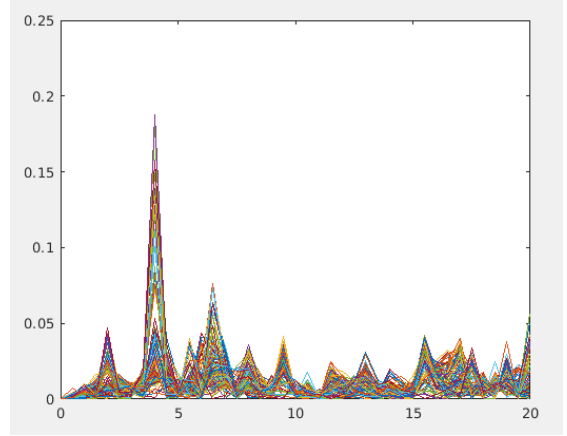
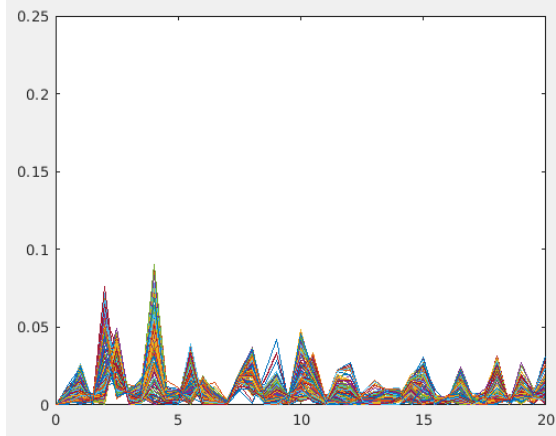
C



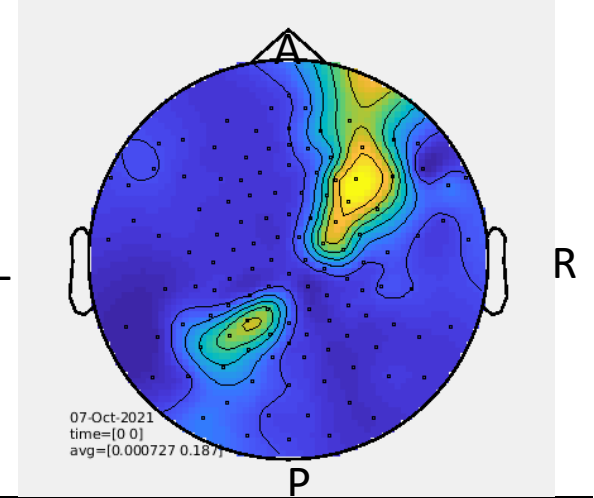
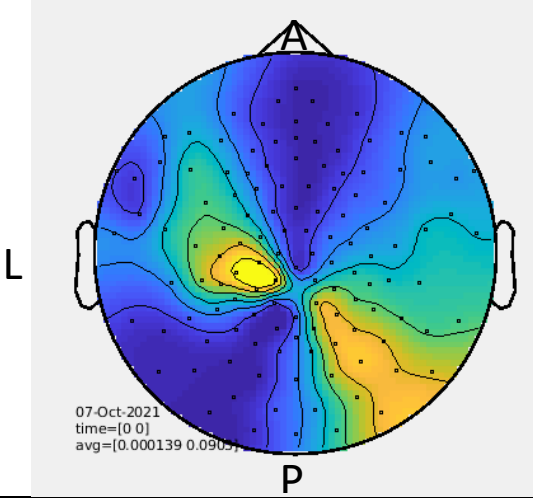
Affected Hand

Non-Affected Hand

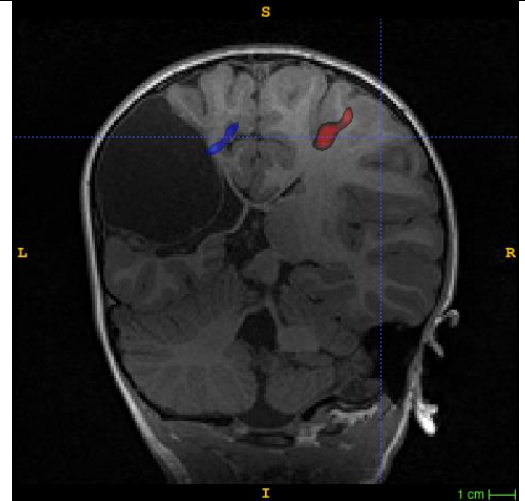
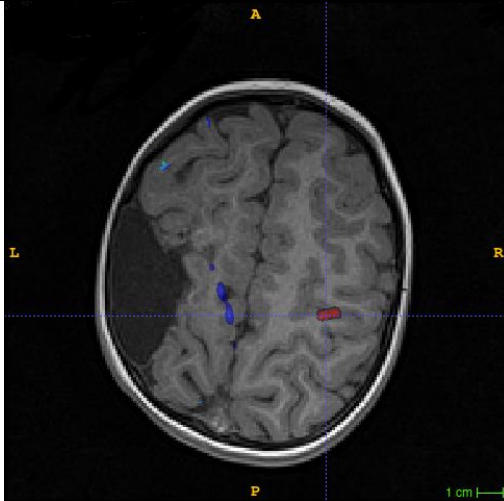
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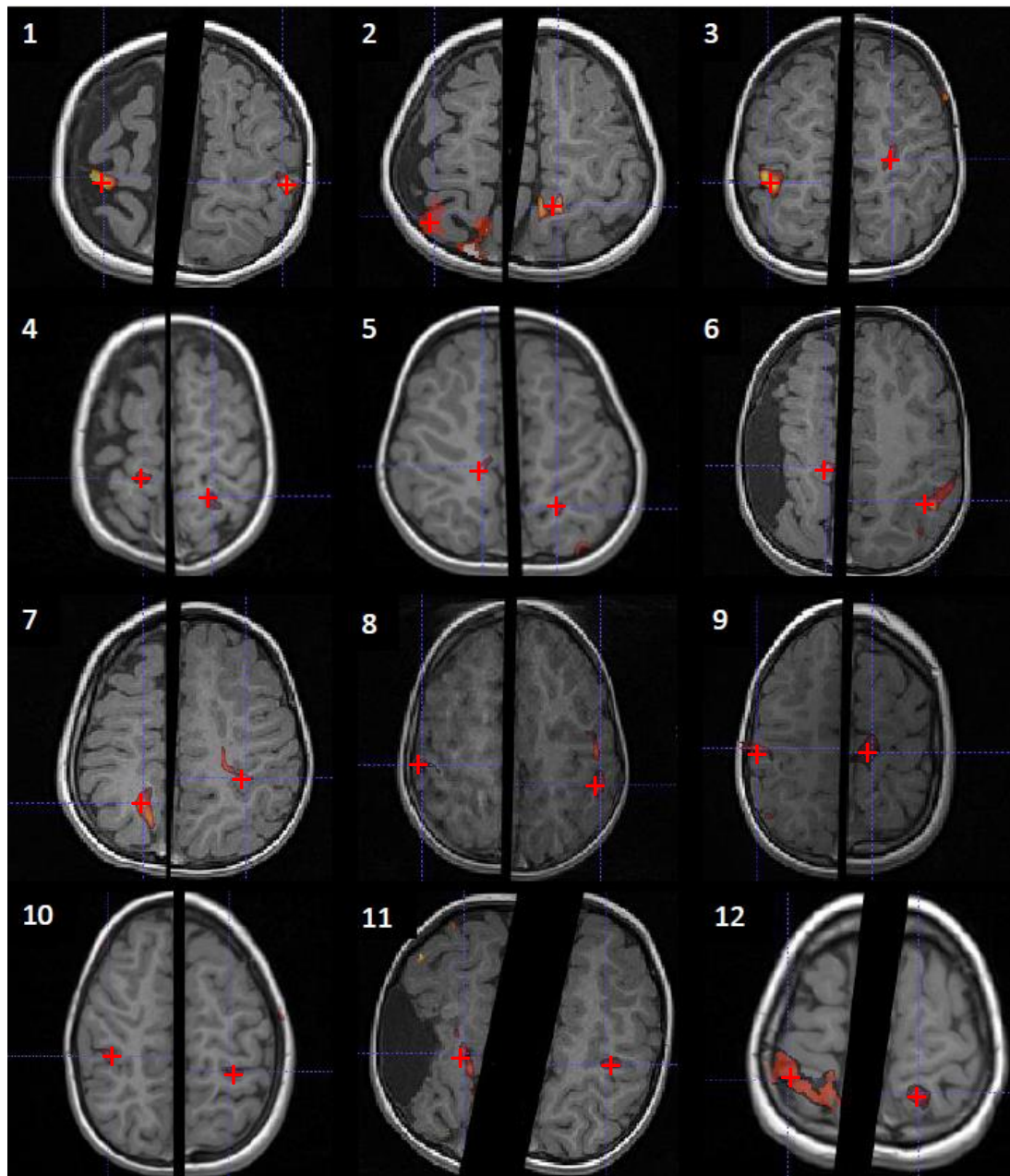


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C





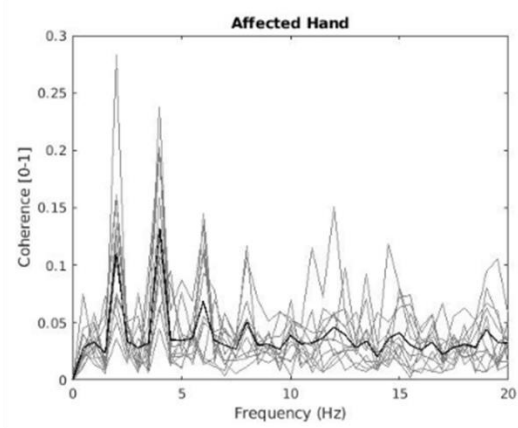
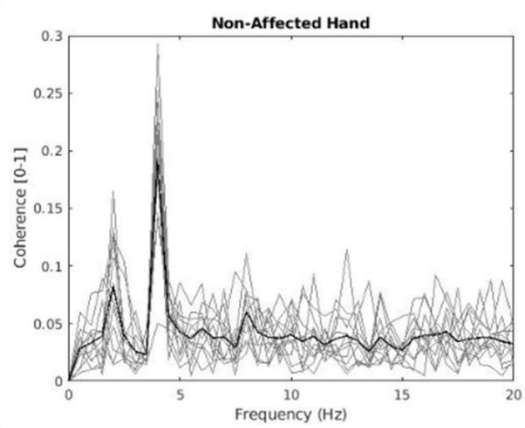


Table 1: Demographic data

Participant	Sex	Age (month)	mini-MACS or MACS level [I-V]	GMFCS level [I-V]	Lesion type	Lesion side
1	M	19	II	I	C-SC	L
2	F	24	III	I	C-SC	L
3	M	26	II	I	SC	R
4	F	27	II	II	SC	L
5	F	44	I	I	SC	L
6	F	45	II	I	C-SC	L
7	F	46	I	I	BM	L
8	F	50	II	I	SC	L
9	F	51	I	I	SC	L
10	F	51	I	I	SC	R
11	M	53	II	I	C-SC	L
12	M	57	II	I	C-SC	L

MACS, Manual Ability Classification System; GMFCS, Gross Motor Function Classification System; C-SC, Cortico-Subcortical; SC, Subcortical; BM, Brain Malformation; R, right; L, left

Table 2: Strength of the coherence peak in the area contralateral to the finger movements and its sublobar location in the source space

Participant	Maximal coherence level / source location			
	Non-Affected Hand		Affected Hand	
	F0	F1	F0	F1
1	0,18* / CL	0,17* / CL	0,14* / CL	0,11* / CM
2	0,16 / CM	0,31* / CM	0,29* / PL	0,16* / PL
3	0,09 / CL	0,25* / CL	0,24* / CL	0,2* / CL
4	0,13* / CL	0,05 / CL	0,08 / CL	0,08 / CL
5	0,14 / CL	0,27* / CL	0,06 / CM	0,13 / CM
6	0,13 / CL	0,21* / CL	0,06 / CL	0,07 / CM
7	0,02 / CL	0,21* / CL	0,13 / CM	0,21* / CM
8	0,02 / CL	0,27* / CL	0,07 / PL	0,22* / CL
9	0,04 / CL	0,16* / CM	0,09* / CL	0,14* / CL
10	0,07 / PL	0,23* / CL	0,12* / CL	0,25* / CL
11	0,06 / CL	0,19* / CL	0,09 / CL	0,13* / CM
12	0,14 / CL	0,19* / CL	0,16 / CL	0,04 / CL

* statistically significant; CL, Central Lateral ; CM ; Central Mesial ; PL, Parietal Lateral