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Cortical dynamics of sensorimotor information processing associated with balance control in adolescents with and without idiopathic scoliosis

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HIGHLIGHTS

- Adolescent idiopathic scoliosis (AIS) shows altered electrocortical dynamics during balance control.
- Cortical dynamics assessment seems sensitive to detect sensorimotor dysfunction.
- Participants with AIS adapt their electrocortical dynamics to maintain balance control.

ABSTRACT

Objective: This study aims at examining the cortical dynamics of sensorimotor information processing related to balance control in participants with adolescent idiopathic scoliosis (AIS) and in age-matched controls (CTL).
Methods: Cortical dynamics during standing balance control were assessed in 13 girls with AIS and 13 age-matched controls using electroencephalography. Time-frequency analysis were used to determine frequency power during ankle proprioception alteration (ankle tendons co-vibration interval) or reintegration of ankle proprioception (post-vibration interval) with or without vision.
Results: Balance control did not differ between groups. In the co-vibration interval, a significant suppression in alpha (8–12 Hz) and beta (13–30 Hz) band power and a significant increase in theta (4–7 Hz) band power were found respectively in the vision and non-vision condition in the AIS group compared to the CTL group. In the post-vibration interval, significant suppressions in beta (13–30 Hz) and gamma (30–50 Hz) band power were observed in the AIS group in the non-vision condition.
Conclusion: Participants with AIS showed brain oscillations differences compared to CTL in the sensorimotor cortex while controlling their balance in various sensory conditions.
Significance: Future study using evaluation of cortical dynamics could serve documenting whether rehabilitation programs have an effect on sensorimotor function in AIS.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a multifactorial disorder characterized by a three-dimensional (3D) deformity of the spine affecting 2–3% of adolescents with girls more severely affected (Weinstein et al., 2008). Progressive scoliosis affects self-image and appearance (Donaldson et al., 2007; Sapountzi-Krepia et al., 2001; Zabjek et al., 2008), activity performance and quality of life (Danielsson et al., 2006; Mahaudens et al., 2010; Tones et al., 2006). The etiopathogenesis of AIS still remains unclear with multifactorial hypotheses including genetic factors, central nervous system (CNS) abnormalities and hormonal dysfunctions during growth (Burwell et al., 2009; Domenech et al., 2010; Edery et al.,

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2011; Edery et al., 2013; Geissele et al., 1991; Herman et al., 1985; Moreau et al., 2004). These factors are suggested to be associated with initiation of idiopathic scoliosis (Veldhuizen et al., 2000). Subsequently, biomechanical factors such as posture asymmetry and muscle imbalance would also play a role in scoliosis progression during the growth period (Reuber et al., 1983; Stokes, 2007). A causal gene of idiopathic scoliosis has recently been identified (Edery et al., 2011; Fendri et al., 2013). The pathogenic nature of this gene relates to its mutated protein found during the early development in the hindbrain-midbrain boundary (Patten et al., 2015), a critical region for brain structuration (Wurst and Bally-Cuif, 2001). This brain region plays an important role in sensory processing and balance control (Boisgontier et al., 2017; Drijkoningen et al., 2015). In addition, altered sensory cortical processing and abnormal connectivity patterns in the motor cortex were found in participants with AIS compared to age matched controls (Cheng et al., 1998; Lao et al., 2008; Wang et al., 2013). Furthermore, outcomes of MRI studies have revealed some structural abnormalities in participants with AIS compared to controls. For example, asymmetry in the ventral pons of the medulla in the area of the corticospinal tracts (Geissele et al., 1991), abnormal cortical thinning of the paracentral region (right hemisphere), the superior frontal region (left hemisphere) and of the precentral gyrus (right hemisphere) (Wang et al., 2012) were observed while the authors of an fMRI study reported abnormal patterns of brain activation in the supplementary motor area during movement execution (Domenech et al., 2011). Thus, these subcortical and cortical alterations could cause sensorimotor control dysfunctions leading to asymmetrical back muscle activity and timing (Cheung et al., 2004, 2005; Shimode et al., 2003), poorer balance control, difficulty in reweighting sensory information during or following a brief period of sensory deprivation and altered cognitive integration of vestibular signals (Haumont et al., 2011; Nault et al., 2002; Pialasse et al., 2015a, 2015b, 2013, 2016; Simoneau et al., 2009).

The results of these behavioral studies, while important on their own, do not permit to assess if cortical brain oscillations, reflecting sensorimotor integration, differ in participants with AIS compared to controls. Recording electroencephalography (EEG) in the sensorimotor areas provides a window into the neural mechanisms related to balance control (Jacobs and Horak, 2007; Varghese et al., 2017). Recently, time-frequency decomposition of EEG signals showed an association between balance control performance and cortical dynamics in different frequency bands at the frontal, central and parietal regions of the cortex. An increase in theta band power (4–7 Hz) and a reduction in alpha–beta band power (8–13 & 13–30 Hz, respectively) was observed in the sensorimotor cortex during challenging standing or walking balance tasks (Hulsdunker et al., 2015a; Peterson and Ferris, 2018; Sipp et al., 2013; Slobounov et al., 2009). These findings suggest that theta oscillations may be associated with sensorimotor processing for detecting and preventing loss of balance. Further, evidences suggest that the functional processing of somatosensory cues relates to specific frequency band of neural oscillations at the cortical level. For instance, alpha oscillations (~8–12 Hz) is a marker of the excitability of the somatosensory cortex (Anderson and Ding, 2011; Pfurtscheller and Lopes da Silva, 1999). Compared to baseline, a suppression of alpha band power represents larger excitability thus a suppression of alpha band power indicates that somatosensory cues are relevant to perform the task optimally (Haegens et al., 2011). Further, power of beta oscillations (~13–35 Hz) prevails during unaltered state but a suppression in beta band power is usually observed prior and during movement in the somatosensory cortex. Thus, beta desynchronization (i.e., suppression of power) is thought to represent processing or somatosensory signals (van Ede et al., 2011; van Ede et al., 2012). Gamma oscillations also have been recorded in the sensorimotor cortex during motor behaviors. As opposed to alpha and beta oscillations, the power of gamma oscillations (30–50 Hz) increases during sensorimotor tasks contributing to enhancement of multimodal sensory integration (Aoki et al., 1999, 2001; Fries, 2015; Lebar et al., 2017; Salenius et al., 1996).

In other studies, comparing brain oscillations in athletes to non-athlete young adults, the authors observed a link between power suppression in the alpha band (reported as event-related desynchronization – ERD) and balance control performance (Del Percio et al., 2009, 2007). Results revealed that alpha band power suppression increases in cortical regions involved in sensorimotor integration in the more challenging task in both groups when vision is available. However, compared to non-athletes, athletes showed less alpha band power suppression associated with this task, suggesting reduced cortical activity in athletes (Del Percio et al., 2009). In another paradigm comparing standing balance control with and without vision, a significant correlation is reported in karate athletes between right centro-parietal alpha ERD and percentage reduction of body sway area, the greater the alpha ERD, the greater the improvement of balance control when vision is available (Del Percio et al., 2007). According to Del Percio et al. (2009), karate athletes maximize processing of visual information for controlling standing balance. The authors concluded that the sensory requirements of a sport activity and the equilibrium training will differently affect the cortical information processing associated with balance control. Overall, these results suggest a link between balance control performance and changes in brain oscillations.

In the present study, we examined the cortical dynamics of sensorimotor information processing related to balance control in participants with AIS and age matched healthy adolescents (CTL) by comparing time-frequency maps of brain sources located in the sensorimotor cortex. Our objective was to investigate whether we could identify specific cortical dynamics associated with ankle proprioception alteration or reintegration while vision was available or not. Since alpha band desynchronizations is a marker of the excitability of the somatosensory cortex (Anderson and Ding, 2011; Pfurtscheller and Lopes da Silva, 1999) and beta band desynchronization is thought to represent processing of somatosensory signals (van Ede et al., 2011; 2012) we hypothesized that compared to CTL participants, AIS participants should show less alpha and beta band power suppression during sudden changes in ankle proprioception state. If this hypothesis is confirmed, it would suggest less efficient sensorimotor integration in AIS compared to CTL. This observation would shed some light on the mechanisms underlying impaired balance control in AIS participants compared to CTL during challenging sensory conditions (Guo et al., 2006; Haumont et al., 2011; Sahlstrand and Lidstrom, 1980; Simoneau et al., 2006b). It is also possible that the neural mechanisms for detecting a loss of balance are less efficient in AIS participants. Because theta oscillation synchronization is observed when participants lose their balance (Peterson and Ferris, 2018; Sipp et al., 2013; Varghese et al., 2014) and it is thought to be related to detection of balance changes (Hulsdunker et al., 2015a; Slobounov et al., 2013), less theta band synchronization in AIS participants would indicate impairments in detecting a sudden change in balance state-space. In addition, as synchronization in the gamma band in the sensorimotor cortex increases with performance during challenging sensorimotor tasks (Aoki et al., 1999; Fries, 2015), poorer balance control in AIS participants should imply gamma band desynchronization compared to controls. Finally, we expect that removing visual information would exacerbate balance control of AIS participants more than control participants thus the absence of alpha and beta band desynchronization and gamma band synchronization should be exacerbated.

2. Materials and Methods

2.1. Participants

Twenty-six adolescent girls between 10 and 18 years of age participated in the present study. They were separated into two groups according to their clinical status, AIS or CTL group. The 13 adolescents with AIS were recruited from two orthopedic clinics (CHU Sainte-Justine & Clinique orthopédie pédiatrique de Québec). Inclusion criteria were: idiopathic scoliosis with a Cobb angle between 15 and 45° and no previous spine surgery or other musculoskeletal disorder. The 13 age-matched control girls were recruited from surrounding schools as well as children of the staff working in the hospitals. Participants in the CTL group had to be exempt of spinal pathologies and of other neurologic or musculoskeletal disorders. Participants answered a short clinical questionnaire to document their medical history, daily and physical activities and symptoms history. This interview was followed by anthropometric measurements. Pain level was determined using the Numeric Pain Rating Scale (NPRS: 0–10) (Childs et al., 2005), since pain is often present in adolescents with idiopathic scoliosis (50–78%) (Landman et al., 2011; Sato et al., 2010; Smorgick et al., 2013) and in healthy adolescents (28–48%) (Calvo-Munoz et al., 2013; Jones et al., 2004; Kjaer et al., 2011) and may alter balance control (Popa et al., 2007) and EEG activity (Jacobs et al., 2010). Parents and participants gave written informed consent to participate and the project was approved by the ethics committees of the two institutions.

2.2. Experimental procedure

Participants stood barefoot on the force platform with their feet 10 cm apart and arms along the body. They performed 50 trials in the two experimental conditions: vision and non-vision, 25 trials in each condition in alternating order. Participants were instructed to close their eyes or to keep them open before the trial onset and to adopt a relaxed standing posture. Each trial lasted 30 seconds and was divided into three intervals: (1) pre-vibration (0–10 s), (2) co-vibration (10–20 s) and (3) post-vibration (20–30 s). The pre-vibration interval served to assess balance control performance during normal upright standing posture. The co-vibration interval allowed to investigate the effect of ankle proprioception alteration on balance control. The post-vibration interval permitted to determine the ability of the participant to reintegrate ankle proprioception. Ankle proprioception was altered by means of co-vibration over the tendons of the soleus/gastrocnemius and tibialis anterior of both ankles. Applying vibration to a muscle tendon specifically activates the muscle spindle primary endings (Burke et al., 1976; Roll and Vedel, 1982). The vibrators were fixed by rubber bands. The four vibrators consisted of unbalanced masses fixed at both extremities of direct current motors rotating at 80 Hz; each motor was inserted into a plastic cylinder and the amplitude of the mechanical oscillation was between ~0.5 and 1 mm.

2.2.1. Experimental settings

Balance control was assessed using a force platform (AMTI, Optima model OP464508-200-STT and amplifier model OPT-SC; AMTI, model OR6-7-1000 and amplifier model AMTI GEN-5D, Watertown, MA, USA) using 16-bit A/D converter (both sites: model NI PCIe-6531, National Instrument, Austin, TX, USA). Electrocortical signals were collected using a 128-channel Hydrogel Geodesic SensorNet (EGI, Eugene, OR, USA) with a Net Amps 300 amplifier or through a 64-channel Hydrogel Geodesic SensorNet (Electrical Geodesics, Inc (EGI), Eugene, OR, USA) with a Net Amps 400 amplifier. EEG recording was sampled at 1000 Hz using Netstation® 4.5 software (EGI, Eugene, OR, USA) and electrode impedances were kept below 40 kΩ. Size of the SensorNet was chosen to match the head size of each participant. To control vibration onset/offset and synchronize EEG and behavioural data, we used microcontrollers (Basic Stamp 2 SX, Parallax, Rocklin, CA, USA and Arduino Mega 2560, Atmel Corporation, San Jose, CA, USA).

2.2.2. Behavioural data processing

Matlab 2018a (Mathworks, Inc., Natick, MA, USA) was used to process platform data. All data were filtered using a zero-lag 4th order low-pass Butterworth filter (cut-off frequency 10 Hz). Platform data was used to calculate center of pressure (COP) and center of gravity (COG). The position of the COG along the AP axis was estimated throughout each trial using a zero-point-to-zero-point double integration technique, also known as the gravity line projection technique (King and Zatsiorsky, 1997; Zatsiorsky and King, 1998). The underlying assumption of this method is that the COP coincides with the vertical line passing through the COM (COG is the vertical projection of the COM) when the horizontal ground reaction force is zero.

Balance control was assessed by calculating the scalar distance between COP and the COG (Gage et al., 2004; Masani et al., 2007). Root mean square value of the COP-COG scalar distance was calculated for an epoch of 8 s in the pre-vibration interval, for the first 2.5 s of the vibration interval, and for the first 2.5 s of the post-vibration interval. Recent studies have reported that the time course of body sway variability during a sudden change in sensory state is approximately 2 s (Honeine et al., 2015; Sozzi et al., 2012). Thus, to assess balance control performance at ankle tendons co-vibration onset and offset, we calculated the root mean square (RMS) value of the COP-COG scalar distance during the first 2.5 s following a sudden change in sensory state.

2.2.3. EEG processing

EEG processing was performed using EEGlab13.6.5b (Swartz Center for Computational Neuroscience, Institute for Neural Computation, University of California San Diego, San Diego, CA, USA). For the EEG preprocessing, EEG signals were first down sampled to 250 Hz and then high-pass filtered using a basic FIR filter (cut-off frequency of 1 Hz). This 1 Hz high-pass filter suppresses low-frequency drifts that are spatiotemporally nonstationary and helps ICA in producing a good decomposition (Frolich and Dowding, 2018). Line noise at 60 Hz and its harmonics were removed using cleanline, an EEGlab plug-in that adaptively estimates and removes sinusoidal artifacts using a frequency-domain regression technique (Bokil et al., 2010). Thereafter, we used the plug-in clean_rawdata to detect and subtract non-stationary high-amplitude artifacts that most probably originated from eye blinks, muscle, and electrode motion and to interpolate or reject periods in the EEG data that exceeded the mean amplitude by 4 standard deviations of a clean portion of the same data. Finally, we referenced the channels to an average reference. Infomax independent component analysis was performed on the cleaned dataset in order to transform the EEG channel data into temporally independent component (IC) signals (Bell and Sejnowski, 1995).

2.2.4. Estimating equivalent current dipoles for EEG sources

Once IC activities were obtained, the location and orientation of a best-fitting equivalent current dipole was fit for each component using the DIPFIT2 (Oostenveld and Oostendorp, 2002) plug-in for EEGLAB. Since MRI structural head images of the participants were not available, a boundary element model based on the Montreal Neurological Institute's (MNI) standard brain template was used for estimation of dipole locations and orientations. The equivalent dipoles were selected if they were in the sensorimotor cortex and

had residual variance smaller than 15% from the spherical forward-model scalp projection.

To select brain sources located in the sensorimotor cortex, independent components were clustered according to their scalp map, dipole location and power spectrum. Clustering was performed within EEGlab using the K-means algorithm. This algorithm creates clusters by minimizing variability within a cluster and maximizing variability between clusters. Independent components with a distance larger than three standard deviations from the mean of the cluster centroid were removed from the analysis. For each group and condition, a total of 10 clusters were created. Thereafter, clusters were inspected to assess the contribution of each participant to the cluster. If one participant contributed to multiple ICs in the sensorimotor cluster, the IC with the lowest residual variance was selected. It might occur that the clustering algorithm failed to identify one IC for a participant (Huster et al., 2015). In this case, we selected the IC with the lowest residual variance that was located within or close to the sensorimotor cortex. Then, we carefully examined the IC activity and its power spectrum to ascertain it contained activity believed to originate from synchronously activity in one cortical patch. Such sources have power spectral densities with inversely related frequency and power and show increased power in frequency bands between 5 and 30 Hz (Onton and Makeig, 2006). Overall, the clustering algorithm failed to include the source of 5 participants (i.e., 2 adolescents with idiopathic scoliosis in vision condition and 3 control participants, 2 in no-vision and 1 in vision condition). For these participants, the sources were identified according to the criteria enumerated above. Both groups' cortical dipoles in the sensorimotor cortex and the average topography in condition vision are illustrated in Fig. 1 (see Supplementary Fig. 1 for condition non-vision). In this study, EEG data were acquired using 64- and 128-channel systems. In an experiment assessing the neural substrates of sensorimotor processing (Melnik et al., 2017), the authors assessed if the number of channels in an EEG system influenced the number of sensorimotor independent components. The authors concluded that the number of channels did not influence the number of independent components located in the sensorimotor cortex.

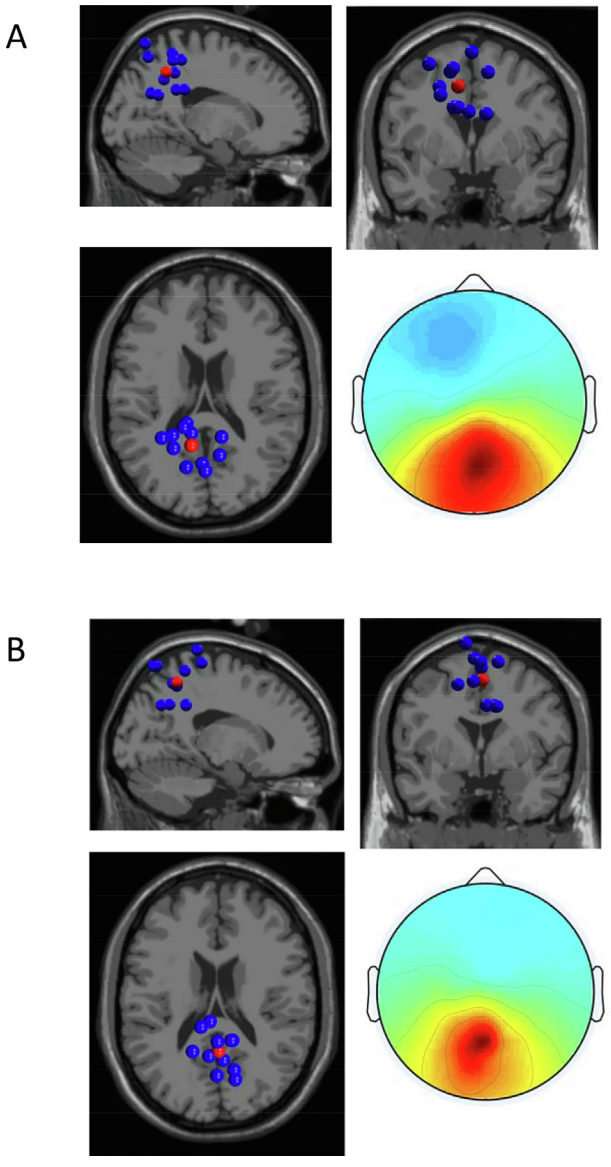

Fig. 1. Cortical dipole locations of the brain sources located in the sensorimotor cortex for the control (panel A) and adolescent idiopathic scoliosis (panel B) groups in the vision condition. Blue dots illustrate participant's dipole with the smallest residual variance and red dots denote cluster centroid. Bottom right panel depicts average scalp topography of the cluster. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To perform time-frequency analysis, we adapted customized Matlab scripts (Cohen, 2014). For each participant, we calculated the time-frequency map of the IC located in the sensorimotor cortex. To do so, single-trial data were first decomposed into their time-frequency representation by multiplying the power spectrum of the IC located in the sensorimotor cortex, obtained from the fast Fourier transform, by the power spectrum of complex Morlet wavelets $e^{i2\pi tf}e^{-t^2/(2\sigma^2)}$ where t is time, f is frequency, which increased from 1 to 50 Hz in 40 linearly spaced steps, and σ defines the width of each frequency band, set according to $n/(2\pi f)$ where n is the number of wavelet cycles and increased from 4 to 12 in logarithmic steps, and then taking the inverse fast Fourier transform (i.e., frequency domain convolution). From the resulting complex signal, an estimate of frequency band specific power at each time point was defined as the squared magnitude of the result of the convolution $Z\left(real[z(t)]^2 + imag[z(t)]^2\right)$. Power was normalized using a decibel (dB) transform (dB power = 10 × log10 [power/baseline]), where the baseline activity was taken as the average power at each frequency band, averaged across conditions, from –0.5 to –0.2 s before ankle tendons vibration. Conversion to a dB scale ensures that data across all frequencies, time points, electrodes, conditions, and participants are in the same scale and thus comparable.

2.3. Statistical analysis

The software Statistica (version 13, Tibco software Inc, Palo Alto, CA, USA) was used to assess if body sway differed between groups. The RMS value of the COP-COG scalar distance was submitted to groups (2: AIS, CTL) by conditions (2: Vision, Non-vision) by intervals (3: Pre-vibration, Vibration and Post-vibration) analysis of variance (ANOVA) with repeated measures on the last two factors. Prerequisites for the ANOVA were verified. First, we tested the homogeneity of the variance using the Box M test. The result of the Box M test (Box M = 33.16, Chi-square = 23.96, p = 0.29) was not significant indicating that the variances within each population was similar. To assess the sphericity, we used Mauchly's test. The results of this test have revealed that the sphericity was neither violated for the conditions (i.e., vision and no-vision) nor for the interaction interval (preVib, Vib, postVib) by condition (vision, no-vision, p = 0.31). However, the sphericity was violated for the intervals (p = 0.01). Thus, for this analysis, the Huynh-Feldt correction was applied. Further, we calculated the Kolmogorov-Smirnov test for each interval and group. None of

the tests were significant, confirming that the data were normally distributed. Post-hoc tests were performed using Tukey test. Anthropometric data of the two groups were compared using Wilcoxon rank sum test. All statistical analyses were set with $p \leq 0.05$.

For the time-frequency analysis, statistical comparisons were performed using t-tests, and multiple comparisons were corrected using cluster-based permutation testing (Maris and Oostenveld, 2007; Nichols and Holmes, 2002), in which the assignment of condition to each data point was randomly shuffled, and statistics were recomputed. After thresholding each permutation map ($p < 0.05$), the t-values were stored. This was repeated 3000 times, creating a distribution of t-values under the null hypothesis. Any pixels in the real data with a t-value at least larger than the 95% of the distribution of null hypothesis were considered statistically significant. This procedure was performed for the conditions vision and non-vision immediately after ankle tendons vibration onset (vibration interval) and immediately following ankle tendon offset (post-vibration interval).

3. Results

3.1. Participants

Anthropometric characteristics of the two groups are presented in Table 1. There were no significant differences in age, height, weight, pain status and number of hours per week of extra-curricular sports activities. Ten participants out of 13 reported doing extra-curricular sports activities in the AIS group compared to 7 participants out of 13 in the CTL group. Sports activities were similar in both groups, such as karate, soccer, volleyball, swimming and hockey. In the AIS group, we also had three participants engaging in dance activities.

3.2. Balance control

The ANOVA revealed that, for both groups, body sway was larger in non-vision compared to vision (main effect of condition: $F(1,46) = 14.21$, $p = 0.00047$) (Fig. 2). In addition, the analysis showed that body sway varied across intervals (main effect of interval: $F(1.6537.77) = 54.69$; $p < 0.00000001$). Post-hoc tests confirmed that body sway was larger during vibration and post-vibration intervals compared to the pre-vibration interval ($p < 0.001$) and that body sway was alike between vibration and post-vibration intervals ($p > 0.05$). Further, analysis revealed a significant interaction of interval by condition ($F(2,92) = 3.48$, $p = 0.035$). Decomposition of this interaction indicated that, for both groups, the increase in body sway between the pre-vibration and vibration interval was larger in both conditions ($p < 0.001$). Amplitude of the body sway during the vibration interval was similar for vision and non-vision ($p > 0.05$) and during the

Table 1
Anthropometric characteristic of participants: mean and standard deviation [SD]

	AIS group Mean [SD]	CTL group Mean [SD]	P value
Age (y)	12.9 [1.0]	13.0 [1.0]	–
Height (cm)	161.1 [7.6]	157.7 [7.5]	0.206
Weight (kg)	50.2 [8.6]	46.5 [9.4]	0.314
Pain	0.8 [1.7]	0.0 [0]	0.125
Extra-curricular sports activities (hours/week)	3.3 [2.6]	2.9 [2.7]	0.734
Scoliosis: Cobb angle (°)	26 [9]/26 [9]	–	–
Thoracic/Thoraco-lumbar or lumbar			

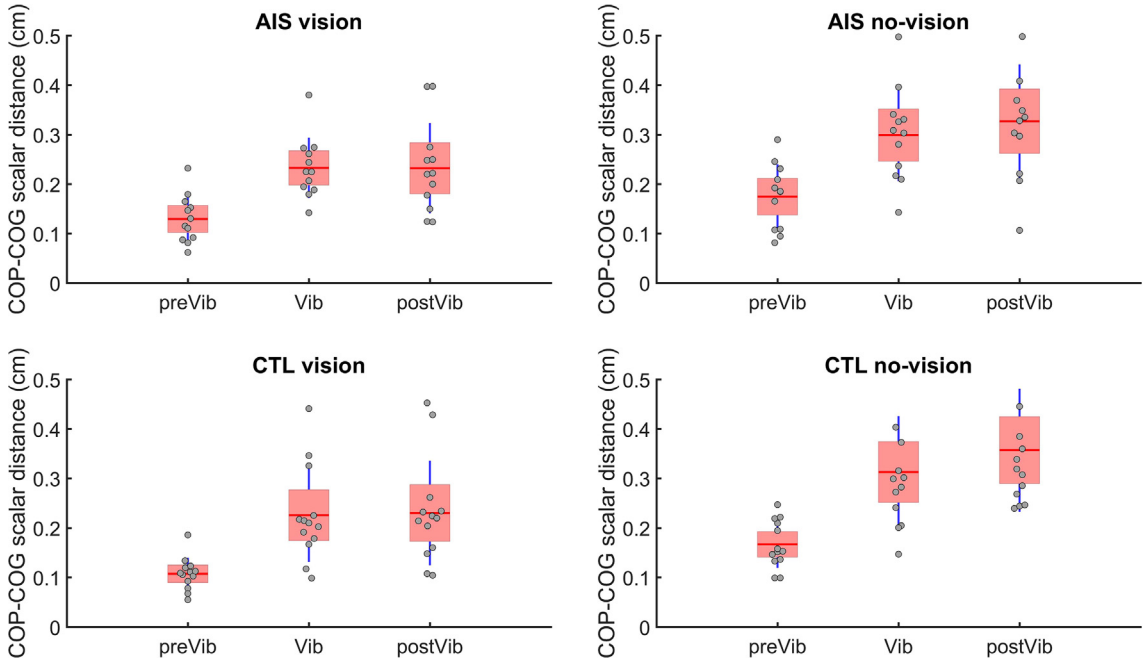

Fig. 2. Group means of the RMS value of the COP-COG scalar distance for the vision (left column) and no-vision conditions (right column) before tendons vibration (preVib), during tendons vibration (Vib) and, following tendons vibration (postVib). On each panel, gray dots depict mean results for each participant. Red horizontal lines illustrate group means while light red boxes denote group standard error of the mean and blue lines depict one standard deviation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

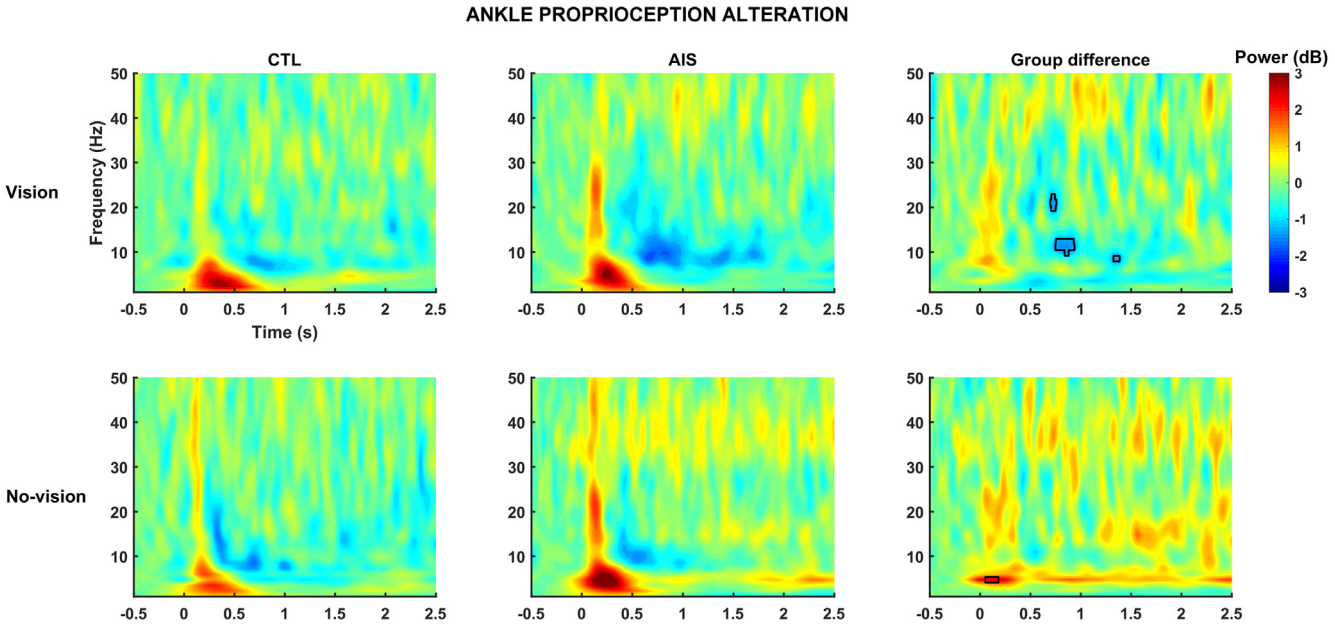

Fig. 3. Time-frequency plots of oscillation power, following ankle tendons vibration onset, as a function of group, condition and group difference. First row depicts time-frequency maps for vision condition whereas second row presents time-frequency maps for non-vision condition. Left column is for CTL group, middle column for AIS group and right column for difference between AIS and CTL groups. Color scale: red colour indicates increase frequency power (ERS) while blue colour indicates decrease frequency power (ERD) with respect to baseline. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

post-vibration interval ($p > 0.05$). All other main effects or interactions were not significant.

3.3. Brain oscillations

For the vision condition, time-frequency analysis (Fig. 3 - upper right panel) revealed a significant suppression in alpha (8–12 Hz) and beta (13–30 Hz) band power for the AIS compared to the CTL group between 0.8 and 1.5 s after ankle tendons vibration onset. In the non-vision condition, a significant increase in theta (4–7 Hz) band power is observed immediately after ankle tendons vibration onset for the AIS group compared to the CTL group (Fig. 3 – lower right panel).

Time-frequency analysis following ankle tendons vibration offset showed significant suppressions of delta (1–3 Hz) and theta (4–7 Hz) band power for the AIS compared to the CTL group in the vision condition between ~1.8 and 2.5 s (Fig. 4). In the non-vision condition, significant suppressions in beta (13–30 Hz) and

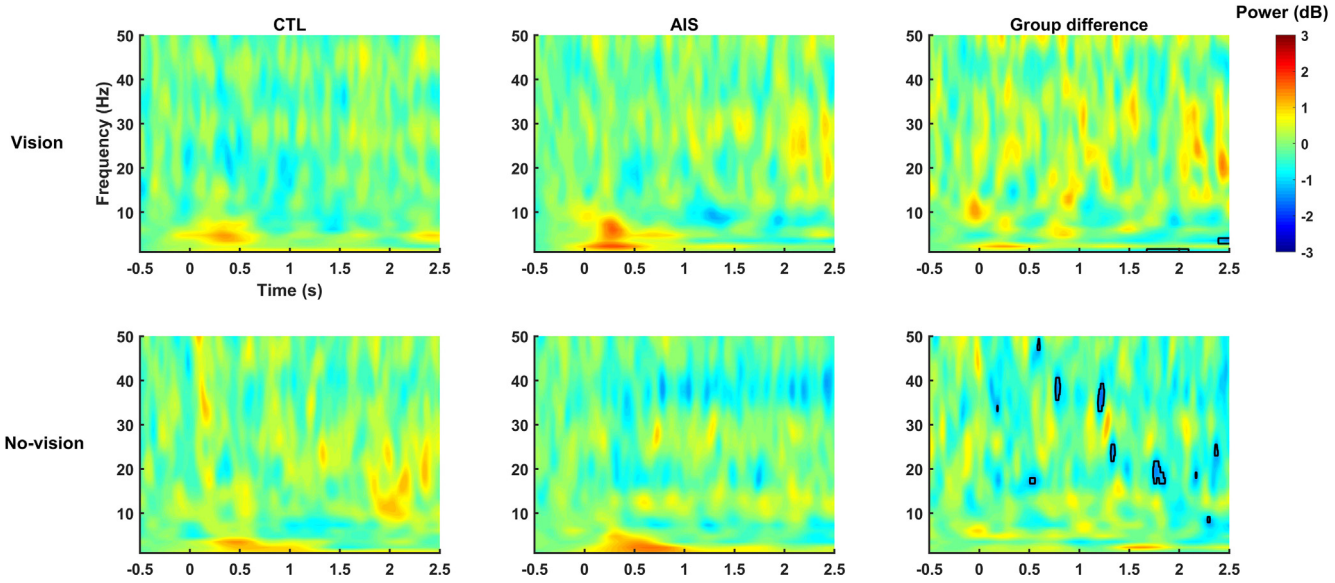

Fig. 4. Time-frequency plots of oscillation power, following ankle tendons vibration offset, as a function of group, condition and group difference. First row depicts time-frequency maps for vision condition whereas second row presents time-frequency maps for non-vision condition. Left column is for CTL group, middle column for AIS group and right column for difference between AIS and CTL groups. Color scale: red colour indicates increase frequency power (ERS) while blue colour indicates decrease frequency power (ERD) with respect to baseline. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

gamma (30–50 Hz) band power are observed for the AIS group compared to the CTL group between 0.5 and 2.5 s post vibration offset.

4. Discussion

The goal of this study was to assess electrocortical dynamics and balance control in participants with AIS and healthy age-matched controls following a sudden change in ankle proprioception state. Behavioral studies have revealed balance control impairment in participants with AIS compared to CTL during sensory transition but the neural mechanisms underlying this difference is not well understood. In this study, by assessing electrocortical oscillations during sensory transition, we wanted to compare the sensorimotor mechanisms of AIS and control participants. We hypothesized that compared to CTL, participants with AIS should show less alpha and beta band power suppression during ankle proprioception alteration (co-vibration) and less theta band power synchronization. We also hypothesized that participants with AIS should show less gamma band power synchronization. As visual information improves balance control, we expected that these differences would be exacerbated in absence of vision. Remarkably, body sway amplitude did not differ between groups either during or following alteration in ankle proprioception. Some studies have demonstrated larger body sway in participants with AIS compared to CTL during challenging sensory conditions (Haumont et al., 2011; Pialasse et al., 2015a; Sahlstrand and Lidstrom, 1980; Simoneau et al., 2006a; Simoneau et al., 2006b) while others reported impaired balance control during upright standing or locomotion only in subgroups of participants with AIS (Gauchard et al., 2001; Guo et al., 2006; Lao et al., 2008; Pialasse et al., 2017). This result is important as one can hypothesize that spine deformation causes a distortion of the body schema (Burwell et al., 2006). Nonetheless, in absence of sudden alterations in sensory information, distortion of the body schema does not necessarily lead to balance control impairment in participants with AIS (Adler et al., 1986; Byl and Gray, 1993; Byl et al., 1997; Herman et al., 1985).

Although the absence of behavioural group differences during or after ankle proprioception alteration contrasted with our hypothesis, overall these findings replicate previous results reporting that balance control impairments could involve only a subgroup of participants with AIS. Another factor influencing balance control performance is the level of physical activity (Baccouch et al., 2015; Del Percio et al., 2009; Del Percio et al., 2007; Gerbino et al., 2007; Perrin et al., 2002). According to Del Percio et al. (2009), sports activities implicating balance training reduce body sway and positively affect cortical information processing associated with balance control. Even though no significant statistical difference was found between groups for the number of hours per week of extra-curricular sports activities, participants with AIS were slightly more active compared to the CTL group. It is thus possible that the balance control task used in this study was not challenging enough for the AIS participants since 10 out of 13 were doing sports activities such as karate and dancing which contribute to decrease body sway in standing balance tasks (Baccouch et al., 2015; Gerbino et al., 2007; Perrin et al., 2002).

Contrary to our hypotheses, compared to CTL, AIS participants showed more alpha and beta band desynchronization when ankle proprioception was altered. This group difference in the electrocortical activity suggests that this adjustment in the functioning of the sensorimotor integration mechanisms led to balance control comparable to control participants. This observation is in line with previous works reporting a suppression of alpha and beta band power and an increase in theta band power in the somatosensory region following a sudden change in sensory state (Hulsdunker et al., 2015a; Sipp et al., 2013; Slobounov et al., 2013; Varghese et al., 2014). Alpha oscillations reflect inhibition of task-irrelevant brain regions suggesting that alpha desynchronization (i.e., power reduction compared to baseline) represents increased in information processing due to inhibition reduction (Babiloni et al., 2014; Klimesch, 2012; Pfurtscheller and Lopes da Silva, 1999). During upright balance control, alpha band desynchronization reflects an increase in processing sensory information relevant to balance control (Del Percio et al., 2007; Hulsdunker et al., 2015b). Reduction in alpha power over the centro-parietal region with increasing body sway has been reported (Hulsdunker et al., 2015b). Thus, the larger alpha desynchronization observed in AIS compared to CTL provides indication that participants with AIS needed more cortical resources than CTL to process sensory information relevant to controlling their body sway. This observation replicates previous results showing that alpha and beta band suppression occurs during challenging balance control tasks (Sipp et al., 2013; Wagner et al., 2016). The authors suggested that beta band power decrease could entail motor inhibition (Wagner et al., 2016). The larger suppression in alpha and beta band power, following ankle tendons vibration in presence of vision, suggests that participants with AIS adapted their balance motor commands to prevent large body sway.

For beta brain oscillations, there seems to be an inverse relationship with the processing of sensorimotor information. Beta synchronization is important during isometric contraction while it is attenuated during voluntary movements (Baker et al., 1997; Kilner et al., 2000; Pfurtscheller, 1981; Sanes and Donoghue, 1993; Schoffelen et al., 2005). During isometric contraction (i.e., tonic muscle contraction), the increase in beta synchronization (Pfurtscheller and Lopes da Silva, 1999; Salmelin and Hari, 1994) has led to the hypothesis that beta synchronization is important for stabilizing the motor commands and possibly preventing new movements (Alegre et al., 2008; Androulidakis et al., 2007; Swann et al., 2009). It may also reflect recalibration of feedback and feedforward control (Kilner et al., 2000). For instance, corrective postural responses to visual feedback are improved following burst of beta activity in the corticospinal tract (Androulidakis et al., 2006). Thus, during unaltered state, beta band oscillations persist in the somatosensory cortex, however, before or during movements desynchronization of beta band oscillations is thought to represent processing of somatosensory information (van Ede et al., 2011, 2012). Hence, beta band power suppression occurring between 0.8 and 1.5 s after vibration onset likely indicates changes in the balance motor commands and processing of sensory information involved in controlling body sway. These changes in brain oscillations may explain why participants with AIS maintained their balance control to the same extent as controls.

When visual cues were unavailable, for both groups, an increase in theta band power early after vibration onset was observed. Increased theta power has been reported as a marker of instability during more challenging balance control tasks (Peterson and Ferris, 2018; Sipp et al., 2013; Slobounov et al., 2009). As a result, theta band power increase could indicate a sudden change in sensory state has just occurred and triggers a default balance motor command. To our knowledge, it is unknown if this increase in theta band power reflects changes in sensory state or in motor command or both. Nonetheless, because the body sway amplitude of participants with AIS was comparable to the one in controls, the significant increase in theta band power may indicate that their sensitivity threshold during ankle proprioception alteration was lower in absence of vision.

Contrary to alpha and beta oscillations, gamma oscillations (i.e., frequency > 30 Hz) increase in the visual and somatosensory regions during visual or proprioceptive stimulation (Pfurtscheller et al., 2003). Increase in gamma oscillations have been proposed

to enforce connection between neuronal populations representing different information and integrate them in a merged percept to facilitate sensorimotor integration (Fries, 2015). In the AIS group, decrease in low-gamma (30–50 Hz) band power was observed when ankle proprioception returned to normal in absence of visual cues. This decrease in low-gamma band power may entail suboptimal ability to combine various sensory information following transient change in sensory state. This finding agrees with difficulty in reweighting ankle proprioception following a brief period of ankle proprioception alteration in adolescents with AIS (Simoneau et al., 2006a). However, results related to the gamma band should be interpreted with caution as these higher frequencies are particularly susceptible to myogenic activity.

The main limitation of our study is the small number of participants considering the diverse aetiology of AIS. We were still able, however, to demonstrate significant electrocortical dynamics differences between adolescents with and without idiopathic scoliosis. Our findings suggest that cortical dynamics assessment may help to detect sensorimotor dysfunction in balance control tasks in participants with AIS. For instance, it is expected that AIS participants with balance control impairment should show alpha and beta band synchronization during a sudden change in sensory information. This synchronization in alpha and beta bands would indicate less excitability of the somatosensory cortex and inefficient processing of somatosensory information relevant to control body sway. It is worth repeating that AIS is a multifactorial disease. Therefore, it is unlikely that the sensorimotor integration mechanisms of all patients with AIS are impaired. Investigating brain activity during tasks requiring sensorimotor integration with a larger cohort may help identify patients with AIS with sensorimotor integration impairment as these patients are more likely to benefit from personalized sensorimotor treatment (Pialasse et al., 2017). Exercises favoring sensorimotor recalibration at an early stage may induce brain reorganisation (Machado et al., 2010; Seidel et al., 2017) and reduce the likelihood of scoliosis progression (Monticone et al., 2014). Future study must verify this suggestion.

5. Conclusion

Participants with AIS showed different electrocortical brain dynamics in the sensorimotor cortex to maintain their level of balance control like age-matched controls. Principal changes in electrocortical dynamics were a significant increase in theta frequency power and a larger suppression of alpha, beta and gamma frequency power when proprioception was altered. These results suggest that participants with AIS adapted their sensorimotor integration mechanisms to prevent large body sway. Overall, the present results suggest that assessing cortical dynamics may be relevant to investigate sensorimotor integration function in AIS. Further studies with larger cohorts are still needed to identify more specifically patients with AIS with sensorimotor integration impairment as well as to determine the contribution of motor control exercises on the cortical sensorimotor information processing.

Declaration of Competing Interest

None of the authors have any potential conflicts of interest to disclose.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clinph.2019.07.005.

References

Adler N, Bleck EE, Rinsky LA, Young W. Balance reactions and eye-hand coordination in idiopathic scoliosis. J Orthop Res 1986;4(1):102–7.
Alegre M, Alvarez-Gerriko I, Valencia M, Iriarte J, Artieda J. Oscillatory changes related to the forced termination of a movement. Clin Neurophysiol 2008;119(2):290–300.
Anderson KL, Ding M. Attentional modulation of the somatosensory mu rhythm. Neuroscience 2011;180:165–80.
Androulidakis AG, Doyle LM, Gilbertson TP, Brown P. Corrective movements in response to displacements in visual feedback are more effective during periods of 13–35 Hz oscillatory synchrony in the human corticospinal system. Eur J Neurosci 2006;24(11):3299–304.
Androulidakis AG, Doyle LM, Yarrow K, Litvak V, Gilbertson TP, Brown P. Anticipatory changes in beta synchrony in the human corticospinal system and associated improvements in task performance. Eur J Neurosci 2007;25(12):3758–65.
Aoki F, Fetz EE, Shupe L, Lettich E, Ojemann GA. Increased gamma-range activity in human sensorimotor cortex during performance of visuomotor tasks. Clin Neurophysiol 1999;110(3):524–37.
Aoki F, Fetz EE, Shupe L, Lettich E, Ojemann GA. Changes in power and coherence of brain activity in human sensorimotor cortex during performance of visuomotor tasks. Biosystems 2001;63(1–3):89–99.
Babiloni C, Del Percio C, Arendt-Nielsen L, Soricelli A, Romani GL, Rossini PM, et al. Cortical EEG alpha rhythms reflect task-specific somatosensory and motor interactions in humans. Clin Neurophysiol 2014;125(10):1936–45.
Baccouch R, Rebai H, Sahli S. Kung-fu versus swimming training and the effects on balance abilities in young adolescents. Phys Ther Sport 2015;16(4):349–54.
Baker SN, Olivier E, Lemon RN. Coherent oscillations in monkey motor cortex and hand muscle EMG show task-dependent modulation. J Physiol 1997;501(Pt 1):225–41.
Bell AJ, Sejnowski TJ. An information-maximization approach to blind separation and blind deconvolution. Neural Comput 1995;7(6):1129–59.
Boisgontier MP, Serbruyns L, Swinnen SP. Physical Activity Predicts Performance in an Unpracticed Bimanual Coordination Task. Front Psychol 2017;8:249.
Bokil Hemant, Andrews Peter, Kulkarni Jayant E, Mehta Samar, Mitra Partha P. Chronux: A platform for analyzing neural signals. J Neurosci Methods 2010;192(1):146–51. https://doi.org/10.1016/j.jneumeth.2010.06.020.
Burke D, Hagbarth KE, Lofstedt L, Wallin BG. The responses of human muscle spindle endings to vibration during isometric contraction. J Physiol 1976;261(3):695–711.
Burwell RG, Aujla RK, Grevitt MP, Dangerfield PH, Moulton A, Randell TL, et al. Pathogenesis of adolescent idiopathic scoliosis in girls - a double neuro-osseous theory involving disharmony between two nervous systems, somatic and autonomic expressed in the spine and trunk: possible dependency on sympathetic nervous system and hormones with implications for medical therapy. Scoliosis 2009;4(24):1–40.
Burwell RG, Freeman BJ, Dangerfield PH, Aujla RK, Cole AA, Kirby AS, et al. Etiologic theories of idiopathic scoliosis: neurodevelopmental concept of maturational delay of the CNS body schema ("body-in-the-brain"). Stud Health Technol Inform 2006;123:72–9.
Byl NN, Gray JM. Complex balance reactions in different sensory conditions: adolescents with and without idiopathic scoliosis. J Orthop Res 1993;11(2):215–27.
Byl NN, Holland S, Jurek A, Hu SS. Postural imbalance and vibratory sensitivity in patients with idiopathic scoliosis: implications for treatment. J Orthop Sports Phys Ther 1997;26(2):60–8.
Calvo-Munoz I, Gomez-Conesa A, Sanchez-Meca J. Prevalence of low back pain in children and adolescents: a meta-analysis. BMC Pediatr 2013;13:14.
Cheng JC, Guo X, Sher AH. Posterior tibial nerve somatosensory cortical evoked potentials in adolescent idiopathic scoliosis. Spine 1998;23(3):332–7.
Cheung J, Halbertsma JPK, Veldhuisen AG, Sluiter WJ, Maurits NM, Cool JC, et al. The relation between electromyography and growth velocity of the spine in the evaluation of curve progression in idiopathic scoliosis. Spine 2004;29(9):1011–6.

Cheung J, Halbertsma JPK, Veldhuisen AG, Sluiter WJ, Maurits NM, Cool JC, et al. A preliminary study on electromyographic analysis of the paraspinal musculature in idiopathic scoliosis. Eur Spine J 2005;14:130–7.
Childs JD, Piva SR, Fritz JM. Responsiveness of the numeric pain rating scale in patients with low back pain. Spine 2005;30(11):1331–4.
Cohen M. Analyzing Neural Time Series Data: Theory and Practice: Cambridge. MA: MIT press; 2014.
Danielsson AJ, Romberg K, Nachemson AL. Spinal Range of motion, muscle endurance, and back pain and function at least 20 years after fusion or brace treatment for adolescent idiopathic scoliosis. Spine 2006;31(3):275–83.
Del Percio C, Babiloni C, Marzano N, Iacoboni M, Infarinato F, Vecchio F, et al. "Neural efficiency" of athletes' brain for upright standing: a high-resolution EEG study. Brain Res Bull 2009;79(3–4):193–200.
Del Percio C, Brancucci A, Bergami F, Marzano N, Fiore A, et al. Cortical alpha rhythms are correlated with body sway during quiet open-eyes standing in athletes: A high-resolution EEG study. Neuroimage 2007;36:822–9.
Domenech J, Garcia-Marti G, Marti-Bonmati L, Barrios C, Tormos JM, Pascual-Leone A. Abnormal activation of the motor cortical network in idiopathic scoliosis demonstrated by functional MRI. Eur Spine J 2011;20(7):1069–78.
Domenech J, Tormos JM, Barrios C, Leone AP. Motor cortical hyperexcitability in idiopathic scoliosis: could focal dystonia be a subclinical etiological factor? Eur Spine J 2010;19(2):223–30.
Donaldson S, Hedden D, Stephens D, Alman B, Howard A, Narayanan U, et al. Surgeon reliability in rating physical deformity in adolescent idiopathic scoliosis. Spine 2007;32(3):363–7.
Drijkoningen D, Leunissen I, Caeyenberghs K, Hoogkamer W, Sunaert S, Duysens J, et al. Regional volumes in brain stem and cerebellum are associated with postural impairments in young brain-injured patients. Hum Brain Mapp 2015;36(12):4897–909.
Edery P, Margaritte-Jeannin P, Biot B, Labalme A, Bernard JC, Chastang J, et al. New disease gene location and high genetic heterogeneity in idiopathic scoliosis. Eur J Hum Gen 2011;19:865–9.
Edery P, Shunmoogum P, Alix E, Moldovan F. Identification of idiopathic scoliosis genes. 50th Anniversary International Phillip Zorab Symposium, June 20–21, The Royal College of Surgeons London, UK, 2013.
Fendri K, Patten SA, Kaufman GN, Zaouter C, Parent S, Grimard G, et al. Microarray expression profiling identifies genes with altered expression in Adolescent Idiopathic Scoliosis. Eur Spine J 2013;22(6):1300–11.
Fries P. Rhythms for cognition: communication through coherence. Neuron 2015;88 (1):220–35.
Frolich L, Dowding I. Removal of muscular artifacts in EEG signals: a comparison of linear decomposition methods. Brain Inform 2018;5(1):13–22.
Gage WH, Winter DA, Frank JS, Adkin AL. Kinematic and kinetic validity of the inverted pendulum model in quiet standing. Gait Posture 2004;19(2):124–32.
Gauchard GC, Lascombes P, Kuhnast M, Perrin PP. Influence of different types of progressive idiopathic scoliosis on static and dynamic postural control. Spine 2001;26(9):1052–8.
Geissele ME, Kransdorf MJ, Geyer MA, Jelinek S, VanDam BE. Magnetic resonance imaging of the brain stem in adolescent idiopathic scoliosis. Spine 1991;16 (7):761–3.
Gerbino PG, Griffin ED, Zurakowski D. Comparison of standing balance between female collegiate dancers and soccer players. Gait Posture 2007;26(4):501–7.
Guo X, Chau WW, Hui-Chan CWY, Cheung CSK, Tsang WWN, Cheng JCY. Balance control in adolescents with idiopathic scoliosis and disturbed somatosensory function. Spine 2006;31(14):e437–40.
Haegens S, Handel BF, Jensen O. Top-down controlled alpha band activity in somatosensory areas determines behavioral performance in a discrimination task. J Neurosci 2011;31(14):5197–204.
Haumont T, Gauchard GC, Lascombes P, Perrin PP. Postural instability in early-stage idiopathic scoliosis in adolescent girls. Spine 2011;36(13). E847-54.
Herman R, Mixon J, Fisher A, Maulucci R, Stuyck J. Idiopathic scoliosis and the central nervous system: A motor control problem. Spine 1985;10(1):1–14.
Honeine JL, Crisafulli O, Sozzi S, Schieppati M. Processing time of addition or withdrawal of single or combined balance-stabilizing haptic and visual information. J Neurophysiol 2015;114(6):3097–110.
Hulsdunker T, Mierau A, Neeb C, Kleinoder H, Struder HK. Cortical processes associated with continuous balance control as revealed by EEG spectral power. Neurosci Lett 2015a;592:1–5.
Hulsdunker T, Mierau A, Struder HK. Higher Balance Task Demands are Associated with an Increase in Individual Alpha Peak Frequency. Front Hum Neurosci 2015b;9:695.
Huster RJ, Plis SM, Calhoun VD. Group-level component analyses of EEG: validation and evaluation. Front Neurosci 2015;9:254.
Jacobs JV, Henry SM, Nagle KJ. Low back pain associates with altered activity of the cerebral cortex prior to arm movements that require postural adjustment. Clin Neurophysiol 2010;121(3):431–40.
Jacobs JV, Horak FB. Cortical control of postural responses. J Neural Transm (Vienna) 2007;114(10):1339–48.
Jones MA, Stratton G, Reilly T, Unnithan VB. A school-based survey of recurrent non-specific low-back pain prevalence and consequences in children. Health Educ Res 2004;19(3):284–9.
Kilner JM, Baker SN, Salenius S, Hari R, Lemon RN. Human cortical muscle coherence is directly related to specific motor parameters. J Neurosci 2000;20 (23):8838–45.
King DL, Zatsiorsky VM. Extracting gravity line displacement from stabilographic recordings. Gait Posture 1997;6(1):559–70.
Kjaer P, Wedderkopp N, Korsholm L, Leboeuf-Yde C. Prevalence and tracking of back pain from childhood to adolescence. BMC Musculoskelet Disord 2011;12:98.
Klimesch W. Alpha-band oscillations, attention, and controlled access to stored information. Trends Cogn Sci 2012;16(12):606–17.
Landman Z, Oswald T, Sanders J, Diab M. Prevalence and predictors of pain in surgical treatment of adolescent idiopathic scoliosis. Spine 2011;36(10):825–9.
Lao ML, Chow DH, Guo X, Cheng JC, Holmes AD. Impaired dynamic balance control in adolescents with idiopathic scoliosis and abnormal somatosensory evoked potentials. J Pediatr Orthop 2008;28(8):846–9.
Lebar N, Danna J, More S, Mouchnino L, Blouin J. On the neural basis of sensory weighting: Alpha, beta and gamma modulations during complex movements. Neuroimage 2017;150:200–12.
Machado S, Cunha M, Velasques B, Minc D, Teixeira S, Domingues CA, et al. Sensorimotor integration: basic concepts, abnormalities related to movement disorders and sensorimotor training-induced cortical reorganization. Rev Neurol 2010;51(7):427–36.
Mahaudens P, Detrembleur C, Mousny M, Banse X. Gait in thoracolumbar/lumbar adolescent idiopathic scoliosis : effect of surgery on gait mechanisms. Eur Spine J 2010;19(7):1179–88.
Maris E, Oostenveld R. Nonparametric statistical testing of EEG- and MEG-data. J Neurosci Methods 2007;164(1):177–90.
Masani K, Vette AH, Kouzaki M, Kanehisa H, Fukunaga T, Popovic MR. Larger center of pressure minus center of gravity in the elderly induces larger body acceleration during quiet standing. Neurosci Lett 2007;422(3):202–6.
Melnik A, Hairston WD, Ferris DP, Konig P. EEG correlates of sensorimotor processing: independent components involved in sensory and motor processing. Sci Rep 2017;7(1):4461.
Monticone M, Ambrosini E, Cazzaniga D, Rocca B, Ferrante S. Active self-correction and task-oriented exercises reduce spinal deformity and improve quality of life in subjects with mild adolescent idiopathic scoliosis. Results of a randomised controlled trial. Eur Spine J 2014;23:1204–14.
Moreau A, Wang DS, Forget S, Azeddine B, Angeloni D, Fraschini F, et al. Melatonin signaling dysfunction in adolescent idiopathic scoliosis. Spine 2004;29 (16):1772–81.
Nault ML, Allard P, Hinse S, Leblanc R, Caron O, Labelle H, et al. Relations between standing stability and body posture parameters in adolescent idiopathic scoliosis. Spine 2002;27(17):1911–7.
Nichols TE, Holmes AP. Nonparametric permutation tests for functional neuroimaging: a primer with examples. Hum Brain Mapp 2002;15(1):1–25.
Onton J, Makeig S. Information-based modeling of event-related brain dynamics. Prog Brain Res 2006;159:99–120.
Oostenveld R, Oostendorp TF. Validating the boundary element method for forward and inverse EEG computations in the presence of a hole in the skull. Hum Brain Mapp 2002;17(3):179–92.
Patten SA, Margaritte-Jeannin P, Bernard JC, Alix E, Labalme A, Besson A, et al. Functional variants of POC5 identified in patients with idiopathic scoliosis. J Clin Invest 2015;125(3):1124–8.
Perrin P, Deviterne D, Hugel F, Perrot C. Judo, better than dance, develops sensorimotor adaptabilities involved in balance control. Gait Posture 2002;15 (2):187–94.
Peterson SM, Ferris DP. Differentiation in theta and beta electrocortical activity between visual and physical perturbations to walking and standing balance. eNeuro 2018;5(4).
Pfurtscheller G. Central beta rhythm during sensorimotor activities in man. Electroencephalogr Clin Neurophysiol 1981;51(3):253–64.
Pfurtscheller G, Graimann B, Huggins JE, Levine SP, Schuh LA. Spatiotemporal patterns of beta desynchronization and gamma synchronization in corticographic data during self-paced movement. Clin Neurophysiol 2003;114 (7):1226–36.
Pfurtscheller G, Lopes da Silva FH. Event-related EEG/MEG syncronization and desynchronization: basic principles. Clin Neurophysiol 1999;110:1842–57.
Pialasse JP, Descarreaux M, Mercier P, Blouin J, Simoneau M. The vestibular-evoked postural response of adolescents with idiopathic scoliosis is altered. PLoS One 2015a;10(11):e0143124.
Pialasse JP, Descarreaux M, Mercier P, Simoneau M. Sensory reweighting is altered in adolescent patients with scoliosis: evidence from a neuromechanical model. Gait Posture 2015b;42(4):558–63.
Pialasse JP, Laurendeau S, Descarreaux M, Blouin J, Simoneau M. Is abnormal vestibulomotor responses related to idiopathic scoliosis onset or severity? Med Hypotheses 2013;80(3):234–6.
Pialasse JP, Mercier P, Descarreaux M, Simoneau M. Assessment of sensorimotor control in adults with surgical correction for idiopathic scoliosis. Eur Spine J 2016;25(10):3347–52.
Pialasse JP, Mercier P, Descarreaux M, Simoneau M. A procedure to detect abnormal sensorimotor control in adolescents with idiopathic scoliosis. Gait Posture 2017;57:124–9.
Popa T, Bonifazi M, Della Volpe R, Rossi A, Mazzocchio R. Adaptative changes in postural strategy selection in chronic low back pain. Exp Brain Res 2007;177:411–8.
Reuber M, Schultz A, McNeil T, Spencer D. Trunk muscle myoelectric activities in idiopathic scoliosis. Spine 1983;8(5):447–56.
Roll JP, Vedel JP. Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. Exp Brain Res 1982;47(2):177–90.
Sahlstrand T, Lidstrom J. Equilibrium factors as predictors of the prognosis in adolescent idiopathic scoliosis. Clin Orthop Relat Res 1980;152:232–6.

Salenius S, Salmelin R, Neuper C, Pfurtscheller G, Hari R. Human cortical 40 Hz rhythm is closely related to EMG rhythmicity. Neurosci Lett 1996;213(2):75–8.
Salmelin R, Hari R. Spatiotemporal characteristics of sensorimotor neuromagnetic rhythms related to thumb movement. Neuroscience 1994;60(2):537–50.
Sanes JN, Donoghue JP. Oscillations in local field potentials of the primate motor cortex during voluntary movement. Proc Natl Acad Sci USA 1993;90 (10):4470–4.
Sapountzi-Krepia D, Valavanis J, Panteleakis GP, Zangana DT, Vlachojiannis PC, Sapkas GS. Perceptions of body image, hapiness and satisfaction in adolescents wearing a Boston brace for scoliosis treatment. J Adv Nurs 2001;35(5):683–90.
Sato T, Hirano T, Ito T, Morita O, Kikuchi R, Endo N, et al. Back pain in adolescents with idiopathic scoliosis: epidemiological study for 43,630 pupils in Niigata City. Japan. Eur Spine J 2010;20(2):274–9.
Schoffelen JM, Oostenveld R, Fries P. Neuronal coherence as a mechanism of effective corticospinal interaction. Science 2005;308(5718):111–3.
Seidel O, Carius D, Kenville R, Ragert P. Motor learning in a complex balance task and associated neuroplasticity: a comparison between endurance athletes and nonathletes. J Neurophysiol 2017;118(3):1849–60.
Shimode M, Ryouji A, Kozo N. Asymetry of premotor time in the back muscles of adolescent idiopathic scoliosis. Spine 2003;28(22):2535–9.
Simoneau M, Lamothe V, Hutin E, Mercier P, Teasdale N, Blouin J. Evidence for cognitive vestibular integration impairment in idiopathic scoliosis patients. BMC Neurosci 2009;10:102.
Simoneau M, Mercier P, Blouin J, Allard P, Teasdale N. Altered sensory-weighting mechanisms is observed in adolescents with idiopathic scoliosis. BMC Neurosci 2006a;7(68):1–9.
Simoneau M, Richer N, Mercier P, Allard P, Teasdale N. Sensory deprivation and balance control in idiopathic scoliosis adolescent. Exp Brain Res 2006b;170:576–82.
Sipp AR, Gwin JT, Makeig S, Ferris DP. Loss of balance during balance beam walking elicits a multifocal theta band electrocortical response. J Neurophysiol 2013;110(9):2050–60.
Slobounov S, Cao C, Jaiswal N, Newell KM. Neural basis of postural instability identified by VTC and EEG. Exp Brain Res 2009;199(1):1–16.
Slobounov SM, Teel E, Newell KM. Modulation of cortical activity in response to visually induced postural perturbation: combined VR and EEG study. Neurosci Lett 2013;547:6–9.
Smorgick Y, Mirovsky Y, Baker KC, Gelfer Y, Avisar E, Anekstein Y. Predictors of back pain in adolescent idiopathic scoliosis surgical candidates. J Pediatr Orthop 2013;33:289–92.
Sozzi S, Do MC, Monti A, Schieppati M. Sensorimotor integration during stance: processing time of active or passive addition or withdrawal of visual or haptic information. Neuroscience 2012;212:59–76.
Stokes IA. Analysis and simulation of progressive adolescent scoliosis by biomechanical growth modulation. Eur Spine J 2007;16(10):1621–8.
Swann N, Tandon N, Canolty R, Ellmore TM, McEvoy LK, Dreyer S, et al. Intracranial EEG reveals a time- and frequency-specific role for the right inferior frontal gyrus and primary motor cortex in stopping initiated responses. J Neurosci 2009;29(40):12675–85.
Tones M, Moss N, Polly Jr DW. A review of quality of life and psychosocial issues in scoliosis. Spine 2006;31(26):3027–38.
van Ede F, de Lange F, Jensen O, Maris E. Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. J Neurosci 2011;31(6):2016–24.
van Ede F, Koster M, Maris E. Beyond establishing involvement: quantifying the contribution of anticipatory alpha- and beta-band suppression to perceptual improvement with attention. J Neurophysiol 2012;108(9):2352–62.
Varghese JP, Marlin A, Beyer KB, Staines WR, Mochizuki G, McIlroy WE. Frequency characteristics of cortical activity associated with perturbations to upright stability. Neurosci Lett 2014;578:33–8.
Varghese JP, McIlroy RE, Barnett-Cowan M. Perturbation-evoked potentials: Significance and application in balance control research. Neurosci Biobehav Rev 2017;83:267–80.
Veldhuizen AG, Wever DJ, Webb PJ. The aetiology of idiopathic scoliosis: biomechanical and neuromuscular factors. Eur Spine J 2000;9:178–84.
Wagner J, Makeig S, Gola M, Neuper C, Muller-Putz G. Distinct beta band oscillatory networks subserving motor and cognitive control during gait adaptation. J Neurosci 2016;36(7):2212–26.
Wang D, Shi L, Chu WC, Burwell RG, Cheng JC, Ahuja AT. Abnormal cerebral cortical thinning pattern in adolescent girls with idiopathic scoliosis. Neuroimage 2012;59(2):935–42.
Wang D, Shi L, Liu S, Hui SCN, Wang W, Cheng JCY, et al. Altered topological organization of cortical network in adolescent girls with idiopathic scoliosis. Plus One 2013;8(12):e83767.
Weinstein SL, Dolan LA, Cheng JCY, Danielsson A, Morcuende JA. Adolescent idiopathic scoliosis. Lancet 2008;371:1527–37.
Wurst W, Bally-Cuif L. Neural plate patterning: upstream and downstream of the isthmic organiser. Nat Rev Neurosci 2001;2:99–108.
Zabjek KF, Coillard C, Rivard CH, Prince F. Estimation of the centre of mass for the study of postural control in Idiopathic Scoliosis patients: a comparison of two techniques. Eur Spine J 2008;17(3):355–60.
Zatsiorsky VM, King DL. An algorithm for determining gravity line location from posturographic recordings. J Biomech 1998;31(2):161–4.