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Article

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Posted Date: March 23rd, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1361270/v2>

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RESEARCH

Brain oscillatory activity in adolescent idiopathic scoliosis

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Abstract

Background: The pathophysiology of Adolescent Idiopathic Scoliosis (AIS) is not yet completely understood, but multi-factorial hypotheses have been proposed including defective central nervous system control of posture, biomechanics alterations and alterations of body schema. AIS could be the expression of a sub-clinical nervous system disorder. The aim of our study was to compare the electroencephalography (EEG) activity in adolescents with AIS and controls, to examine the brain oscillatory changes related to balance control and inquire possibly related body schema representational alterations.

Methods: We recorded EEG data and balance data, with arms in both the neutral position and laterally elevated with elbow flexed at 90° (with eyes open and closed), in 14 healthy subjects and in 14 subjects with AIS. A re-adaptation of the Image Marking Procedure (IMP) was used to assess the body schema.

Results: Our results revealed no balance control difference between groups; higher EEG alpha relative power over sensorimotor areas ipsilateral to the side of the curve and a significant increase of theta relative powers localized over the central areas in AIS participants compared to healthy subjects. The delta body perception index (BPI) score (BPI shoulder minus BPI waist) resulted significantly different between the two groups. The inclinations of the perceived interacromial axes in girls having thoracic principal curve, and bisiliac axes in girls with lumbar principal curve, was opposite to the real inclination.

Conclusions: Our results provide evidence of an increased theta activity, a lateralized alpha activity and an altered body schema perception in AIS subjects. Whether these processes are a cause or a consequence of AIS needs to be further investigated.

Keywords: EEG; body schema; theta power; sensorimotor areas; balance

Background

Adolescent Idiopathic Scoliosis (AIS) is a three-dimensional morphological spinal deformity, characterized by the deviation of the spine in the frontal plane (>10 Cobb degrees) and the concurrent rotation of the affected vertebral bodies [1]. Epidemiological studies report an estimated prevalence of 1-3% among adolescents (10-16 years), with girls being more severely affected [2].

The cause and pathophysiology of AIS is not yet completely understood, but multi-factorial hypotheses have been proposed: genetic predisposition, hormonal

dysfunctions [3], defective postural control by the central nervous system (CNS) [4], and alterations of body schema [5, 6, 7]. There is growing evidence of cortical involvement in AIS suggesting that AIS could be the expression of a sub-clinical nervous system disorder. Indeed, visuo-spatial perceptual impairments, body spatial orientation alterations, and sensory integration disorders have been described [8]. According to the neurodevelopmental theories of AIS, a temporal imbalance between the musculoskeletal maturation and the central sensorimotor integration processes occurring in the posterior parietal cortex (PPC), would in turn result in improper trunk muscles response to compensate for scoliosis initiating process [8]. This theory postulates an altered body schema, defined as the internal, unconscious representation of our body boundaries and shape, updated by sensory information to set proper motor output [9].

Observations of impaired motor control were reported on brain imaging studies suggesting that an anomalous sensorimotor integration contributes to the cause of AIS, but there is uncertainty about the level of the central nervous system accounting for this dysfunction. Studies using magnetic resonance imaging (MRI), functional MRI (fMRI) and electroencephalography (EEG) revealed anomalies in the CNS: asymmetries in brainstem corticospinal bundles [10], volumetric differences between adolescents with AIS and controls in brain regions functionally related to motor control and coordination [11], abnormal patterns in the motor network of adolescents during movement execution [12].

EEG studies reported, for the first time, paroxysmal activity at rest [13] – i.e., bilaterally synchronous activity spread over large areas of both hemispheres. An increase of the amplitude of the peak in alpha rhythm ([7.5-12.5] Hz) was found at central, frontal, parietal and occipital regions indicating the need for increased cortical processing to maintain balance control in normal upright standing in adolescents with AIS compared to healthy controls [14]. The increase in theta frequency power and suppression of alpha, beta and gamma powers were also observed when proprioception was altered [15].

A Transcranial Magnetic Stimulation (TMS) study reported lower intracortical inhibition, higher motor cortex excitability, and preserved spinal inhibitory circuits [16]. Whereas the study of Kimiskidis and colleagues does not support the concept of a generalized brain asymmetry: upper limb findings were within normal limits whereas lower limb testing revealed only a trend towards increased asymmetries of cortical latencies and central motor conduction time [17].

The aim of our study was to compare the EEG activity in adolescents with AIS and controls, to examine the brain oscillatory changes related to balance control and inquire possibly related body schema representational alterations. Results may represent a valuable biomarker of AIS progression and offer novel therapeutic targets according to the identified pathophysiological patterns.

Methods

Participants

Fourteen adolescent girls with a confirmed diagnosis of AIS [18] (age range: 13-17 years; Cobb angle: 20°-55°; Risser sign: 0-4; no spine surgery) and fourteen adolescent girls without AIS (age range: 11-16 years; no spinal pathology or any known

neurological or musculoskeletal disorders; no clinically relevant back hump) were recruited at the Adolescence Spine Diseases Diagnostic and Therapeutic Centre of the Padova University Hospital and Sports Medicine and at Physical Activities Unit - “ai Colli” Social Health Department of the Padova Hospital (Tables 1 and 2). Controls (CTRL) were enrolled from a population of sporty females (involved in sport activities for less than 10 hours per week). A team of physicians with expertise in adolescent spine diseases collected the anamnestic information and the clinical data (Tables 3). Parents gave their written informed consent and the project was approved by Ethics Committee of the Teaching Hospital of Padua (protocol n. 31708). All methods were performed in accordance with relevant guidelines and regulations.

All the participants underwent a physical examination: trunk asymmetries, shoulders and hips inclination sides were registered. Bunnell’s scoliometer was used to measure the paravertebral humps in the forward bent position [19, 20]. For the AIS group only, we collected the last standing full-spine posterior-anterior radiological image recorded within the last three months prior participating in the study. Cobb angle method was used to measure curves entity [21], while the apical vertebral rotation was recorded by means of the Pedrolle method [22] either or Nash and Moe method [23]. The side and the anatomical site of the scoliosis convexity was collected (Table 3). All the AIS participants were treated using a full-time brace.

Prior to data collection, height and body mass of the participants were collected and handedness was assessed with the Oldfield Questionnaire [24], with all subjects being right-handed.

Experimental Paradigm

Data were acquired in different upright standing postures on a force platform: with eyes open and closed for 3 minutes (*OE standing* and *CE standing*); with arms raised laterally to 90° with eyes open and closed for 1 minute (*OE arms up* and *CE arms up*). Participants were instructed to keep their feet at their shoulder width, looking at a fixation cross (~ 3m in front of the participant) during the eyes open conditions (see Supplementary Materials). AIS subjects performed the experiment without the brace.

EEG data

EEG signals (32-channels system; BrainAmp 32MRplus, BrainProducts GmbH, Munich, Germany) were acquired using an analogic anti-aliasing band pass-filter at 0.1–1000 Hz and converted from analog to digital using a sampling rate of 500 Hz. The reference was between Fz/Cz and ground anterior to Fz. The data were processed in Matlab R2018b (MathWorks, Natick, MA) using personalized scripts based on EEGLAB toolbox (<http://www.sccn.ucsd.edu/eeglab>) [25]. The EEG recordings were band-pass filtered from 1 to 30 Hz (the optimal Chebyshev finite impulse response filters were designed using Parks–McClellan algorithm, the order was customized to minimize the error in the pass and stop bands). Noisy channels were identified by visual inspection and interpolated using the nearest-neighbour spline method (average percentage of channels interpolated: 6.5%). Eyes movements and cardiac activity were removed using independent component analysis (FastICA algorithm implemented in EEGLAB) based on the waveform, topography and time

course of the component (average percentage of components removed: 9.9%), and data were re-referenced to the average reference. Individual epochs containing non-stereotyped artifacts were also identified by visual inspection and removed from further analysis (average percentage of epochs removed: 7.4%).

The fast Fourier transform was applied to non-overlapping epochs of 2 seconds and then averaged across epochs. The recordings were Hanning windowed to control for spectral leakage. Power spectra were estimated for all frequencies between 1 and 30 Hz, then the relative power (%) was calculated by dividing the power of each frequency bands (delta [1–4] Hz, theta [4.5–7.5] Hz, alpha [8–12] Hz, and beta [13–30] Hz) with the total power of [1–30] Hz.

A laterality index (LI), describing the contrast in amount of activation (i.e., relative power in alpha band) between the right and left hemisphere, was calculated during all the tasks according to:

$$LI = \frac{P_I - P_C}{P_I + P_C} \quad (1)$$

where P_I is the average of power of central electrodes ipsilateral to the curve (C4, Cp2 and P4 for AIS subjects with right main curve; C3, Cp1 and P3 for AIS subjects with left main curve) and P_C is the average of power of central electrodes contralateral to the curve (C3, Cp1 and P3 for right main curve; C4, Cp2 and P4 for left main curve). LI can thus range from +1 (exclusively ipsilateral) to -1 (exclusively contralateral).

Considering that the curve may cause an asymmetric EEG topography, we a priori divided our participants with right ($N = 10$ participants) and left ($N = 4$) main curve in performing the statistical comparisons with controls. Because relative power values were not normally distributed, non-parametric tests were applied. We performed two-sided Wilcoxon rank sum tests to compare relative power in each frequency bands among healthy controls and AIS subjects with right main curve ($p < 0.05$). Considering the sample size and the exploratory nature of the study, no corrections for multiple comparisons were performed in hypothesis testing.

Balance and motion data

Participants were equipped with nine retroreflective markers placed on the tubercle of the seventh cervical vertebra (C7), on the posterior aspect of the acromion (bilaterally and on the most prominent point), on the lateral epicondyle of humerus (bilaterally), and on both styloid process of ulna and radius (bilaterally). 3D marker trajectories were collected with a 10 IR-camera stereophotogrammetric system (Vero v2.2, Vicon Motion Systems Ltd, UK; 100 Hz). Labelling, gap filling and smoothing (via a Woltring routine [26]) of marker trajectories were conducted within Vicon Nexus (v2.11, Vicon Motion Systems Ltd, UK).

Participants were instructed to find a comfortable position for their feet while standing on a force platform (9 components; BERTEC 4060-10, Bertec Corporation, Ohio, US; 2000 Hz). Feet position was marked on the floor with adhesive tape to ensure consistent positioning among trials. The relative foot placement was measured to estimate the base of support, which is approximated to the area of a trapezium having the following dimensions: the big toe distance (BTD) as the

largest parallel side, the inter-malleolar distance (IMD) as the smallest parallel side, and the distance of big toes from the line joining the heel extremities (effective foot length, EFL) as the height [27]. Additionally, the maximum foot width (MFW) was collected, defined as the widest aspect of the foot, perpendicular to line joining the distal end of the great toe to midpoint of the heel [27]. Participants were asked to stand as still as possible to record the Center of Pressure (COP) trajectory and assess their balance control performances. Before calculating balance parameters, COP time series were low-pass filtered with a recursive 2nd-order Butterworth filter, cut-off equal to 10 Hz. Epochs of 40 s per recording were considered for the analysis [28].

The following parameters were calculated from the COP trajectory to assess balance control performances of the participants: (i) length of COP trajectory (PL); (ii) area of the ellipse containing the 95% of the COP points (EA); (iii) range of motion (ROM) and root mean square (RMS) of the COP displacement along the anterior-posterior (ROM-AP and RMS-AP, respectively) and medial-lateral (ROM-ML and RMS-ML, respectively) directions [29]. Parameters were then normalized by the participants' height, body mass, base of support and maximum foot width via a detrending normalization technique [30, 27]. The detrending normalization consists in estimating the correlation between each parameter and subjects' anthropometry, and then iteratively correcting each parameter with the linear model that best fits the data. This method keeps values with their original range and measurement unit, but it removes any dependencies from confounding variables [30].

Markers were considered to estimate the elbow angle $\varepsilon(t)$ in the *OE arms up* and *CE arms up* conditions. In brief: the average of the wrist markers approximates the wrist joint centre and the forearm segment is defined by the line joining the elbow marker to this point; the arm segment is defined by the line joining the shoulder marker to the elbow marker; the elbow angle time series $\varepsilon(t)$ is estimated as the angle between the forearm and the arm segments. The following parameters have been defined to quantify the variation over time of the elbow angle and its symmetry between left and right sides:

- directional root mean square (dRMS, °):

$$dRMS = \begin{cases} RMS\{\varepsilon(t)\}, & \text{if } \bar{\varepsilon}(t)|_{t=38,\dots,40} - \bar{\varepsilon}(t)|_{t=1,\dots,3} \geq 0 \\ -RMS\{\varepsilon(t)\}, & \text{if } \bar{\varepsilon}(t)|_{t=38,\dots,40} - \bar{\varepsilon}(t)|_{t=1,\dots,3} < 0 \end{cases} \quad (2)$$

with $\bar{\varepsilon}$, being the time average of the elbow angle over the selected time window;

- coefficient of variation of the angle (CV, %), i.e., the $\frac{RMS}{\bar{\varepsilon}(t)} \cdot 100$;
- Symmetry index (SI, %):

$$SI = \frac{\bar{\varepsilon}_L(t) - \bar{\varepsilon}_R(t)}{\bar{\varepsilon}_L(t) + \bar{\varepsilon}_R(t)} \cdot 100. \quad (3)$$

Balance and motion data were tested for possible differences between-groups (AIS vs. CTRL) via two-sided Wilcoxon rank sum tests ($p < 0.05$). A paired two-sided Wilcoxon rank sum test was instead used to test for possible effect of the eyes condition within-group (OE vs. CE, $p < 0.05$).

Body schema assessment

A re-adaptation of the Image Marking Procedure (IMP) was used to assess the body schema [31]. In this projection test, participants were asked to stand blindfolded in front of a roll of wrapping paper pretending looking themselves in a mirror. The experimenter stood behind the subject firmly touching with his fingertip seven chosen body parts, namely: the top of the head, the acromioclavicular joints (right and left), waist width (right left), and the trochanters of the femoral bones (right and left). Each participant was provided with a pencil and asked to make a cross on the paper where the touched body part was imagined to be projected (see Supplementary Materials). At the end of the marking, participants approached the paper to allow the experimenter to mark the actual position of the touched points with the use of an L-shape ruler placed at 90-degree angle relative to the longitudinal axis of the body. Distances in cm between the corresponding right and left points of shoulders, waist and hips marked by the subjects (perceived size: PS) and by the experimenter (actual size: AS) were measured with a ruler. For each subject, body perception indices (BPIs) related to each body district (shoulders, waist, and hips) were calculated using the following formula:

$$BPI = \frac{PS}{AS} * 100 \quad (4)$$

A general BPI (BPIg), determined as the BPIs average was calculated as well. Based on BPIg scores, participants were classified as: hypo-schematic (underestimation of actual body size, BPIg < 99.4 %; adequate body size estimators (BPIg > 99.4 %); hyper-schematic (over-estimation of actual body size, BPI > 112.3 %) [32]. To assess possible body schema distortions on the vertical axis, we compared the actual deviation from verticality (degrees) and its lateralization (right or left) with the perceived ones. Toward this aim, we defined for each subject an angle formed by the prolongation of the segments connecting right and left perceived points of shoulders, waist or hips, (depending on the principal curve location), and by the segment connecting the corresponding right and left actual points. To characterize curve laterality, we assumed positive values if the perceived curve convexity was right-oriented, and negative values if it was left-oriented (see Supplementary Materials).

As BPIs scores were normally distributed (Shapiro-Wilk normality test) we performed unpaired two-sampled t-test to compare AIS and controls BPIs scores related to each body district and BPIs average scores ($p < 0.05$). To evaluate eventual body schema distortions related to the whole trunk perception, we additionally calculated BPIs shoulder/waist ratio, as the delta between these two measures and we performed unpaired two-sample t-test between groups ($p < 0.05$).

Results

EEG data

Average results from power spectral density analysis are summarized in Fig. 1 and Fig. 2 for healthy controls and AIS participants. Significant differences ($p < 0.05$) between healthy subjects and AIS participants with right main curve were founded in slow rhythms (delta and theta) over central and parietal electrodes. Alpha changes were observed over bilateral sensorimotor areas with a significant distribution only

over C3 during *CE arms up* (Fig. 2). Comparison between healthy subjects and AIS participants with left main curve indicated significant differences over central regions in delta and theta bands during all the tasks and in alpha band over both sensorimotor areas during *CE arms up* and over left sensorimotor and parietal areas during *OE standing* and *CE standing*. EEG data demonstrated a more pronounced alpha activation in the central regions in AIS subjects, compared to healthy controls, with power increase of the sensorimotor area ipsilateral to the main scoliotic curve, as evidence by the significant changes of LI ($p < 0.05$) mainly in AIS subjects with right main curve during *CE arms up* (Fig. 3).

Balance and motion data

Figure 4 shows results of balance performances as assessed via EA, PL, RMS-AP and RMS-ML in *standing* (panel A) and *arms up* (panel B) conditions with both eyes open and closed (white and gray fill color, respectively) in both AIS and CTRL groups. No differences were obtained between groups, whereas a strong significance ($p < 0.001$) was obtained when testing differences between *OE arms up* and *CE arms up* conditions for PL (Figure 4B). A weak significant difference ($p < 0.05$) was obtained for RMS-AP in AIS group between *OE* and *CE standing* (Figure 4A). From results on motion data, the only significant difference was found for the SI in the CTRL group ($p < 0.05$). (See Supplementary Materials).

Body schema data

BPIg scores did not differ between healthy subjects and AIS group (AIS: mean $\pm$ SD=88.47 $\pm$ 19.75; CTRL: mean $\pm$ SD= 86.31 $\pm$ 16.64, p-value = 0.75) as well as BPIs related to each body district: BPI of shoulders (AIS mean $\pm$ SD: 81.88 $\pm$ 21.24; CTRL mean $\pm$ SD: 85.55 $\pm$ 18.00, p-value = 0.62), BPI of waist (AIS mean $\pm$ SD: 97.94 $\pm$ 31.13; CTRL mean $\pm$ SD: 91.37 $\pm$ 16.03, p-value = 0.48), BPI of hips (AIS mean $\pm$ SD: 85.59 $\pm$ 21.39; CTRL mean $\pm$ SD: 82.00 $\pm$ 22.75, p-value = 0.67). BPIg scores in both AIS and CTRL groups, resulted mainly hypo-schematic with 8 of 14 AIS girls and 12 of 14 CTRL having BPIg scores lower than 99.4 %.

The BPI delta (BPI shoulder minus BPI waist) resulted significantly different between the two groups (mean $\pm$ SD BPI delta of AIS group: 29.52 $\pm$ 18.72 vs. controls: 12.35 $\pm$ 9.3; $p=0.004$) (Fig. 5A).

Qualitative analysis of the test showed that in 12 out of 14 subjects with AIS the inclinations of the perceived interacromial axes in girls having thoracic principal curve and bisiliac axes in girls with lumbar principal curve was opposite to the real inclination (Fig. 5B). Conversely, controls' perception of their inclination resulted opposite to the real inclination in 3 out of 14 cases (Fig. 5C).

Discussion

Our results revealed no differences in balance performances between groups but higher EEG alpha relative power over sensorimotor areas ipsilateral to the side of the curve, although the difference was not statistically significant (except for AIS subjects with left main curve), most likely due to the inter-subjects variability. However, a significant LI increase in alpha range was observed in AIS participants with main right curve compared to healthy subjects during arms up with eyes closed,

demonstrating an imbalance between the two sensorimotor areas. The test of body schema revealed no differences between controls and AIS girls for the single body districts but underlined a possible alteration in the overall trunk representation, namely in the perception of the shoulders-waist proportion, and in its inclination.

These results are in line with fMRI data showing Blood Oxygen Level Dependent (BOLD) activation increase of motor areas and a greater interhemispheric asymmetry index [12].

The increase of alpha power could indicate an increase of communication due to the task. The increase of brain activity may be a compensatory strategy to overcome sensorimotor dysfunction. A possible explanation of these changes could be attributed to impaired sensorimotor integration predominantly at the cortical level, results found also in other studies [12, 14]. Maybe scoliosis onset is preceded by sensorimotor control impairments that last during curve progression. This in turn could lead to develop an altered body schema of the trunk and its inclination. However, we cannot exclude the possibility that our finding on the abnormally widest perceived waist compared to shoulders could be the result of brace treatment. Indeed, body schema is plastic by definition, and capable of incorporating objects in short times [33].

The main result of the study is the significant increase of delta and theta relative powers, compared to healthy subjects, localized over the central areas. Theta frequency band is recognized to be involved in balance control. Theta band activity intensifies when control demands are increased [34]; it is reported to rise with increasing balance demand in parietal areas [35], as well as in frontal areas [36, 37, 38]; it has also been suggested to represent error detection and processing during postural maintenance [35]. Theta power increase with task complexity has been demonstrated in multiple contexts, including dual tasks [39] where an increase of cortical recruitment was found to keep up performance in the elderly.

Gebel *et al.* [40] found significant increases of theta frequency band power in frontal and central areas with increasing balance task difficulty in adolescents. Moreover, previous studies on healthy adults reported that the increase in theta power may originate from the anterior cingulate cortex and sensorimotor areas, which are highly involved in sensory information processing [35, 41].

In our AIS subjects, the theta power increase within central clusters may reflect a higher information processing load due to increased postural demands caused by the scoliosis. The no balance difference and the increased brain activity in this frequency range could reflect greater postural control. These results suggest that AIS subjects adapted their brain activity to prevent large body sway.

Before identifying the therapeutic target, other neurophysiological investigations must be carried out: high-density EEG to localize cortical sources; connectivity analysis to understand whether the alterations detected in the rhythms are also reflected in terms of connections between the brain areas of the motor sensory network. A methodological limitation of this study is the approach of sensor space localization by means of only 30 EEG channels. Source localization analysis requires at least an EEG system with 64 channels for data acquisition. Therefore, future studies may use high-density EEG systems to specify and localize the functional areas during

increasing postural demands. Moreover, it could be interesting to explore the influence of brace on body perception. In this pilot study, indeed, we only considered subjects which already underwent brace treatment.

These abnormal EEG findings may represent a valuable biomarker of scoliosis progression and offer novel therapeutic targets as for example training based on biofeedback, evaluating the performance by monitoring EEG changes. The marked lateralisation observed and body schema alterations could also be useful for setting up personalized and targeted corrective postural exercises. Nowadays, treatment options for scoliosis consider exclusively biomechanics perspectives, except for some innovative approaches and hypotheses, still needing scientific evidence. One future development is the investigation of the EEG as a tool to assess the probable development of scoliosis in the individual case. Thanks also to the development of mobile EEG systems, it will be possible to study the sensorimotor components even during movement tasks used to increase postural instability (e.g. by using a balance board).

Conclusions

Our results provide evidence of an increased theta activity and a lateralized alpha activity in AIS subjects. Whether these processes are a cause or a consequence of AIS needs to be further investigated. The identification of an abnormal EEG pattern may describe a much more complex physiopathology of AIS and promote new multi-domain treatment approaches to improve patients' care quality.

Acknowledgements

The authors would like to thank Michela Agostini e Lisa Ragazzo for help in data collection.

Funding

This work was supported by the "Department of excellence 2018-2022" initiative of the Italian Ministry of education (MIUR) awarded to the Department of Neuroscience - University of Padova and by REACT EU - PON "Ricerca e Innovazione" 2014-2020", DM 1062/2021 (MR).

Abbreviations

AIS Adolescent Idiopathic Scoliosis; CNS Central Nervous System; PPC Posterior Parietal Cortex; MRI Magnetic Resonance Imaging; fMRI functional Magnetic Resonance Imaging; EEG Electroencephalography; TMS Transcranial Magnetic Resonance Imaging; LI Laterality Index; BTD big toe distance; IMD inter-malleolar distance; EFL effective foot length; MFW maximum foot width; COP Center of Pressure; PL sway path length; EA ellipse area; AP Antero-Posterior; ML Medio-Lateral; RMS Root Mean Square; SI symmetry index; QoL Quality of Life; SRS Scoliosis Research Society; PS Perceived Size; AS Actual Size; BPI Body Perception Index; BPIg general Body Perception Index;

Ethics approval and consent to participate

Parents gave their written informed consent and the project was approved by the Ethics Committee of the Teaching Hospital of Padua, Padova, Italy (protocol n. 31708)

Availability of data, materials and code

The datasets generated and/or analysed during the current study are not publicly available due to participants' privacy. Anonymous Data and Code will be made available upon reasonable request to the Corresponding Author. None of the experiments was preregistered.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Conceptualization and data collection: MB, MR, RDM, EF. Patient recruitment: FC, FG, MDG, SM. Data analysis: MB, MR, RDM, EF. Supervision: SM. Original draft preparation: MB, MR, RDM, EF. All authors critically discussed the results. All the authors read, reviewed and approved the final manuscript.

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Figures

Figure 1 Topographic maps of relative power (%) in delta [1–4] Hz, theta [4.5–7.5] Hz, alpha [8–12] Hz, and beta [13–30] Hz bands, during *OE arms up* and *OE standing*, averaged from 14 healthy subjects (first row), 10 AIS subjects with right main curve (second row) and 4 AIS subjects with left main curve (third row). The fourth and the fifth rows represent *p*-maps derived from the Wilcoxon rank sum test (AIS with right main curve: AIS - R vs. CTRL; AIS with left main curve: AIS - L vs. CTRL). Statistical results were highlighted with (+) for $p < .05$.

Figure 2 Topographic maps of relative power (%) in delta [1–4] Hz, theta [4.5–7.5] Hz, alpha [8–12] Hz, and beta [13–30] Hz bands, during *CE arms up* and *CE standing*, averaged from 14 healthy subjects (first row), 10 AIS subjects with right main curve (second row) and 4 AIS subjects with left main curve (third row). The fourth and the fifth rows represent *p*-maps derived from the Wilcoxon rank sum test (AIS with right main curve: AIS R vs. CTRL; AIS with left main curve: AIS L vs. CTRL). Statistical results were highlighted with (+) for $p < .05$.

Figure 3 Grand-average LI in alpha band during *CE arms up* for controls (CTRL), AIS subjects with right main curve (AIS - R) and AIS subjects with left main curve (AIS - L). On each box, the central red line indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' symbol. Significant difference ($p < .05$) was observed between CTRL and AIS - R.

Figure 4 Balance performances as assessed via confidence ellipse area (EA), sway path length (PL) and the root mean square of center of pressure trajectory in the anterior-posterior and medial-lateral directions (RMS-AP and RMS-ML, respectively) in: **A)** *standing*, and **B)** *arms up* conditions. Boxplots are filled with white for eyes open (*OE*) and gray for eyes closed (*CE*). Statistical results were highlighted with: '***' for $p < 0.001$, '**' for $p < 0.01$, '*' for $p < 0.05$, and '.' for $p < 0.10$.

Figure 5 BPI delta values defined as the difference between shoulder BPI and waist BPI in: **A.** A significant difference emerged between mean delta BPIs of AIS and control groups ($p < 0.01$). **B:** On the x axis are plotted the actual Cobb angles while on the y axis the perceived angles as measured with IMP. To characterize curve laterality, we assigned positive values when curves' convexity was right-oriented, and negative values when left-oriented. In the AIS group 12 out of the 14 girls perceive their curve orientation as opposite to the real one. **C:** For the control group, as no Cobb angle measure was available, we plotted actual angles (x axis) and perceived angles (y axis) as measured with IMP. Laterality was determined as for the AIS group. Just 3 out of 14 girls perceive their curve orientation as opposite to the real one.

Tables

Table 1 AIS subjects' descriptive characteristics.

Subject ID	Age (years)	Menarche (months)	Weight (kg)	Height (m)	BMI	Sport (type)	Sport (hours a week)
1	17,1	25	53,5	1,69	18,73	dance	3
2	13,7	12	52,0	1,62	19,94	-	-
3	13,9	19	44,0	1,61	17,08	dance	1
4	14,1	20	62,0	1,75	20,24	-	-
5	15,7	42	66,0	1,64	24,69	gymnastic	6
6	14,0	25	57,0	1,65	20,94	swim	3
7	15,0	no	45,5	1,71	15,65	volleyball	4
8	16,3	17	38,0	1,48	17,35	-	-
9	13,6	13	54,0	1,63	20,32	dance	7
10	14,0	33	54,0	1,48	24,65	-	-
11	15,1	34	54,0	1,64	20,20	dance	5
12	15,7	43	44,0	1,62	16,77	athletics	5
13	14,2	40	54,0	1,64	20,08	-	-
14	15,9	46	44,0	1,58	17,63	-	-

Table 2 Controls' descriptive characteristics.

Subject ID	Age (years)	Menarche (months)	Weight (kg)	Height (m)	BMI	Sport (type)	Sport (hours a week)
1	14,7	43	84,5	1,6	33,64	gymnastic	9
2	14,0	13	48,5	1,6	19,80	gymnastic	10
3	14,0	24	48,5	1,6	18,83	-	-
4	11,6	1	50,0	1,5	20,95	boxe	3
5	13,4	8	52,0	1,6	21,37	volleyball	7
6	15,5	46	52,0	1,6	20,44	athletics	3
7	14,8	21	67,0	1,6	25,22	gymnastic	8
8	15,5	36	45,0	1,6	17,47	gymnastic	5
9	14,2	13	52,0	1,8	16,98	handball	4,5
10	14,6	24	56,5	1,6	21,14	gymnastic	9
11	13,7	4	50,0	1,7	17,30	swim	10
12	13,6	26	49,0	1,6	20,26	dance	5
13	16,6	65	70,5	1,7	24,39	volleyball	7
14	14,9	36	50,0	1,6	20,16	dance	5

Table 3 Anthropometric characteristic of AIS subjects

Subject ID	Brace (months)	Cobb (deg)	Curve Site	Curve lateralization	Risser Sign (%)
1	48	20	Thoracic	right	100
2	20	21	Thoracic	right	80
3	30	38	Thoracic	right	100
4	1	43	Thoracic	right	75
5	19	21	Lumbar	right	100
6	4	24	Thoracic	right	40
7	19	25	Thoracolumbar	right	90
8	7	55	Thoracic	right	85
9	1	25	Lumbar	right	10
10	65	22	Thoracic	right	100
11	27	27	Lumbar	left	60
12	1	24	Lumbar	left	100
13	30	28	Lumbar	left	85
14	41	28	Lumbar	left	100

Figures

Figure 1

Topographic maps of relative power (%) in delta [1–4] Hz, theta [4.5–7.5] Hz, alpha [8–12] Hz, and beta [13–30] Hz bands, during *OE arms up* and *OE standing*, averaged from 14 healthy subjects (first row), 10 AIS subjects with right main curve (second row) and 4 AIS subjects with left main curve (third row). The fourth and the fifth rows represent p-maps derived from the Wilcoxon rank sum test (AIS with right main curve: AIS - R vs. CTRL; AIS with left main curve: AIS - L vs. CTRL). Statistical results were highlighted with (+) for $p < .05$.

Figure 2

Topographic maps of relative power (%) in delta [1–4] Hz, theta [4.5–7.5] Hz, alpha [8–12] Hz, and beta [13–30] Hz bands, during *CE arms up* and *CE standing*, averaged from 14 healthy subjects (first row), 10 AIS subjects with right main curve (second row) and 4 AIS subjects with left main curve (third row). The fourth and the fifth rows represent p-maps derived from the Wilcoxon rank sum test (AIS with right main curve: AIS R vs. CTRL; AIS with left main curve: AIS L vs. CTRL). Statistical results were highlighted with (+) for $p < .05$.

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