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Review

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ABSTRACT

The aim of this study was to compare postural stability in a group of preterm-born children aged 4–6 years old and in a group of age-matched full-term control children by exploring both spatial and temporal analysis of the Center of Pressure (CoP).

Twenty-nine children born prematurely (mean age: 5.38 ± 0.17) and twenty-nine age-matched full-term control children participated in this study. Postural control was tested on both a stable and an unstable platform (from Framiral®) in three different visual conditions: eyes open fixating a target, eyes closed, and with vision perturbed by optokinetic stimulation.

We observed a significant increase of both surface area and mean velocity of the CoP in pre-term children compared to full-term control children, particularly in an unstable postural condition. The spectral power indices increased significantly in pre-term children with respect to full-term control children, while the cancelling time was not different between the two groups of children tested.

We suggested that poor postural stability observed in preterm children could be due to immaturity of the cortical processes (the occipital parietal prefrontal cortex) involved in motor control. Preterm children could have an inappropriate compensation of sensory inputs when they are tested in difficult postural and/or visual conditions.

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1. Introduction

During the recent decades, the incidence of infants born very preterm (*i.e.* born before 32 gestational weeks) has increased, and approximately 7% of premature children are born in France every year [1]. During childhood and adolescence, children born prematurely have a greater risk of developing major handicaps, motor and cognitive impairments such as hearing loss, cerebral palsy, mental retardation and/or blindness [2–4]. A study by Pin et al. [5] carried out on motor development in a group of 63 preterm infants from 4 to 8 months, showed that motor behavior was impaired in preterm children with respect to term peers and that they showed poor motor skills for the supine, prone and sitting positions. Some investigations [6,7] reported that poor motor capabilities are associated with increased difficulties in focusing attention and learning, causing school failure; Holmström & Larsson [8] reported poor motor coordination and behavioral as well as emotional difficulties in preterm children, and also poor visual-spatial abilities that could be due to a lack of occipital-parietal-frontal neural circuitries [9]. Wang et al. [10] found that in preterm infants (of 6 and 12 months) the development of postural control was poor with respect to that of preterm infants and it was related to the development of fine motor skills. Recently, Dusing et al. [11] showed that very preterm infants compared to a group of preterm born infants presented postural deficits.

An important aspect to obtain body postural stabilization is the development of the visual system. Soon after birth, visual development progresses rapidly and improves during the first year of life [12]; consequently, an early evaluation of visual and perceptual capacity could be a useful method to detect a delayed development. As shown [13], visual, vestibular and somatosensory information act together to control postural stability. In static conditions, postural control implies body orientation, which is generally aligned to the gravity vector.

According to several studies on postural development, age-related changes in the use of vision to control posture exist both in infants

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[14,15] and in children [16,17]. In agreement with these authors, young children are more visuo-dependent in comparison with adult subjects [18,19], and at the age of 4, children still have extreme difficulty at remaining stable in an upright position with their eyes closed [20].

Our team [21] recently carried out a study on a group of prematurely born children aged 3–4 years and a second group of age-matched full-term control children in order to compare their postural stability and their integration of the subjective visual vertical. We showed that postural stability was poor in the first group when compared to the second one, and that in both groups of children posture was significantly perturbed by a dual task when children had to perform subjective visual vertical assessment. These authors suggested that such poor postural control reported in pre-term children could be due to an immaturity of the cortical processes as well as reduced attentional resources.

The present study aims to compare the development of postural capabilities in a group of very preterm-born children aged 4.2–6.9 years old *versus* a group of age-matched full-term control children, using two types of analyses: analysis in the spatial domain (a classical analysis used in the majority of studies dealing with developmental postural examination), but also temporal analysis (wavelet transformation). Moreover, in order to understand better how visual, vestibular and proprioceptive information develop during childhood, different visual as well as postural conditions were used.

In the light of the above considerations, we advanced the hypothesis that postural control can be poor in preterm-born children if compared to that of full-term control children, particularly when vision is perturbed in an unstable condition. We argued that the presence of larger postural sway in the former could be a result of the morphological and functional immaturity of their central nervous system.

2. Methods

2.1. Subjects

Children born between 24 and 28 completed weeks of gestation in the Neonatal Intensive Care Unit of Robert Debré Hospital were enrolled. Our sample comprised 29 children aged between 3.4 and 6.6 years (mean age: 5.38 ± 0.17). Children characteristics are described in Tables 1 and 2. Follow-up involved cerebral magnetic resonance imaging (MRI) at term equivalent-age without sedation, ophthalmologic (visual acuity) and orthoptic examination (absence of heterotropia) and audiometric test at 2, 12 and 36 months, as well as medical and psychometric assessments up to the age of 7 years.

Brain MRI at term-equivalent age was used to evaluate the presence and degree of white matter disease, including gray matter injury (GMI) and white matter injury (WMI), and punctate white matter lesions. The WMI score was obtained by adding the subscores of white matter signal abnormality (the so-called diffuse excessive high signal intensity, DEHSI), periventricular white matter volume loss, presence of cystic abnormalities, ventricular dilation, and thinning of corpus callosum.

Table 1
Clinical characteristics of the two groups of children tested: Mean and minimum and maximum values (in square brackets) of the birth weight (in g), gestational age (in weeks), number of boys and girls, walking age (in months) and number of preterm children with normal MRI at 40 corrected GA.

	Preterm n = 29	Controls n = 29
Birth weight (g)	840 [650–1130]	3700 [3350–3870]*
Gestational age (weeks)	26.3 [24.2–27.6]	39.2 [38–40]*
Boys/girls	16/13	15/14
Walking age (months)	17 [11–24]	13.4 [12–16]*
Normal MRI at 40 corrected GA	11/25	ND

* Asterisks indicate significant difference between the two groups of children.

The GMI score was obtained by adding the subscores of cortical abnormalities, quality of gyral maturation, and size of subarachnoid space.

2.2. Clinical data

After the medical consultation, the neuropsychologist conducted an interview with and neuropsychological assessment of each child (between 4 and 6 years). During the interview with the patient and his/her parents, information was collected concerning pregnancy, maternal employment, walking age, rehabilitation (physiotherapy, psychomotor rehabilitation), *etc*. Cognitive outcomes were assessed using the Wechsler Preschool and Primary Scale of Intelligence, Third and Fourth Editions (WPPSI-III). The WPPSI is a norm-referenced test of cognitive abilities for children aged 2 years, 6 months to 7 years, 7 months. The information was utilized from four composite scores: verbal intelligence (Verbal intellectual quotient, IQ in the WPPSI-III, Verbal Comprehension Index in the WPPSI-IV) estimates verbal reasoning, comprehension and knowledge; performance intelligence (Performance IQ in the WPPSI-III, Visual-Spatial Index in the WPPSI-IV) estimates nonverbal reasoning, including spatial processing and perceptual organization; processing speed (Processing Speed Q in the WPPSI-III, Processing Speed Index in the WPPSI-IV) estimates discrimination speed and oculomotor coordination.

Each of the composite scores has an expected mean of 100 and a standard deviation (SD) of 15. Scores were grouped as average, borderline, and delayed based on SD intervals (85–115, 70–84 [1SD below mean], ≤69 [2 SD below mean], respectively).

Visuospatial abilities were measured by the Design copying (NEPSY-II), Block design and Bug Search with mean of 10 and SD of 3.

A group of full-term control children of similar age was also examined. They had normal values of ophthalmologic/orthoptic, audiometric and vestibular examination; WPPSI was done for each of these children and the full-scale intellectual quotient was in the normal range (between 90 and 110).

The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional Human Experimentation Committee (Comité Consultatif d'Ethique Local, Robert-Debré Pediatric Hospital). Written informed consent was obtained from the children's parents after an accurate explanation of the experimental procedure.

2.3. Postural recording

Static postural performance of each child was evaluated using Multitest Equilibre from Framiral® (www.framiral.fr). We measured also the displacement of the center of pressure by using nonlinear analysis methods such as the wavelet transformation method [22] allowing a better understanding of eventual deficits in the dynamics of the postural control as reported by our previous works [23,24].

2.4. Experimental procedure

Experimental procedure is similar to that use [23,24]. Postural recording was performed on stable (S) and unstable (U) platform and each experimental session included three different viewing conditions: eyes open fixing a target (EO), eyes closed (EC), and eyes open with perturbed vision (OKN). The order of the conditions varied randomly across children. Subjects were asked to stay as stable as possible.

2.5. Postural parameters

2.5.1. Classical analysis in the spatial domain

In order to quantify postural performance, we analyzed two postural parameters: i) The surface of the Center of Pressure (CoP) (cm^2) corresponding to an ellipse with 90% of CoP excursions; ii) the mean speed

Table 2
Clinical test and MRI results in preterm children. Wechsler Preschool and Primary Scale of Intelligence, Third Edition and Fourth Edition (WPPSI-III; WPPSI-IV): verbal intelligence (V); performance intelligence (VS); processing speed (PS); full scale intellectual quotient (FSIQ), blocks (B), bug search (BS), design copying (DC); test not done (ND). Abnormal values are in gray box.

Child	Walking age (months)	WPPSI V	WPPSI VS	WPPSI PS	WPPSI FSIQ	WPPSI B	WPPSI BS	DC	MRI
C1	18	63	56	ND	ND	3	ND	8	1
C2	16	111	94	100	103	8	11	9	0
C3	12	95	85	82	82	8	5	7	0
C4	17	50	92	83	64	10	9	10	1
C5	14	95	94	106	98	11	10	8	ND
C6	18	100	85	82	88	9	8	7	0
C7	16	75	97	110	82	8	10	9	ND
C8	17	63	103	71	75	9	6	10	0
C9	17	63	85	71	72	7	7	10	0
C10	13	108	109	88	105	11	9	11	0
C11	15	75	77	91	74	7	7	5	0
C12	21	66	85	63	63	6	6	9	1
C13	11	114	85	85	101	7	7	11	ND
C14	18	100	82	88	87	7	7	6	1
C15	20	80	71	69	66	5	6	6	0
C16	15	95	88	103	100	10	10	9	0
C17	13	80	92	74	76	5	9	9	0
C18	18	60	79	53	60	7	3	4	1
C19	13	102	75	88	96	8	8	5	1
C20	15	63	58	66	51	5	7	8	1
C21	19	72	100	85	77	8	7	8	0
C22	24	92	91	94	93	8	10	10	ND
C23	16	98	97	115	95	8	9	13	1
C24	15	78	85	67	70	9	6	6	1
C25	17	81	77	59	73	7	4	7	1
C26	21	89	85	97	ND	9	11	9	1
C27	17	62	52	ND	53	1	ND	ND	0
C28	18	87	100	110	92	10	10	15	0
C29	15	63	106	97	82	13	9	14	0

(mm/s) of the CoP.

2.5.2. *Temporal analysis, wavelet transformation*

In order to study the frequency of the CoP displacements in the time domain we applied a wavelet nonlinear analysis obtained by Framiral® (see [25] for more details). The spectral power index was calculated as the decimal logarithm for the frequency bands 0.05–0.5 Hz (F1), 0.5–1.5 Hz (F2), higher than 1.5 Hz (F3) in both antero-posterior and medio-lateral directions (PIy and PIx, respectively).

Furthermore, another parameter calculated for the antero-posterior directions was the Cancelling Time (CT) of each frequency band. The Cancelling Time is the total time during which the spectral power index of the body sway for the frequency range is cancelled by the posture control mechanisms.

2.6. *Statistical analysis*

Statistical analyses were performed using ANOVA test to compare the two groups of children in the aforementioned conditions (EO-S, EC-S, OKN-S, EO-U, EC-U and OKN-U, respectively). The post-hoc comparisons were made with the least significant different (LSD) test. The effect of a factor was considered as significant when the *p*-value was below 0.05.

3. Results

Twenty-nine children born prematurely from 24 to 27 GA (mean age of 26.3 GA) participated in the study and twenty-nine full-term control children were also studied as controls (Table 1). ANOVA run on birth weight, gestational age, number of boys and girls and walking age for the two groups of children (pre-term and full-term children) showed significant difference on birth weight, gestational age and walking age (all $p < 0.0001$). Audiometric test was normal for all children. Eleven preterm children wore glasses (myopia and/or hypermetropia correction).

Table 2 shows WPSSI outcomes of the entire cohort as compared to population norms. Cerebral MRI was performed in 25 preterm children at term equivalent-age corrected; it was normal in 13 children only. The other preterm infants had abnormal scores for white matter injury and white matter signal intensity.

3.1. *Classical postural data in spatial domain*

Fig. 1A shows the surface area of the CoP (cm^2) for both groups of children tested (pre-term and full-term children) in each of the six conditions run (EO, EC, OKN, for stable and unstable conditions, respectively). ANOVA showed a significant effect of group ($F_{(1,56)} = 14.92$, $p < 0.0002$): pre-term children had a significantly higher surface of the CoP compared to that of full-term control children. The ANOVA also showed a significant effect of the postural condition ($F_{(1,56)} = 9.06$, $p < 0.004$): the surface area of the CoP was significantly larger in unstable than in stable condition. The ANOVA also showed a significant effect of visual condition ($F_{(2,112)} = 3.35$, $p < 0.03$); the LSD test reported that the surface of the CoP under perturbed vision was significantly larger than that measured in the eyes open and eyes closed conditions (both $p < 0.002$). ANOVA failed to show any interaction effect (group x visual condition ($F_{(1,56)} = 0.34$, $p = 0.55$); group x postural condition ($F_{(2,112)} = 2.07$, $p = 0.12$); and visual x postural condition ($F_{(2,112)} = 0.96$, $p = 0.38$)).

Fig. 1B shows the mean velocity of the CoP (mm/s) for both groups of children tested (pre-term and full-term children) in each of the six conditions run (EO, EC, OKN, for stable and unstable conditions, respectively). The ANOVA showed a significant effect of group ($F_{(1,56)} = 17.57$, $p < 0.0001$): pre-term children had a significantly

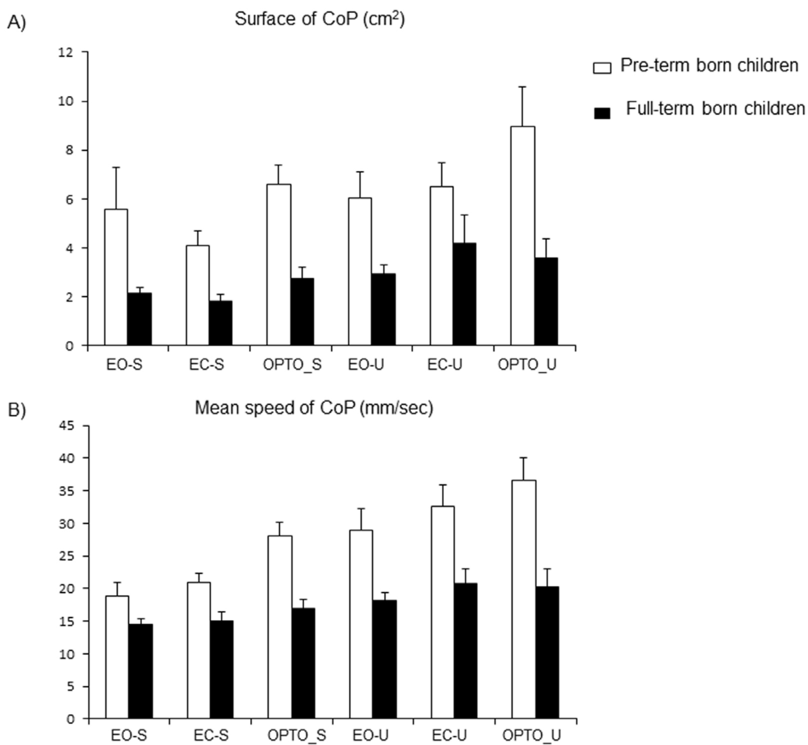

Fig. 1. Surface area in cm^2 (A) and mean velocity in mm/s (B) of the CoP for the two groups of children in the six conditions tested (eyes open, EO, eyes closed EC, and with optokinetic stimulation, OKN) on stable (S) and unstable (U) platform. Vertical bars indicate the standard error.

higher mean velocity of the CoP compared to that of full-term control children. The ANOVA showed a significant effect of postural condition ($F_{(1,56)} = 32.33$, $p < 0.0001$): the mean velocity of the CoP was significantly greater in unstable than in stable condition. The ANOVA showed a significant effect of visual condition ($F_{(2,112)} = 12.40$, $p < 0.0001$). The post-hoc test showed that the mean speed of the CoP was significantly higher in the perturbed vision condition than in the eyes open and eyes closed conditions (both $p < 0.0001$). The ANOVA also showed two significant interactions between group and postural condition ($F_{(1,56)} = 5.62$, $p < 0.02$) and between group and visual condition ($F_{(2,112)} = 4.40$, $p < 0.01$). The mean velocity of the CoP was significantly higher in pre-term children with respect to the full-term control children under unstable condition ($p < 0.001$) and also under perturbed vision ($p < 0.001$). ANOVA failed to show a significant interaction between visual and postural condition ($F_{(2,112)} = 0.65$, $p = 0.5$).

3.2. Temporal analysis, wavelet transformation

Fig. 2 shows the spectral power indices in antero-posterior direction for both groups of children tested (pre-term and full-term children), for each frequency (L: Low; M: Medium; and H: High) in each of the six conditions tested (EO-S, EC-S, OKN-S, EO-U, EC-U and OKN-U, respectively).

The ANOVA showed that a significant effect of group was present ($F_{(1,56)} = 21.94$, $p < 0.0001$): pre-term children showed a spectral power index significantly higher compared to that of full-term children. The ANOVA also showed a significant effect of postural condition ($F_{(1,56)} = 16.09$, $p < 0.0001$): the spectral power index was significantly greater in unstable than in stable condition. Moreover, the ANOVA showed a significant effect of visual condition ($F_{(2,112)} = 6.29$, $p < 0.002$). The post-hoc test showed that the spectral power index in antero-posterior direction was significantly higher in perturbed visual condition than in eyes open and eyes closed conditions (both, $p < 0.001$).

The ANOVA also reported a significant effect of frequency ($F_{(2,112)} = 2972$, $p < 0.0001$). The spectral power index for low frequency was significantly higher than those recorded in the medium and high frequencies (both $p < 0.001$). The ANOVA additionally showed a significant interaction between group and vision ($F_{(2,112)} = 4.28$, $p < 0.01$): the spectral power index was significantly higher in pre-term children than in full-term control children, for all conditions and particularly for the perturbed vision condition ($p < 0.01$). Furthermore, there was a significant interaction between group and frequency ($F_{(2,116)} = 7.92$, $p < 0.0006$): independently of condition, the spectral power index was significantly higher in pre-term children for low frequency than those recorded for medium and high frequencies (all $p < 0.001$). Finally there was a significant interaction between group, vision condition and frequency ($F_{(2,116)} = 8.29$, $p < 0.0004$): the spectral power index was significantly higher in pre-term children

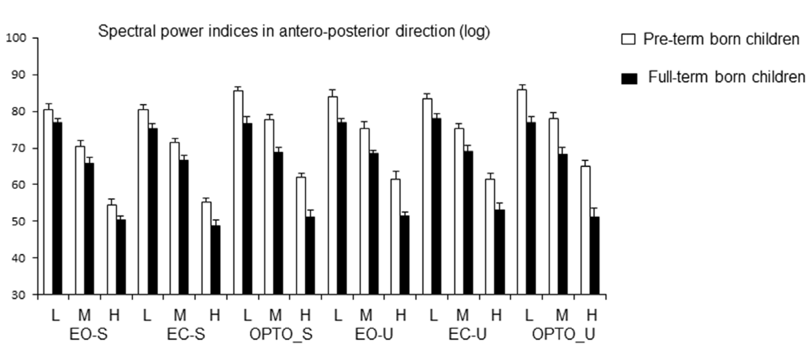

Fig. 2. Spectral power indices in antero-posterior direction for the two groups of children for each frequency band (L, low, M, medium, and H, high), in all conditions tested (EO-S, EC-S, OKN-S, EO-U, EC-U and OKN-U). Vertical bars indicate the standard error.

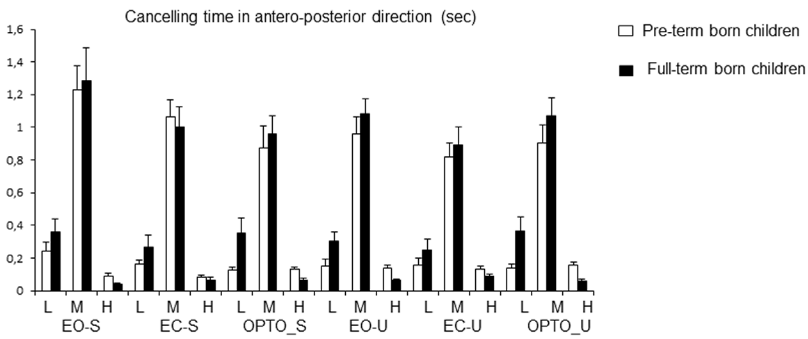

Fig. 3. Cancelling time in antero-posterior direction for the two groups of children for each frequency (L, low, M, medium and H, high), in all conditions tested (EO-S, EC-S, OKN-S, EO-U, EC-U and OKN-U). Vertical bars indicate the standard error.

than in full-term control children for all frequencies and particularly for high frequency in the unstable condition ($p < 0.0001$).

Fig. 3 shows the Cancelling Time in antero-posterior direction for both groups of children tested (pre-term and full-term children), for each frequency (L: Low; M: Medium; and H: High) in each of the six conditions tested (EO-S, EC-S, OKN-S, EO-U, EC-U and OKN-U, respectively). The ANOVA failed to show a significant group effect ($F_{(1,56)} = 1.89$, $p = 0.17$). In contrast it showed a significant effect of postural condition ($F_{(1,56)} = 4.13$, $p < 0.04$), of visual condition ($F_{(2,112)} = 4.25$, $p < 0.01$) and of frequency ($F_{(2,112)} = 181.30$, $p < 0.0001$).

4. Discussion

4.1. Spatial domain analysis showed poor postural capabilities in pre-term born children, particularly in unstable postural condition and with perturbed vision

The present study confirms and enlarges our previous study on pre-term children [21]: the surface and the mean velocity of the CoP are larger in pre-term children with respect to full-term control children. The novelty here is that postural stability is poor in more difficult conditions, for instance when vision is perturbed by optokinetic stimulation, suggesting poor capability of pre-term children to adapt vestibular, somatosensoric perception and cerebellar processing to compensate such perturbed information and to provide good postural control. Note, however, that a significant interaction effect was found between group and postural conditions for mean velocity only, and not for the surface area of the CoP. This finding is in line with our previous reports [25,26] in children with neurodevelopmental disabilities showing that the mean velocity of the CoP was more sensible than the surface area of the CoP when a muscular effort was needed.

Peterka [27] advanced the hypothesis that when one sensory input is absent or defective, the other subsystems compensate for the impairment by playing a more important role (*i.e.*, reweighting of the sensory system). Pre-term children are not able to do such adaptive compensations, most likely because of their impaired functioning of the occipital parietal prefrontal cortex involved in visual-motor control, according to previous findings [4]. Finally, recall that Fawcett [28] also reported a relationship between cognitive performance and postural control in children with neurodevelopmental deficits. Further studies testing neuropsychological capabilities and postural control on a population of children of different ages will be useful in order to improve knowledge on this important issue.

4.2. For both groups of children, postural stability is similar under different visual conditions

An interesting and new aspect of our study is that we did not find any difference in postural stability between eyes open and eyes closed conditions. This is in contrast with previous studies [20], in which it was shown that young children were more visuo-dependent than adults. Our study is also in contrast with another study [18] in which, by an electromyography (EMG) analysis, these authors examined postural capabilities in healthy children of different ages (15–31 months, 4–6 years and 7–10 years). They showed that in 4–6 years old children postural stability was variable and that at this age children used visual information to stabilize their posture. Furthermore, the authors reported that it is only at about 7–10 years that children develop postural strategies similar to those reported in adults, suggesting that only later on are they able to integrate both vestibular and proprioceptive inputs to obtain a good stability of the body. The different finding observed in our study, namely a similar postural stability with eyes open or eyes closed, could be due to the capability of children to focus their attention even when they have their eyes closed (maybe because they were motivated to maintain good postural control in this condition). This result reinforces the hypothesis that an attentional cost is strictly correlated with postural sway control [29]. This finding is also in agreement with a study by our group [23], in which we explored postural stability in a large group of healthy children with the same experimental setup. Maybe it could be interesting to use other experimental condition in order to confirm these findings.

4.3. Wavelet transformation showed larger spectral power indices in children born prematurely

The frequency analysis revealed that for all frequency bands, particularly for unstable postural conditions, the spectral power indices were significantly higher for the group of pre-term children than for full-term control children, suggesting that children born prematurely use significantly more energy to control body sway, particularly when postural condition is difficult (unstable platform) and vision perturbed by optokinetic stimulation. Several previous studies by other groups [22] and ours [23–25] advanced the hypothesis that smaller spectral power index is related to better postural control because subjects do less effort to control the CoP displacement.

Finally the results on the cancelling time showed a similar behavior for pre-term and full-term born children. Recall that the canceling time is the total time during which the spectral power of the body sway (for a specific frequency band) is cancelled by the postural control mechanisms (for details, see [25]). The present result suggested that pre-term children are as able as full-term control children to engage the postural control system in order to reduce body sway, particularly by minimizing muscular effort required for controlling postural stability.

5. Conclusion

Our current findings show that postural control is impaired in pre-term children (from 4 to 6 years old) with respect to that of age-matched full-term control children, most likely due to a later development of cortical structures involved in visuo-motor control. Finally, the parameters taken into account and based on both spatial and temporal analysis of the CoP could be used as a reference for further studies dealing with pathological motor development in children.

Competing interests

The authors have declared that no competing interests exist.

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