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Abstract
Purpose To analyse postural performances of strabismic children, both in the spatial and the temporal domains, by wavelet transformation, comparing both stable and unstable situations.
Methods Twenty-six strabismic children aged from 4 to 11 years old and 26 age-matched normal children participated in the study. Postural performances were evaluated using the Framiral® platform. Posture was recorded in the following conditions: eyes open fixating a target and eyes closed on stable and unstable platforms.
Results For both strabismic and non-strabismic children, the surface and the mean velocity of the center of pressure (CoP) were significantly larger in the eyes closed on unstable platform condition, but this was much more pronounced in case of strabismus. Spectral power index and cancelling time were also found to be altered in strabismic children compared to non-strabismic children.
Conclusions This data demonstrates poor postural stability for both groups on an unstable platform with the eyes closed. However, strabismic children had significantly worse performance than non-strabismic children. Strabismic children also engage more energy to stabilize their posture by using visuo-vestibular sensory inputs to compensate their altered vision due to strabismus, in comparison to non-strabismic children.

Keywords Children · Strabismus · Postural control · Spatial and temporal analyses

Marie-Désirée Ezane and Cynthia Lions contributed equally to this work.

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Introduction

Postural control is a complex process which allows obtaining a coordinated relation of the various physical segments of the body. Muscle effectors involved in postural control are connected to various structures in the central nervous system, such as the basal ganglia, the brainstem, the cerebellum, and various cortical areas [1–3]. Different inputs are also responsible for good postural control, including those transmitted through the proprioceptive and exteroceptive, vestibular, and visual afferents. The congruence of all of this information is necessary to reach an appropriate posture within the current environment. Thus, a deficit in one of these inputs may lead to an imbalance in other sensory inputs and consequently may lead to postural disequilibrium [4]. Peterka hypothesized that when one sensory input is defective, the other subsystems compensate for the impairment by playing a more important role (i.e., reweighting of the sensory system) [5]. It is most likely that adaptive mechanisms could be at the origin of such changes [6–8]. It is unknown how strabismus and the accompanying abnormal vision may alter these mechanisms.

This question is especially pertinent, given that approximately 2 % of children under the age of 7 years old have strabismus [9] and that it is one of the most common visual disorders in infancy. Strabismus is characterized by an abnormal alignment of the eyes. It can be convergent or divergent, horizontal, or vertical. In most cases, this leads to amblyopia and/or abnormal binocular vision. Presently, the management of strabismus combines optical treatment, prevention or treatment of amblyopia with monocular patching, and surgical realignment of the eyes, with the final goal to preserve or to recover normal binocular vision. But this does not completely correct visual impairments in numerous cases. As a consequence, the posture of strabismic children is often altered but this phenomenon is poorly documented.

Currently, few studies examining postural control in children with strabismus are available in the literature [10–15]. Odenrick et al. [10] observed a higher instability in children with divergent strabismus than in children with convergent strabismus. In a static situation, Matsuo et al. [11] showed that strabismic children (from 3 to 12 years old) are more unstable if their eyes are closed, compared to a condition when their eyes are open. Also in a static situation, Legrand et al. [13] observed poor postural control in children from 4 to 8 years old with divergent or convergent strabismus, and provided evidence of an improvement in postural control in these children 2 months after strabismus surgery. Finally, still conducting experiments in a static situation, our group revealed recently that abnormal postural control takes place in strabismic children compared to non-strabismic age-matched children [14]. Firstly, we showed that postural control in strabismic children was impaired both while fixating a target and while performing saccades in comparison to non-strabismic children; importantly, postural balance in strabismic children improved during a double task of ocular saccades compared to a simple task of fixation. Finally, using a stable platform, we showed that strabismic children were more unstable in Tandem condition (one foot in front of the other) than in Romberg condition (feet together). They were also more unstable with a foam pad than without a foam pad. These results led us to the conclusion that strabismic children use more proprioceptive information than non-strabismic children to control their posture in a static situation [15].

All of these studies on postural balance in strabismic children have obviously shed new light on the impact of strabismus on posture. But our knowledge about this area still remains incomplete. Indeed, to summarize, all of these studies have been realized by using a stable platform, and the unstable (moving) situations have thus remained unexplored. The center of pressure (CoP) has only been analysed spatially, and the behaviour of this CoP over time is thus unknown. The respective role of the different sensory systems also still remains unclear. However, new tools and new analyses are now available and may help going forward, in particular the Multitest Equilibre from Framiral® (www.framiral.fr). This permits analysis of the CoP in both the spatial and the temporal domains. In particular, important information on the dynamic of the CoP may be obtained by applying nonlinear analysis methods, such as the wavelet transformation method. Indeed, a study by Ghulyan et al. has demonstrated that a dynamic analysis of posture allows better discrimination of the pathological effects on postural control [16]. Lacour et al. have also described the limitations of the traditional posturography method, suggesting that the spatial analysis of the CoP could lead to misevaluations of the balance control system [17]. Note also that Yelnik and Bonan have shown that temporal analysis allows us to gain insight into the physiological and pathological mechanisms underlying postural stability impairment in patients suffering from balance disorders [18]. As found by Bernard-Demanze et al., the use of wavelet transformation for exploring postural control is very relevant. Such analysis can reveal deficits or changes in the dynamics of the postural control system which are not shown by the more traditional posturography undertaken with static analysis. In addition, such analysis may contribute to identify which sensory systems are implicated or altered during a given postural task [19].

In the present study, we approached postural performances in strabismic children both in the spatial and the temporal domains, by wavelet transformation, comparing both stable and unstable situations. The postural capabilities of strabismic children were compared to those of a group of age-matched non-strabismic children. We also aimed to identify which sensory systems, among the visual, proprioceptive, and vestibular systems, are recruited more by strabismic subjects to stabilize their posture.

Method

Subjects

Twenty-six strabismic children aged from 4 to 11 years old (mean age 6.53±0.34 years) participated in this study. Strabismic children were recruited from the Department of Ophthalmology, Robert Debré University Hospital in Paris. The subjects were not premature, nor were they subject to associated disease with their strabismus. Twenty-six age-matched non-strabismic children (mean age 6.71±0.36 years) were also tested as controls. All subjects underwent ophthalmologic and orthoptic evaluation, and were naïve to postural recording. No training or simulation was undertaken prior to starting the first test.

The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional Human Experimentation Committee (Comité de Protection des Personnes, CPP Ile de France V, Hôpital Saint-Antoine). Written informed consent was obtained from the children's parents after the nature of the procedure had been explained.

Ophthalmologic and orthoptic evaluations

Ophthalmologists and orthoptists from the Department of Ophthalmology conducted respectively ophthalmologic and orthoptic examinations of all strabismic children to evaluate their visual function. Three different parameters were evaluated. The visual acuity (with glasses correction) was first measured for each eye separately at far distance (5 m) with the "Monoyer chart", an optometric chart containing ten rows of letters, each row corresponding to 1/10 visual acuity. Heterotropia, i.e., the manifest deviation of one eye, was then measured at near (33 cm) and far (5 m) distances by using the "cover–uncover test". Finally, the stereo-acuity threshold based on disparity detection was finally evaluated with the TNO random dot test for stereoscopic depth discrimination.

Clinical data of each strabismic child are reported in Table 1. To summarize, the monocular visual acuity was normal in both eyes (≥20/20) for 21 children. Five children had visual acuity of between 20/63 and 20/25. Eleven children had intermittent exotropia; nine children had binocular vision of 15" to 240" seconds of arc. Thirteen children had early onset esotropia without any binocular vision. Two children had acquired accommodative esotropia without binocular vision.

Clinical data of each non-strabismic child are reported in Table 2. All control age-matched children had normal monocular visual acuity (≥20/20), and normal binocular vision (≥60 seconds of arc with the TNO test). None of them had strabismus.

Material

Postural performances of children were evaluated using the Multitest Equilibre from Framiral® (www.framiral.fr). This material consists in a force plate mounted on a translator which allows a translation of the subject in the antero–posterior (*y*) or the medio–lateral direction (*x*). A computer-controlled mechanism allows sinusoidal displacements of 62 mm amplitude with adjustable velocities and frequencies. In our experimental conditions, the ramp mode allowed forward and backward translations of the force plate, with constant linear velocities of 0.03 m/s and 0.07 m/s. For the sinusoidal mode, the frequency was 0.25 Hz. The CoP displacement was sampled at 40 Hz and 100 Hz in the stable and unstable conditions respectively, and digitized with 16-bit precision [16, 19].

Postural recording procedure

Postural procedure was similar to those used in our previous study (see Gouleme et al. [20] for details). Children were placed in a dark room, standing up on the Framiral® platform, with their feet placed on the footprints, their arms along the body, and their shoulders apart.

Postural recording was performed in two situations, being stable (S) and unstable (U). Two different viewing conditions were also applied: eyes open fixating a target (EO) and eyes closed (EC). During the eyes open condition, subjects had to fixate a small red light at a distance of 250 cm. The duration for each postural recording was 30 seconds, with 15 seconds of rest between each condition to reduce possible fatigue effects. The order of the conditions varied randomly across children. Children were asked to stay as still as possible.

Classical analysis in spatial domain

The surface area (cm^2) and the mean velocity (mm/s) of the CoP were analyzed. The surface area of the CoP is an efficient measurement of the CoP's spatial variability [21] while the mean velocity of the CoP represents a good index of the amount of neuromuscular activity required to regulate postural control [22, 23]. The mean velocity of the CoP is the mean velocity of the CoP displacements over the sampled period, that is, the sum of the displacement scalars over the sampling period divided by the sampling time. These two postural parameters allow efficient measurement of CoP spatial variability.

Temporal analysis, wavelet transformation

We applied a wavelet analysis to study the frequencies of the CoP displacements. This analysis and associated parameters were obtained from Framiral (www.framiral.fr; see [19, 24]). The spectral power index was calculated as the decimal logarithm for the three frequency bands: low: 0.05–0.5 Hz, medium: 0.5– 1.5 Hz and high: greater than 1.5 Hz, in both the antero–posterior and medio-lateral directions (PIy and PIx respectively). The spectral power index in the higher band is minimal in healthy subjects during quiet standing, but it can be larger with aging, in cases of postural pathology, or in unstable postural conditions [25]. The hypothetical physiological origin of the different bands is as follows: 0–0.5 Hz, visual–vestibular [25–27]; 0.5–1.5 Hz, cerebellar [27]; 1.5-10 Hz, somesthesic [17, 19].

The cancelling time (CT) of each frequency band was also calculated for the antero–posterior (CTy) and medio–lateral (CTx) sway, i.e., the total time during which the spectral power index of the body sway for the frequency range was cancelled by the postural control mechanisms; the longer the cancelling time of a frequency band, the better the postural control [19, 24]. Remember that cancelling time is the time required to use sensorial inputs for controlling posture. Thus, the longer this time is, the more children use their sensorial information to maintain postural stability. By contrast, a short cancelling time reveals a low search time of sensorial inputs, and thus a poor use of such information to maintain postural control.

Statistical analysis

Data were entered in an ANOVA with repeated measures using two main factors—the viewing condition (eyes open

Table 1 Clinical characteristics of the strabismic children

Children (years)	Glasses correction	Corrected visual acuity	Angle of strabismus (prism D)	Stereoacuity (TNO)	Type of strabismus
C1 (4.0)	RE: +3.25 (−1.00) 180°	RE:20/20	40 ET	–	Acquired esotropia
	LE: +3.50	LE:20/20	50E'T		
C2 (4.4)	RE: +7.50	RE: 20/20	50 ET	–	Acquired esotropia
	LE: +7.50	LE: 20/20	55 E'T		
C3 (4.8)	RE: −8.25 (2.00) 160°	RE: 20/20	30-35 XT	–	Intermittent exotropia
	LE: +0.50 (−1.25) 10°	LE: 20/20	30-35 X'X'T		
C4 (4.9)	RE: +4.75 (−1.50) 20°	RE: 20/20	35 ET	–	Early onset esotropia
	LE: +4.50 (−1.00) 165°	LE: 20/20	35 E'T		
C5 (4.9)	RE: +1.75 (−0.50) 180°	RE: 20/20	30 ET	–	Early onset esotropia
	LE: +1.50 (−0.25) 17°	LE: 20/20	18 E'T		
C6 (5.2)	RE: +3.75 (−0.75) 180°	RE: 20/20	25 ET	–	Early onset esotropia
	LE: +3.75 (−0.75) 10°	LE: 20/20	30 E'T		
C7 (5.2)	RE: 0.00	RE: 20/20	50 ET	–	Early onset esotropia
	LE: 0.00	LE: 20/20	50 E'T		
C8 (5.3)	RE: +3.50 (−1.00) 5°	RE: 20/20	30-35 ET	–	Early onset esotropia
	LE: +3.50	LE: 20/20	30-35 E'T		
C9 (5.4)	RE: +2.50 (−0.50) 100°	RE: 20/20	25 ET	–	Early onset esotropia
	LE: +2.50 (−0.75) 10°	LE: 20/20	25 E'T		
C10 (5.8)	RE: +1 (−0.50) 50°	RE: 20/20	25 XX'T	60"	Intermittent exotropia
	LE: +0.50	LE: 20/20	35 XXT		
C11 (5.8)	RE: +0.75 (−2.50) 180°	RE: 20/20	30 XT	60"	Intermittent exotropia
	LE: +1.25 (−2.25) 15°	LE: 20/20	35 X'X'T		
C12 (6.2)	RE: −7.00 (−2.25) 170°	RE : 20/32	35 ET	–	Early onset esotropia
	LE: −7.25 (−2.25) 145°	LE : 20/20	440 E'T		
C13 (6.3)	RE : +0.75	RE : 20/20	60 ET	–	Early onset esotropia
	LE: +0.75	LE : 20/20	65 E'T		
C14 (6.3)	RE: +1.75 (−1.25) 185°	RE: 20/50	50-55 ET	–	Early onset esotropia
	LE: +1.75 (−1.00) 56°	LE: 20/63	50-55 E'T		
C15 (6.4)	RE: +3.00 (−1.00) 175°	RE: 20/20	10 ET	–	Early onset esotropia
	LE: +2.00	LE: 20/20	14 E'T		
C16 (6.4)	RE: +1.75 (−0.50) 10°	RE: 20/20	35 XT	–	Intermittent exotropia
	LE: +1.50 (−0.50) 5°	LE: 20/20	18 X'X'T		
C17(6.9)	RE: 0.00	RE: 20/20	30 XXT	60"	Intermittent exotropia
	LE: 0.00	LE: 20/20	4 X'		
C18 (7.1)	RE: +0.25 (−0.75) 170°	RE: 20/20	30 XXT	240"	Intermittent exotropia
	LE: +0.50 (−0.75) 20°	LE: 20/20	14 X'X'T		
C19 (7.4)	RE: (−0.50) 175°	RE: 20/20	20-25 XT	60"	Intermittent exotropia
	LE: +1.00 (−1.25) 25°	LE: 20/20	18 X'X'T		
C20 (7.7)	RE: +5.00 (−0.75) 145°	RE: 20/32	30-35 E'T	–	Early onset esotropia
	LE: +6.25 (−2.00) 180°	LE: 20/25	12 ET		
C21 (7.9)	RE: +2.00 (−1.00) 175°	RE: 20/20	16 XT	60"	Intermittent exotropia
	LE: +2.50 (−1.50) 175°	LE: 20/20	18 X'X'T		
C22 (8.4)	RE: +4.75 (−0.50) 25°	RE: 20/20	40 ET	–	Early onset esotropia
	LE: +4.25 (−0.25) 152°	LE: 20/20	35 E'T		
C23 (8.4)	RE: +6.00 (−0.50) 10°	RE: 20/20	14 ET	–	Early onset esotropia
	LE: +7.50 (−0.75) 160°	LE: 20/ 32	14 E'T		
C24 (9.0)	RE : +2.25 (−0.25) 25°	RE: 20/20	30 XXT	15"	Intermittent exotropia
	LE : +2.25 (−0.25) 15°	LE: 20/20	25 X'X'T		
C25 (9.7)	RE : +0.25 (−0.75) 110°	RE: 20/20	25 XXT	30"	Intermittent exotropia

Table 1 (continued)

Children (years)	Glasses correction	Corrected visual acuity	Angle of strabismus (prism D)	Stereoacuity (TNO)	Type of strabismus
C26 (11.0)	LE : (−0.50) 45° RE : (−0.50) 160° LE : (−0.75) 180°	LE: 20/20 RE: 20/20 LE: 20/20	4 E' 25 XXT 25 X'X'T	60"	Intermittent exotropia

Data are reported for each of the 26 subjects who participated in this study (C1 to C26), whose age ranged from 4 to 11 years. Their individual glasses correction, corrected visual acuity, angle of strabismus, stereoacuity, and type of strabismus are reported in the successive columns of the table. LE, RE: left eye and right eye respectively. The deviation of the eyes was assessed with the cover–uncover test and prism; the binocular vision was evaluated with the TNO test for stereoscopic depth discrimination. X–XT=intermittent exotropia measured at far distance (5 m); X'–X'T=intermittent exotropia measured at near distance (30 cm); E'T and ET, esotropia measured at far (5 m) and at near (30 cm) distance, respectively

and eyes closed), the postural parameters (stable and unstable platform)— and two groups of children (strabismic and non-strabismic) as inter-subject factors. We performed this analysis for the following parameters: individual means of their surface, velocity, power index, and cancelling time. The post-hoc analysis was done with the Fisher LSD post-hoc test. The effect of a factor was considered as significant when the *p*-value was below 0.05.

Results

Postural data in the spatial domain

Data on postural stability were obtained here by measuring the surface and the mean velocity of the CoP. This was achieved in both strabismic and non-strabismic children, while they were placed on a stable (S) or an unstable (U) platform, with their eyes open (EO) or eyes closed (EC).

Surface of CoP

Figure 1a summarizes the data obtained on the surface area of the CoP, and reveals clear differences both between groups and experimental conditions.

Firstly, independently of the condition, the mean surface areas of the CoP in strabismic children were systematically significantly larger than those found for non-strabismic children: from 2.6 to 4.3 cm^2 vs 1.2 to 2.2 cm^2. The analysis of variance (ANOVA) showed that this difference between groups was significant ($F_{(1.50)}=4.31$, $p<0.04$).

Secondly, the mean surface area of the CoP varied according to the experimental condition. Both groups had in common that the surface of the CoP was significantly larger in the unstable condition than in the stable condition (ANOVA, $F_{(1,50)}=5.46$, $p<0.02$). Both groups also displayed the largest value of the surface area of the CoP when eyes were kept closed ($F_{(1.50)}=4.84$, $p<0.03$). But again, strabismic children displayed the largest values of the CoP, meaning worse postural performances.

Mean velocity of the CoP

Figure 1b summarizes the data obtained in respect of the mean velocity of the CoP and reveals clear differences both between groups and experimental conditions.

Firstly, independently of the condition, the mean velocity in strabismic children was significantly higher than in non-strabismic children: from 15.6 to 23.2 cm/s vs 11.8 to 15.5 cm/s. The analysis of variance (ANOVA) showed that this difference between groups was significant ($F_{(1.50)}=5.31$, $p<0.02$).

Secondly, the mean velocity of the CoP varied according to the experimental condition. Both groups had in common that the velocity of the CoP was significantly larger in the unstable condition than in the stable condition. The analysis of variance (ANOVA) showed that such difference between groups was significant ($F_{(1.50)}=24.65$, $p<0.0001$). Both groups also displayed the largest value in respect of velocity of the CoP in the "eyes closed" condition compared to the "eyes open" condition. The analysis of variance (ANOVA) showed that such a difference between groups was significant ($F_{(1.50)}=11.39$, $p<0.001$). But again, the strabismic children distinguished themselves from the non-strabismic group by displaying the largest mean velocities of the CoP.

To summarize, these data indicate that strabismic children have to develop more muscular activity than non-strabismic children to maintain their posture. Again, this is more visible when they are placed in an unstable environment instead of a stable one, and when the eyes are closed and they are completely deprived of vision.

Temporal analysis, using wavelet transformation

As previously set out, the aim here was to compare the "frequencies" of displacements of the CoP for both experimental groups, in the different situations described above. This was achieved by calculating the spectral power index (PI) and then the cancelling time (CT) for each frequency, for postural sways in the antero-posterior direction (y) and the medio-lateral one (x).

Table 2 Clinical characteristics of the non-strabismic children

Non-strabismic children (years)	Visual acuity	Stereoacuity (TNO)	NPC (cm)	Phoria far	Phoria near
N1 (4.2)	RE:20/20 LE:20/20	60”	5	0	−4
N2 (4.2)	RE: 20/20 LE: 20/20	60”	0	−2	−4
N3 (4.6)	RE: 20/20 LE: 20/20	60”	4	0	−2
N4 (5.1)	RE: 20/20 LE: 20/20	60”	0	0	1
N5 (5.2)	RE: 20/20 LE: 20/20	60”	4	2	1
N6 (5.4)	RE: 20/20 LE: 20/20	60”	0	0	2
N7 (5.4)	RE: 20/20 LE: 20/20	60”	0	0	4
N8 (5.4)	RE: 20/20 LE: 20/20	60”	5	−2	−1
N9 (5.6)	RE: 20/20 LE: 20/20	60”	2	0	0
N10 (6.25)	RE: 20/20 LE: 20/20	60”	3	0	−2
N11 (6.6)	RE: 20/20 LE: 20/20	60”	0	0	0
N12 (7.0)	RE : 20/20 LE : 20/20	60”	3	0	2
N13 (7.3)	RE : 20/20 LE : 20/20	60”	1	0	−2
N14 (7.6)	RE: 20/20 LE: 20/20	60”	0	0	0
N15 (7.7)	RE: 20/20 LE: 20/20	30”	0	0	−4
N16 (7.7)	RE: 20/20 LE: 20/20	60”	3	0	0
N17 (8.5)	RE: 20/20 LE: 20/20	60”	3	2	2
N18 (8.8)	RE: 20/20 LE: 20/20	30”	3	0	2
N19 (8.8)	RE: 20/20 LE: 20/20	60”	3	2	0
N20 (9.0)	RE: 20/20 LE: 20/20	60”	4	0	−2
N21 (9.0)	RE: 20/20 LE: 20/20	30”	0	0	0
N22 (9.0)	RE: 20/20 LE: 20/20	60”	0	−2	−2
N23 (9.0)	RE: 20/20 LE: 20/20	60”	0	0	0
N24 (9.5)	RE: 20/20 LE: 20/20	60”	3	−1	−2
N25 (9.7)	RE: 20/20 LE: 20/20	60”	3	−4	−2
N26 (11.0)	RE: 20/20 LE: 20/20	60”	1	−2	−2

Data are reported for each of the 26 non-strabismic children who participated in this study (N1 to N26), whose age ranged from 4.2 to 11.0 years. LE, RE: left eye and right eye. The deviation of the eyes was assessed with the cover–uncover test and prism at far distance (5 m) and at near distance (30 cm); negative values represent a divergent deviation, positive values a convergent deviation. The binocular vision was evaluated with the TNO test for stereoscopic depth discrimination. The near point of convergence was examined by placing a small accommodative target at 30 cm in the midplane in front of the child and moving it slowly towards the eyes until one eye lost fixation

Spectral power indices in the antero-posterior and medio-lateral directions

Figure 2a reports the spectral power indices for postural sways in the antero-posterior direction (PIy) in all four conditions which were tested for both strabismic and non-strabismic children. As seen in the CoP results, the analysis of variance (ANOVA) showed first a significant difference between groups ($F_{(1.50)}=8.29$ $p<0.005$). Independent of the conditions, the PIy were systematically significantly higher in strabismic children than in non-strabismic children.

Analysis of variance (ANOVA) additionally showed a significant effect of vision ($F_{(1.50)}=7.82$, $p<0.007$). Independent of the group of children, the PIy were smaller when eyes were open.

ANOVA also showed a significant effect of frequency ($F_{(2.100)}=26.26$, $p<0.0001$). The PIy for low frequency were significantly higher than those recorded in the medium and high frequencies (both $p<0.0001$).

Analysis of variance (ANOVA) furthermore showed a significant interaction between posture and frequency ($F_{(2.100)}=10.72$, $p<0.0001$). The PIy for medium and high frequencies were found to be higher in the unstable condition than in the stable one (all $p<0.0001$).

No effect of the postural condition (stable vs unstable platform) was found.

Figure 2b shows the spectral power indices for postural sways in the medio–lateral direction (PIx), for all four conditions tested in strabismic children and non-strabismic children. The analysis of variance (ANOVA) again showed a significant difference between the groups ($F_{(1.50)}=4.49$, $p<0.03$). The spectral power index was systematically significantly higher in strabismic children than in non-strabismic children.

Analysis of variance (ANOVA) also revealed a significant effect of the postural condition ($F_{(1.50)}=10.28$, $p<0.002$), showing that its value was significantly higher in the unstable condition than in the stable one.

Additionally, the analysis of variance showed a significant effect on the frequency ($F_{(2.100)}=1881$, $p<0.0001$). Independent of the group or the condition, the PIx for low frequency were significantly higher than those recorded for medium and high frequencies (all $p<0.0001$).

Further, the analysis of variance (ANOVA) showed a significant interaction between group, vision and frequency ($F_{(2.100)}=3.54$, $p<0.03$): independent of condition, the PIx were significantly higher in strabismic children than in non-strabismic children, for all frequencies and for the “eyes closed” condition.

Altogether, these data confirm that both strabismic children and non-strabismic children are less stable when placed on an unstable platform while their eyes are closed, and that postural performances of strabismic children are significantly inferior to those of non-strabismic children. But they additionally

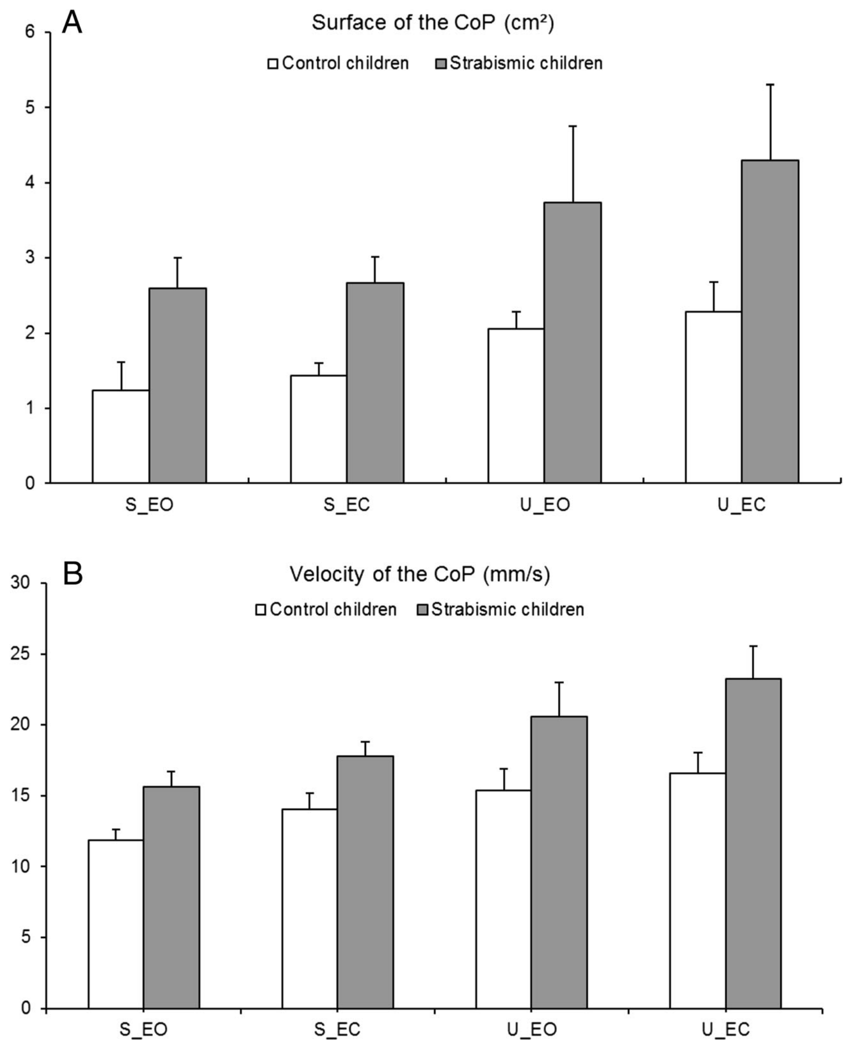


Fig. 1 Surface and mean speed of the CoP. Means and standard deviations of the surface area of the CoP in cm^2 (**a**) and of the mean velocity of CoP in cm/s (**b**) while strabismic and non-strabismic children were placed on stable (*S*) and unstable (*U*) platform, while their eyes were open (*EO*) or closed (*EC*)

allow us to demonstrate that the displacements of the CoP of strabismic children are altered in both the antero–posterior and the medio–lateral directions, whatever the frequency to which they are associated.

Cancelling times in antero–posterior and medio–lateral directions

The cancelling times (CT) were compared between groups, experimental conditions, directions of body sways, and frequencies.

Figure 3a shows the CT in the antero–posterior direction (CTy) for all four conditions that were tested for both strabismic and non-strabismic children. As above, the analysis of variance (ANOVA) showed a significant effect of group ($F_{(1.50)}$=4.08, p<0.04). The CTy appeared first to be significantly shorter in strabismic children than in non-strabismic children.

Analysis of variance (ANOVA) also showed a significant effect of vision ($F_{(1.50)}$=7.53, p<0.008) by revealing that, independent of the group, the CTy was longer in the "eyes open" condition.

Additionally, ANOVA showed a significant effect of frequency ($F_{(2.100)}$=202, p<0.0001), showing that the CTy for medium frequency was significantly longer than that recorded for low and high frequencies (all p<0.0001).

No effect of the postural condition (stable vs unstable platform) was found.

Finally, Fig. 3b reports the cancelling time in the medio–lateral direction (CTx), for all four conditions tested in strabismic and non-strabismic children. Analysis of variance (ANOVA) showed only a significant effect of frequency ($F_{(2.100)}$=38.36, p<0.0001). More precisely, it indicated that the CTx was significantly longer for low frequencies than for medium and high frequencies (all p<0.0001). Notice, however, that the CTx for medial frequencies were significantly higher than those for high frequencies.

With CT values being systematically inferior in strabismic subjects compared to non-strabismic subjects, these data strengthen the idea that the postural control of strabismic

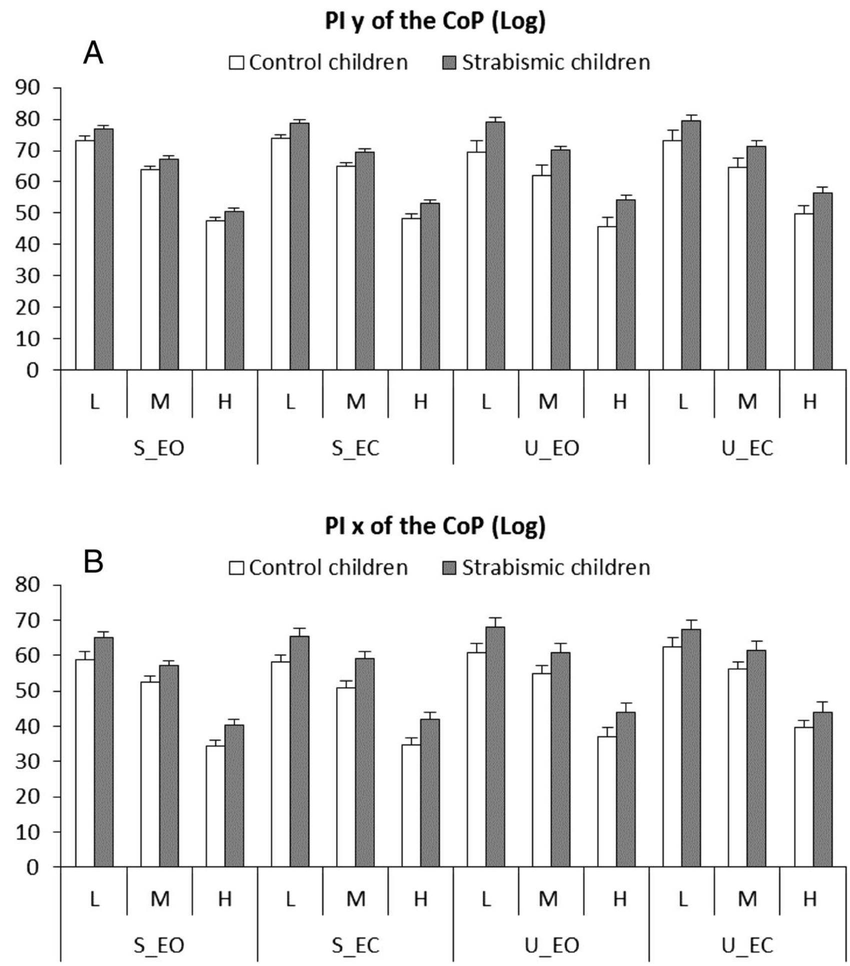


Fig. 2 Analysis of the frequencies of displacement of the CoP. The spectral power indices (*PI*) were calculated (in log) for postural movements in the antero-posterior (**a**) and the medio-lateral (**b**) directions of both strabismic and control subjects. As previously, they were placed under the different experimental conditions under study: *S_EO*, *S_EC*, *U_EO* and *U_EC*, with S and U for stable and unstable platform respectively while EO and EC corresponding to the conditions "eyes open" and "eyes closed" respectively. For each condition, three classes of frequency band were distinguished: *L*, low, *M*, medium, and *H*, high. To allow comparison between groups and conditions, the mean and the standard deviations of each IP were systematically calculated

children is altered compared to non-strabismic children both in the antero–posterior (y) and the medio–lateral (x) directions, even if the eyes are open. However, the data also show that the postural control is better for body sways with medial frequencies in the antero–posterior direction and for body sways with low frequencies in the medio–lateral direction. They also establish that, in all cases, the postural control is worst for the highest frequencies.

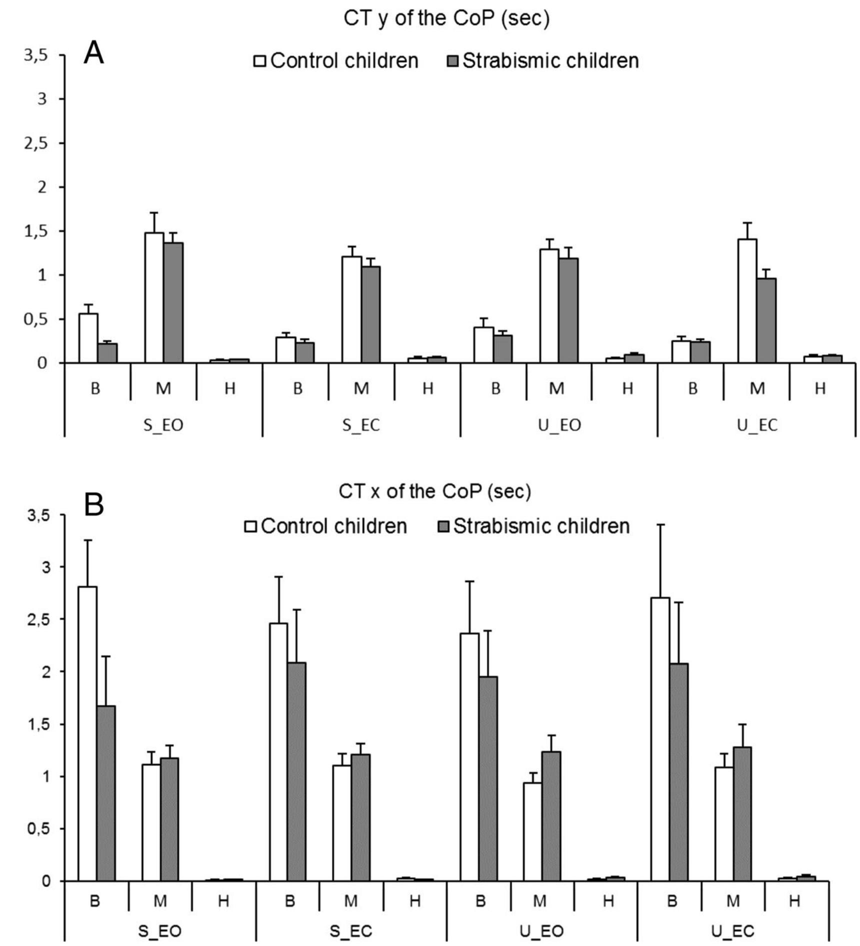
Discussion

The main findings of this study are as follows: *(i)* data obtained through temporal analyses of posture have confirmed those obtained through spatial analyses, i.e., that postural control is poor in strabismic children compared to that of age-matched non-strabismic children, *(ii)* postural control changes as a function of condition: for both groups of children, stability is better with eyes open on the stable platform, and *(iii)* different postural strategies are used by strabismic children as opposed to non-strabismic children. These findings are discussed individually below.

Strabismic children are more unstable than non-strabismic children

Through the spatial analysis of posture, we found that the surface and the mean velocity of the CoP are significantly larger in strabismic children than in non-strabismic age-matched children. Additionally, through the temporal analysis of posture, we showed that the spectral power indices and the cancelling times in the antero–posterior and the medio–lateral directions are respectively higher and shorter in strabismic than in non-strabismic children. All of the data for each axis showed the same effect, demonstrating that the posture of strabismic children is less stable than the posture of non-strabismic children. Such data confirm previous findings about postural control in strabismic children [10–13]. However, most of these studies did not compare strabismic children with age-matched non-strabismic children. Recently, Lions et al. [14] showed that postural stability in strabismic children (with and without binocular vision) was poor when compared to non-strabismic children of the same age. Subsequently, these same authors also demonstrated that strabismic children use more proprioceptive information to compensate for their visual deficit than non-strabismic age-matched children to control their posture [15].

Fig. 3 Cancelling times of each frequency band during antero–posterior and medio–lateral body sways. Means and standard deviations of the cancelling time (in sec) in the antero-posterior (**a**) and medio–lateral (**b**) directions for each frequency (*B*, low, *M*, medium and *H*, high) in all conditions tested for strabismic and non-strabismic children (*S_EO*, *S_EC*, *U_EO*, *U_EC*, as defined as in Fig. 2)



Altogether, such data strongly suggest that impairment of the postural control in strabismic children results from their poor visual input.

Stability is better with eyes open on the stable platform for both groups of children

Whether we applied the spatial or the temporal analysis of posture, we have demonstrated here that postural stability is the poorest when children (strabismic and non-strabismic children) have their eyes closed: the surface area of the CoP and the mean velocity of the CoP values are higher in such a "non-visual" situation. The spectral power indices and the cancelling times for both antero–posterior and medio–lateral body sways are also respectively larger and shorter when both eyes are closed. This is in line with studies by Assaiante and Amblard [28] and Shumway-Cook and Woollacott [29] showing the important role of vision for visually unimpaired children in controlling their posture. This also aligns with Matsuo et al., who showed that strabismic subjects display better postural control with their eyes open [11]. Even if it is impaired, vision in strabismic children thus still contributes to stabilize postural equilibrium.

On the other hand, the surface and the mean velocity of CoP have been found to be significantly higher when children (both strabismic and non-strabismic) are standing on an unstable platform compared to a stable one. The spectral power indices and the cancelling times for both the antero–posterior and the medio–lateral directions were also found to be respectively higher and shorter in the unstable condition compared to the stable one. These results are new and suggest that, in this unstable condition, when plantar proprioceptive information is misleading, it is more difficult to maintain good balance, especially for strabismic children. As reported in our previous work, proprioceptive inputs are important for controlling posture, particularly in the strabismic population [15]. Consequently, when such information is not correct, children have more difficulties in controlling their stability.

Strabismic children use different postural strategies with respect to non-strabismic children

The most interesting novelty in this study is the use of the temporal analysis of the CoP. To our knowledge, it is the first time that the postural control in strabismic children has been quantified in this way. As previously outlined above, both the spectral power indices and the cancelling times of body sway that were established in that context first made it possible to confirm data that were established using the spatial analyses, which validates the method. In both cases, strabismic children are shown to be less stable than non-strabismic children, in particular when the eyes are kept closed. However, the temporal analysis additionally permitted new and complementary information to be obtained, in particular in respect of the various frequencies of the body sways, and thus the energy spent to stabilize posture, in both experimental groups and in the different conditions. Of great interest is that the comparison of these frequencies allowed a better understanding of the way(s) in which the body compensates the postural anomalies causes by strabismus. Strabismic children have been found to have a significantly higher spectral power index than age-matched non-strabismic children. Thus, they engage more energy in ensuring a good postural control than non-strabismic age-matched children. This aligns with spatial data obtained by measuring the mean velocity of the CoP. Through temporal analysis, we have also shown that this occurs both in the antero–posterior and the medio–lateral directions, whatever the frequency of the body sways.

We also found in both groups (strabismic and non-strabismic children) that the spectral power index is significantly higher for low frequencies than for medium and high frequencies. This strengthens the idea that the most important inputs for controlling postural stability are the visual and vestibular information, while proprioceptive inputs (which are believed to be associated with high frequencies [17, 19]) are less important.

Finally, we have shown that the cancelling time, which allowed quantifying the body sways in the antero–posterior direction, was systematically shorter in strabismic children compared to non-strabismic children. This held true for all three examined frequencies. This confirms a poorer postural control in strabismic children compared to non-strabismic children. As discussed above, the longer the cancelling time is, the better the postural control, due to the fact that it is the time required to use sensorial inputs to maintain efficiently postural control. According to previous works by Dumitrescu and Lacour [24] and Bernard-Demanze [19], a shorter cancelling time as reported in strabismic children could suggest a low use of sensorial information and thus poor postural control. The fact that we have observed such abnormal values in one direction only (antero–posterior) could be related to the fact that in such a direction, the visual inputs are mostly used to obtain good balance control and strabismic children are lacking in such normal input.

Conclusion

Our data show that strabismic children are less stable than non-strabismic children, and that they engage more energy in assuring good postural control. Both spatial and temporal analyses confirm that postural control is poor in strabismic children with respect to age-matched non-strabismic children. Postural control changes depended on the condition: for both groups of children, stability is better with eyes open on the stable platform. However, temporal analysis of the CoP revealed different postural strategies used by strabismic children compared to non-strabismic children.

It might be interesting to explore further the postural control in strabismic children in the future by using a larger population and comparing different types of strabismus (convergent and divergent strabismus), with and without binocular vision. It would also be interesting to study the evolution of the postural control 2 months after realignment of ocular axes through surgery, and to quantify any eventual postural improvement.

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Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements) or non-financial interest (such as personal or professional relationships, affiliations, knowledge, or beliefs) in the subject matter or materials discussed in this manuscript.

References

1. Leigh RJ, Zee DS (2006) The neurology of eye movements. Oxford University Press, New York
2. Massion J (1994) Postural control system. Curr Opin Neurobiol 4: 877–887
3. Mergner T, Rosemeier T (1998) Interaction of vestibular, somatosensory and visual signals for postural control and motion perception under terrestrial and microgravity conditions–a conceptual model. Brain Res Brain Res Rev 28:118–135
4. Brandt T (2003) Vertigo: its multisensory syndromes. Springer, New York
5. Peterka RJ (2002) Sensorimotor integration in human postural control. J Neurophysiol 88:1097–1118
6. Mergner T, Maurer C, Peterka RJ (2002) Sensory contributions to the control of stance: a posture control model. Adv Exp Med Biol 508:147–152
7. Bernard-Demanze L, Burdet C, Berger L, Rougier P (2004) Recalibration of somesthetic plantar information in the control of undisturbed upright stance maintenance. J Integr Neurosci 3:433–451

8. Carver S, Kiemel T, Jeka JJ (2006) Modeling the dynamics of sensory reweighting. Biol Cybern 95:123–134. doi:10.1007/s00422-006-0069-5
9. Williams C, Northstone K, Howard M et al (2008) Prevalence and risk factors for common vision problems in children: data from the ALSPAC study. Br J Ophthalmol 92:959–964. doi:10.1136/bjo.2007.134700
10. Odenrick P, Sandstedt P, Lennerstrand G (1984) Postural sway and gait of children with convergent strabismus. Dev Med Child Neurol 26:495–499
11. Matsuo T, Narita A, Senda M et al (2006) Body sway increases immediately after strabismus surgery. Acta Med Okayama 60:13
12. Matsuo T, Yabuki A, Hasebe K et al (2010) Postural stability changes during the prism adaptation test in patients with intermittent and constant exotropia. Invest Ophthalmol Vis Sci 51:6341–6347
13. Legrand A, Quoc EB, Vacher SW et al (2011) Postural control in children with strabismus: Effect of eye surgery. Neurosci Lett 501:96–101. doi:10.1016/j.neulet.2011.06.056
14. Lions C, Bui-Quoc E, Bucci MP (2013) Postural control in strabismic children versus non strabismic age-matched children. Graefes Arch Klin Exp Ophthalmol 251:2219–2225. doi:10.1007/s00417-013-2372-x
15. Lions C, Bui Quoc E, Wiener-Vacher S, Bucci MP (2014) Postural control in strabismic children: importance of proprioceptive information. Integr Physiol 5:156. doi:10.3389/fphys.2014.00156
16. Ghulyan V, Paolino M, Lopez C et al (2005) A new translational platform for evaluating aging or pathology-related postural disorders. Acta Otolaryngol (Stockh) 125:607–617. doi:10.1080/00016480510026908
17. Lacour M, Bernard-Demanze L, Dumitrescu M (2008) Posture control, aging, and attention resources: models and posture-analysis methods. Neurophysiol Clin Neurophysiol 38:411–421. doi:10.1016/j.neucli.2008.09.005
18. Yelnik A, Bonan I (2008) Clinical tools for assessing balance disorders. Neurophysiol Clin Clin Neurophysiol 38:439–445. doi:10.1016/j.neucli.2008.09.008
19. Bernard-Demanze L, Dumitrescu M, Jimeno P et al (2009) Age-related changes in posture control are differentially affected by postural and cognitive task complexity. Curr Aging Sci 2:139–149
20. Gouleme N, Gerard CL, Bui-Quoc E, Bucci MP (2014) Spatial and temporal analysis of postural control in dyslexic children. Clin Neurophysiol Off J Int Fed Clin Neurophysiol. doi:10.1016/j.clinph.2014.10.016
21. Chiari L, Rocchi L, Cappello A (2002) Stabilometric parameters are affected by anthropometry and foot placement. Clin Biomech Bristol Avon 17:666–677
22. Maki BE, Holliday PJ, Fernie GR (1990) Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc 38:1–9
23. Geurts AC, Nienhuis B, Mulder TW (1993) Intrasubject variability of selected force-platform parameters in the quantification of postural control. Arch Phys Med Rehabil 74:1144–1150
24. Dumitrescu M, Lacour M (2004) Analyse mathématique par décomposition en ondelettes des signaux stabilométriques. Avantages par rapport à l'approche classique de la FFT. Nouvelles méthodes de traitement du signal posturographique, Michel Lacour. Solal Editeur, Marseille
25. Nashner LM (1979) Organization and programming of motor activity during posture control. Prog Brain Res 50:177–184. doi:10.1016/S0079-6123(08)60818-3
26. Kohen-Raz R, Himmelfarb M, Tzur S et al (1996) An initial evaluation of work fatigue and circadian changes as assessed by multiplate posturography. Percept Mot Skills 82:547–557
27. Paillard T, Costes-Salon C, Lafont C, Dupui P (2002) Are there differences in postural regulation according to the level of competition in judoists? Br J Sports Med 36:304–305
28. Assaiante C, Amblard B (1993) Ontogenesis of head stabilization in space during locomotion in children: influence of visual cues. Exp Brain Res 93:499–515. doi:10.1007/BF00229365
29. Shumway-Cook A, Woollacott MH (1985) The growth of stability: postural control from a development perspective. J Mot Behav 17:131–147