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Review

Spatial and temporal postural analysis: a developmental study in healthy children

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ABSTRACT

The aim of this study was to explore further the development of postural control in healthy children. The novelty of this study was to resort to both spatial and temporal analysis of the center of pressure (CoP).

Forty-six healthy children from 4 to 16 years old (mean age: 9.1 ± 3 years) and a group of 13 healthy adults (mean age: 25 ± 3 years) participated to this study. Postural control was tested on both a stable and an unstable platform in three different visual conditions: eyes open fixating a target, under optocinetic stimulation, and eyes closed.

Resul*ts showed a significant decrease of both surface area as well as mean velocity of the center of pressure (CoP) during childhood. With the children's increasing age, the spectral power indices decreased significantly and the canceling time increased significantly.

Such improvement in postural control could be due to a better use of sensorial inputs and cerebellar integration during development, allowing subjects to achieve more efficient postural control.

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1. Introduction

Postural control is maintained in accordance with depending to the perception of our environment. In case of disturbances, there is a compensatory answer to maintain postural control. However, this compensatory answer is intimately linked to evaluation of afferent information: vestibular, visual and proprioceptive from our sensorial input (Diener et al., 1986). Indeed, postural control involves an intricate relationship between sensory information from sensorial input and motor activity (Lacour and Borel, 1993). In everyday life, quiet standing is a rather simple postural task that is regulated automatically by subcortical nervous structures and spinal motoneuronal pools (Massion, 1994). Multisensory feedback serves to regulate posture control by continuously updating the internal model of the body's position, and this model changes the motor commands responding to the environmental context and to any constraints (Mergner and Rosemeier, 1998). To maintain a good postural control humans have to integrate multisensory inputs: vestibular, visual and proprioceptive information (Brandt, 2003).

Several studies on postural development reported age-related changes in healthy children. For instance Forssberg and Nashner (1982), using two platforms – one for each foot – and EMG recording, showed that children under 7.5 years are already able to control their postural stability; however, in case of environment changes (dynamic support), children below 7.5 years are not able to adapt their motor response and to re-weigh sensorial information in order to maintain an efficient postural control. Based on these findings, these authors suggested that automatic processes to maintain postural stability develop early in children and involve lower cognitive capabilities, while adaptive processes necessary for adjusting to environmental changes develop later during childhood and adolescence. Shumway-Cook and Woollacott (1985) conducted an EMG and cinematography study to examine postural control 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 is variable and at this age children use visual information to stabilize their posture. It is only at about 7–10 years that children develop postural strategies similar to those reported in adults, integrating both vestibular and proprioceptive inputs.

A more recent study by Cuisinier et al. (2011) compared postural stability in children from 7 to 11 years old and in a group of young adults (mean age: 25 years old), and showed an improvement in postural stability with age. Moreover, these authors showed that when a somatosensory perturbation was applied (vibration on the ankle) the velocity of CoP of children increased significantly, while those of adults did not change. This result suggested that the ability to compensate and re-weigh sensorial inputs to maintain postural stability develops later on in children, after 11 years. Furthermore, a study by Barozzi et al. (2014) analyzed postural stability by testing different conditions (eyes open, eyes closed, with and without foam pads under the feet) in a large population of healthy children (289) divided into two groups of age (one from 6 to 10 years old and another from 11 to 14 years old) and they compared these results to those of a group of 30 healthy young adults. These authors showed an improvement of postural stability with age independently of the conditions tested; quite importantly, they also reported that at 13–14 years of age postural stability had not achieved the adult level, suggesting that the maturation of central and peripheral structures responsible for postural control are still developing during adolescence.

Nonlinear analysis methods such as the wavelet transformation method (Tinetti, 1986) and the stabilogram-diffusion analysis (Daubechies, 1991) are frequently used for investigating posture control. Such analysis reveals effects in the dynamics of the postural control system that are not shown by the more traditional posturography method based on spatial analysis only. A study by Ghulyan et al. (2005) has demonstrated that dynamic postural analysis allowed a better discrimination of age effect on posture. Moreover, Lacour et al. (2008) have described the limits of the traditional static posturography method, suggesting that the spatial analysis of the center of pressure could lead to misevaluations of the balance control system. They support the hypothesis of the usefulness and physiological relevance of the additional parameters provided by the wavelet analysis. As shown by Bernard-Demanze et al. (2009), the use of wavelet transformation for exploring postural control is very relevant. Indeed, such analysis could reveal deficits or changes in the postural system that are not shown by the more traditional posturography done with static spatial analysis.

Hong et al. (2008) compared postural strategies applying dynamic analysis to two groups of children of 6 and 10 years old and to a group of young adults (18–23 years old). Subjects were asked to stay sitting on a chair with and without support under their feet; a force platform was used to record the antero-posterior and medio-lateral direction displacement of CoP. In line with previous works, they found that the path length of CoP decreased with age. The new finding of this study was that the postural dynamic analysis showed a significant increase in relative entropy of sway motion in the adult group compared to the younger children group. These authors suggested that the changes in the dynamics of sitting postural sway in young children (compared to that of adults) could be due to their motor experiences.

Based on all these findings, the present study aims to explore further the development of postural control in healthy children, using not only analysis in the spatial domain (classical analysis used in the majority of studies dealing with developmental postural examination) but also temporal analysis (wavelet transformation). Also, in order to know better how visual, vestibular and proprioceptive information develop during childhood, different visual as well as postural conditions were used.

2. Methods

2.1. Participants

Forty-six healthy children and teenagers (20 males and 26 females) from 4.2 to 16.8 years, with a mean age of 9.3 ± 3 years and a median age of 9 years (IQR = 4.75 years), participated to the study. A group of 13 healthy young adults from 20.4 to 32.4 years with a mean age of 25 ± 3 years and a median age of 24.8 years (IQR = 2.5 years) was also examined. All participants were voluntary and were recruited among friends and relatives of personnel working in the hospital, or they were healthy children accompanying brothers or sisters to the hospital. Young adult subjects were part of the medical and paramedical staff of the hospital. All participants had to fulfill the following criteria: no known neurological or psychiatric abnormalities, no balance disorders and no visual stress or difficulties with either near or far vision. Exclusion criteria were drug treatment or orthopedic abnormality.

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 I). Written informed consent was obtained from children's parents and from adult subjects after the nature of the procedure had been explained.

2.2. Materials

Postural performances of subjects were evaluated using Multitest Equilibre (also called Balance Quest) from Framiral® and a static/dynamic platform by Micromedical Technologies (www.framiral.fr). It consisted of a force plate mounted on a translator, which allowed for a subject's translation in the antero-posterior (y) or medio-lateral direction (x). A computer-controlled mechanism allows the platform to make sinusoidal displacements of a 62 mm amplitude with adjustable velocities and frequencies. 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 static and dynamic conditions, respectively, and digitized with 16-bit precision (Ghulyan et al., 2005; Bernard-Demanze et al., 2009).

2.3. Postural recording procedure

Subject was in a dark room on the Framiral® platform. He/she was positioned on the platform, with parallel feet placed on the footprints, arms along the body, and shoulders apart (between 10 and 32 cm).

Postural recording was performed on stable (S) and unstable (U) platform with three different viewing conditions: eyes open fixating a target (EO), eyes closed (EC) and eyes open with perturbed vision (optocinetic stimulation, OPTO). During the eyes open condition subject had to fixate a small red light at distance of 250 cm. The optocinetic stimulation was performed by an optocinetic ball that was projected on a wall at a distance of 250 cm from the subject's eyes and turned with 158 per s angular speed (Ionescu et al., 2006). The duration for each postural recording was 30 s, with a 15-s rest period between each condition to reduce possible fatigue effect. The order of the conditions varied randomly across subjects. Subjects were asked to stay as stable as possible.

2.4. Classical analysis in spatial domain

The surface area (cm^2) and the mean velocity (mm/s) of the center of pressure (CoP) were analyzed in order to quantify postural performance. The surface area of CoP is an efficient measure of CoP spatial variability, corresponding to an ellipse with 90% of CoP excursions (Chiari et al., 2002). The mean velocity of the CoP represents a good index of the amount of neuromuscular activity required to regulate postural control (Maki et al., 1990; Geurts et al., 1993). 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.

2.5. Temporal analysis, wavelet transformation

We applied a wavelet analysis to study the frequency of the CoP displacements. This analysis and associated parameters were obtained from Framiral (www.framiral.fr; see Dumistrescu and Lacour, 2006; Bernard-Demanze et al., 2009).

The spectral power index was calculated as the decimal logarithm for the frequency bands 0.05–0.5 Hz, 0.5–1.5 Hz, higher than 1.5 Hz on the antero-posterior and medio-lateral sways (PI*y* and PI*x*, respectively). The spectral power index in the higher band is minimal in healthy subjects during quiet standing, but it can be observed with aging, in postural pathology or in dynamic postural conditions (Nashner, 1979). The hypothetical physiological significance of the different bands is as follows: 0–0.5 Hz visual-vestibular (Nashner, 1979; Kohen-Raz et al., 1996; Paillard et al., 2002), 0.5–1.5 Hz cerebellar (Paillard et al., 2002) and 1.5 Hz reflexive loops (Lacour et al., 2008; Bernard-Demanze et al., 2009).

Moreover the canceling time (CT) of each frequency band was also calculated for the antero-posterior (CT*y*) and medio-lateral (CT*x*) sway, *i.e.*, the total time during which the spectral power index of the body sway for the frequency range was canceled by the posture control mechanisms; the longer the canceling time of a frequency band, the better the posture control (Dumistrescu and Lacour, 2006; Bernard-Demanze et al., 2009). Canceling time is the time required to use sensorial inputs for controlling posture. Thus, the longer this time to maintain postural control, the more children use sensorial information. A short canceling time reveals a low quest time of sensorial inputs and thus a poor use of such information to maintain postural control.

2.6. Statistical analysis

Data were analyzed using the linear regression models with classical data in spatial domain and frequency analysis for all conditions tested (EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U). Predictor variables for each test were the subjects' age (in years). The effect of a factor was considered as significant when the p-value was below 0.05. Statistical analysis using two-way ANOVAs was also applied in order to compare the different visual and postural conditions (EO, EC and OPTO on static (S) and unstable support (U), respectively). The effect of a factor is significant when the *p*-value is below 0.05.

3. Results

3.1. Classical postural data in spatial domain

3.1.1. Surface of CoP

Fig. 1 shows the surface area of CoP (cm^2) in each condition tested (respectively EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U) as a function of the age of each subject tested and the regression line.

There is a significant effect of age: the surface of CoP decreased significantly while the age of subject increased. The R^2 value reached significance for the surface of CoP measured in all conditions tested on stable platform (EO, EC and OPTO, respectively $R^2 = 0.11$, $p < 0.01$; $R^2 = 0.12$, $p < 0.01$; $R^2 = 0.18$, $p < 0.04$). Moreover, the R^2 value reached significance for the surface of CoP measured in two unstable conditions: EC and OPTO (respectively $R^2 = 0.07$; $R^2 = 0.16$, all $p < 0.03$).

The analysis of variance (ANOVA) showed a significant effect of postural condition ($F_{(1,58)} = 14.06$, $p < 0.001$). Independently of age, the surface of CoP was significantly larger in unstable than in stable condition ($p < 0.001$). Moreover, the analysis of variance (ANOVA) showed a significant effect of visual condition ($F_{(2,116)} = 7.17$, $p < 0.001$): the surface of CoP was significantly smaller in eyes open and in eyes closed condition than in perturbed vision condition (all $p < 0.001$).

3.1.2. Mean velocity of CoP

Fig. 2 shows the mean velocity of CoP (mm/s) in all conditions tested (respectively EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U) as a function of the age of each subject tested and the regression line.

There is a significant effect of age: that the mean velocity of CoP decreased significantly while the age of subjects increased. The R^2 value reached significance for the mean velocity of CoP measured in all conditions tested on stable platform (EO-S, EC-S and OPTO-S, respectively $R^2 = 0.41$; $R^2 = 0.40$; $R^2 = 0.40$, all $p < 0.01$). Moreover, the R^2 value reached significance for the mean velocity of CoP measured in two unstable conditions: EC-U and OPTO-U (respectively $R^2 = 0.08$; $R^2 = 0.06$, all $p < 0.03$).

The analysis of variance (ANOVA) showed a significant effect of postural condition ($F_{(1,58)} = 23.24$, $p < 0.001$). Independently of age, the mean velocity of CoP was significantly greater in unstable condition than in stable condition ($p < 0.001$). Moreover, the analysis of variance (ANOVA) showed a significant effect of visual condition ($F_{(2,116)} = 7.44$, $p < 0.001$): the mean velocity of CoP was significantly smaller in eyes open than in eyes closed condition ($p < 0.001$). Also, the mean velocity of CoP was significantly smaller in eyes open than with perturbed visual condition ($p < 0.002$).

3.2. Temporal analysis, wavelet transformation

3.2.1. Spectral power indices

Fig. 3 shows the spectral power indices in antero-posterior direction (Fig. 3A) and in medio-lateral direction (Fig. 3B, respectively PI*y* and PI*x*) for each frequency (L: low, M: medium and H: high) in all conditions tested (respectively EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U) as a function of the age of each subject tested and the regression line.

In the antero-posterior direction, there was a significant effect of age: the PI*y* decreased significantly while the age of subjects increased. On stable platform, for the three visual conditions tested, the R^2 value reached significance in all frequency bands (all

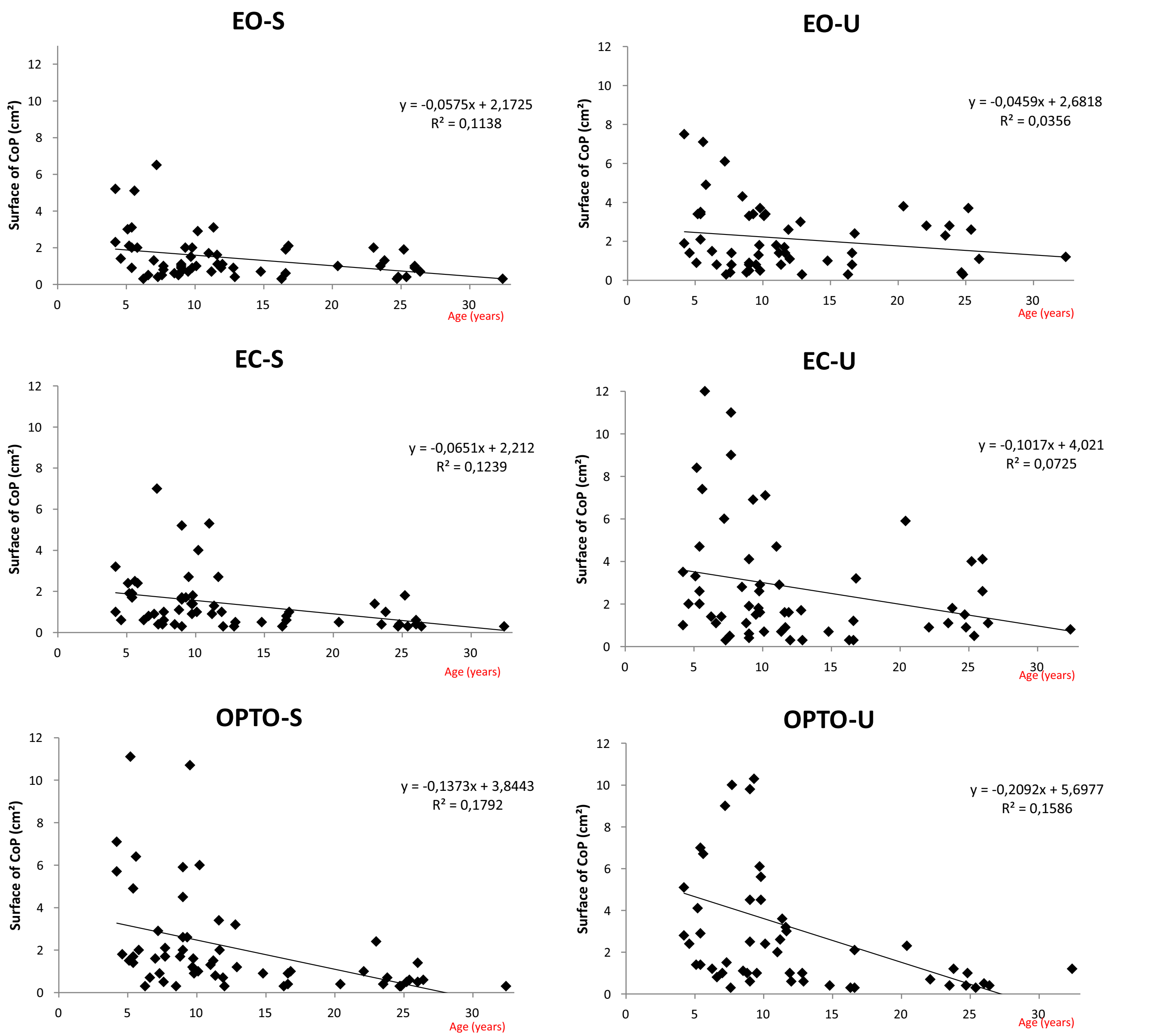

Fig. 1. Surface of CoP in cm^2 in the six conditions (eyes opened, EO, eyes closed EC and with optocinetic stimulation OPTO) on stable (S) and unstable (U) platform for each subject tested. Line represents the corresponding regression.

$R^2 < 0.42$, all $p < 0.01$). There was no significant effect of age in any unstable condition.

In medio-lateral direction there was a significant effect of age showing that the PI*x* decreased significantly while the age of subjects increased. The R^2 value reached significance in EO condition on stable platform for low and high frequencies (respectively $R^2 = 0.08$, $p < 0.02$ and $R^2 = 0.22$, $p < 0.01$), in all frequencies in EC condition (respectively $R^2 = 0.11$; $R^2 = 0.21$; $R^2 = 0.22$, all $p < 0.01$) and in OPTO condition for low and medium frequencies (respectively $R^2 = 0.21$; $R^2 = 0.30$, all $p < 0.01$). Moreover, on unstable platform the R^2 value reached significance for low and high frequencies in OPTO condition (all $R^2 = 0.07$, all $p < 0.02$).

The analysis of variance (ANOVA) showed a significant effect of visual condition ($F_{(2,116)} = 4.35$, $p < 0.02$): the spectral power index in antero-posterior direction (PI*y*) was significantly higher in perturbed visual condition than in eyes open and eyes closed condition (respectively $p < 0.004$ and $p < 0.05$). The analysis of variance (ANOVA) also showed a significant effect of postural condition ($F_{(1,58)} = 4.49$, $p < 0.03$). Independently of age, the spectral power index in medio-lateral direction (PI*x*) was significantly smaller in stable than in unstable condition ($p < 0.03$). However, there is no significant effect of visual condition on spectral power index in medio-lateral direction (PI*x*).

3.2.2. *Canceling time*

Fig. 4 shows the canceling time in antero-posterior (Fig. 4A) and in medio-lateral direction (Fig. 4B, respectively CT*y* and CT*x*) for each frequency (L: low, M: medium and H: high) in all conditions tested (respectively EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U) as a function of the age of each subject tested and the regression line.

There was a significant effect of age of the CT*y*: the CT*y* value increased significantly while the age of subjects increased. The R^2 value reached significance for the CT*y* measured in all conditions tested (EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U) for low frequency (all $R^2 < 0.03$, all $p < 0.01$).

There was no significant effect of age on CT*x*.

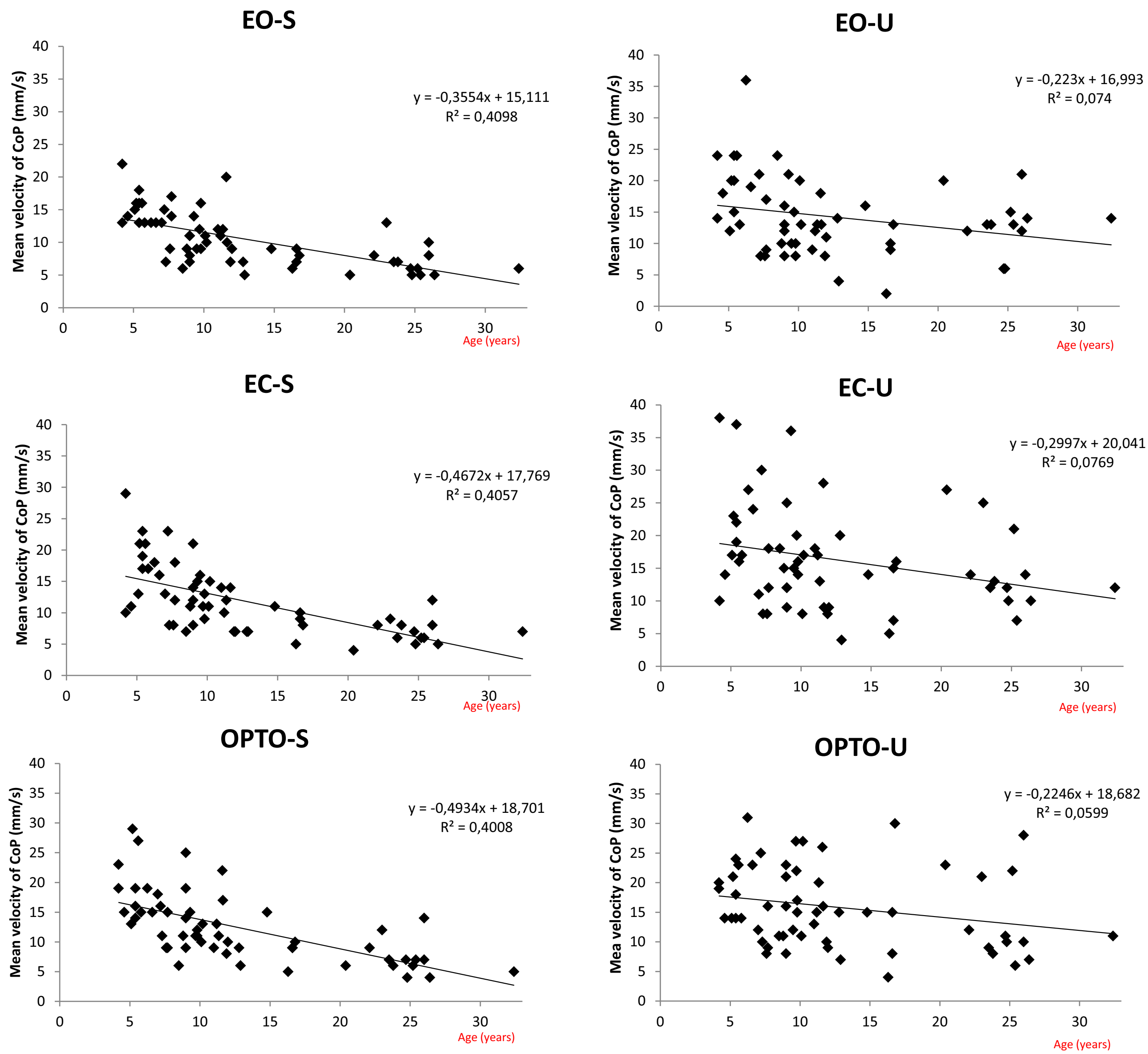

Fig. 2. Mean velocity of CoP in mm/s in the six conditions (eyes opened, EO, eyes closed EC and with optocinetic stimulation OPTO) on stable (S) and unstable (U) platform for each subject tested. Line represents the corresponding regression.

The analysis of variance (ANOVA) showed a significant effect of visual condition ($F_{(2,116)} = 3.24$, $p < 0.04$). Independently of age, the canceling time in antero-posterior direction (CT*y*) was significantly longer in eyes open than in eyes closed condition ($p < 0.01$).

The analysis of variance (ANOVA) also showed a significant effect of postural condition ($F_{(1,58)} = 4.97$, $p < 0.03$). Independently of age, the canceling time in medio-lateral direction (CT*x*) was significantly shorter in stable than in unstable condition ($p < 0.03$). Moreover, the analysis of variance (ANOVA) shows a significant effect of visual condition ($F_{(2,116)} = 3.36$, $p < 0.04$): the canceling time in medio-lateral direction was shorter in eyes open than in perturbed visual condition ($p < 0.01$).

4. Discussion

The main findings of this study are summarized in Table 1 and are as follows: (i) spatial domain analysis showed a significant decrease of surface and mean velocity of the CoP as subjects' age increased; (ii) the PI analyzed by wavelet transformation in medio-lateral and antero-posterior direction decreased significantly with increasing age of subjects; (iii) the CT in antero-posterior direction only increased with age. These findings are discussed individually below.

Table 1
Summary of the most important results. Significant effect of age, of the postural and of the visual conditions is shown for each postural parameter analyzed (surface and mean velocity of the CdP, spectral power indices and the canceling time in both *y* and *x* directions).

Postural parameters	Effect of age	Effect of postural condition	Effect of visual condition
Surface area of the CoP	X	X	X
Mean velocity of the CoP	X	X	X
PI*y*	X		X
PI*x*	X	X	
CT*y*	X		X
CT*x*		X	X

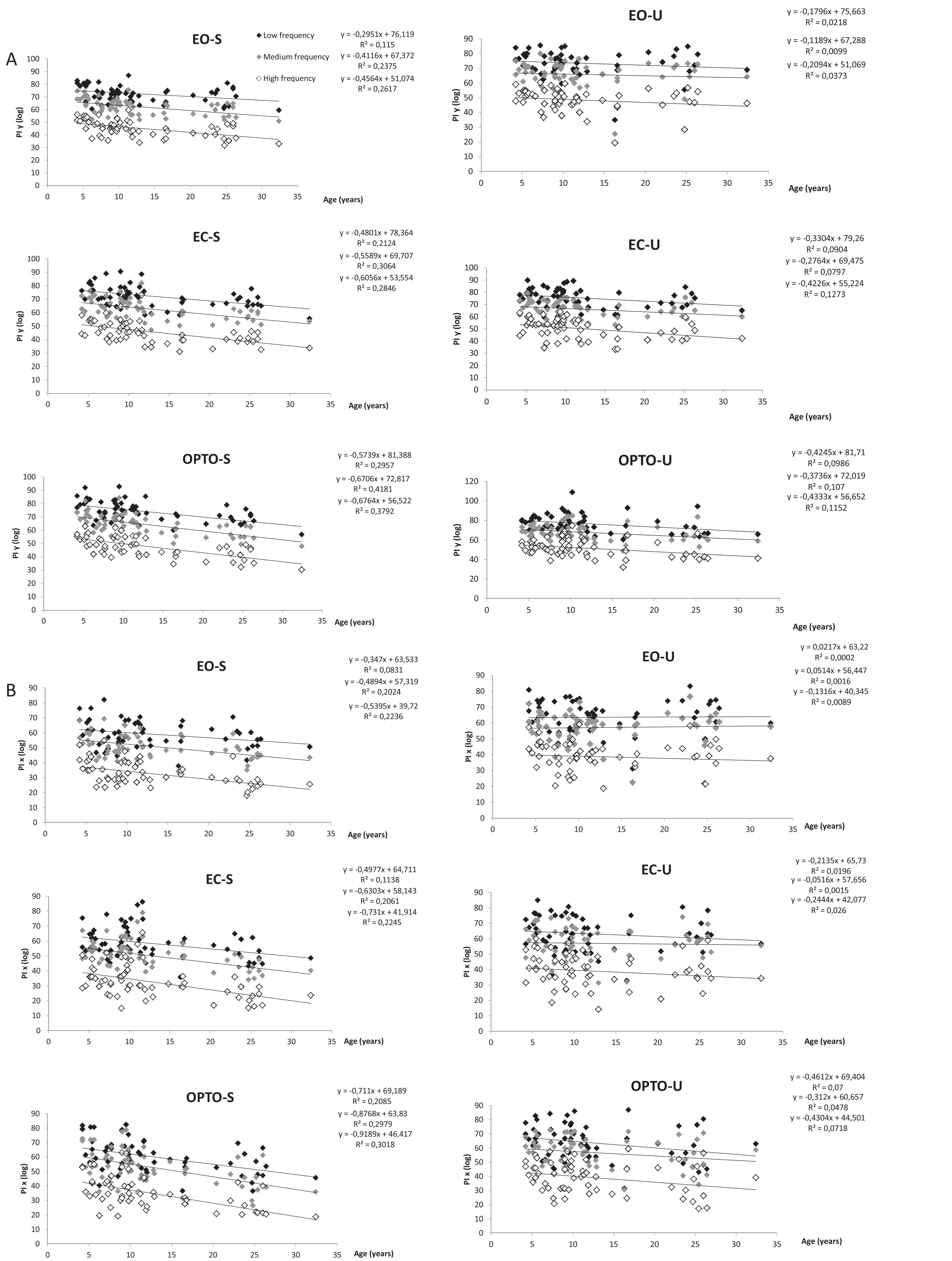

Fig. 3. Spectral power indices in antero-posterior direction (A) and in medio-lateral direction (B) (respectively PI*y* and PI*x*), for each frequency band (L, low, M, medium and H, high) in all conditions tested (EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U), for each subject tested. Line represents the corresponding regression.

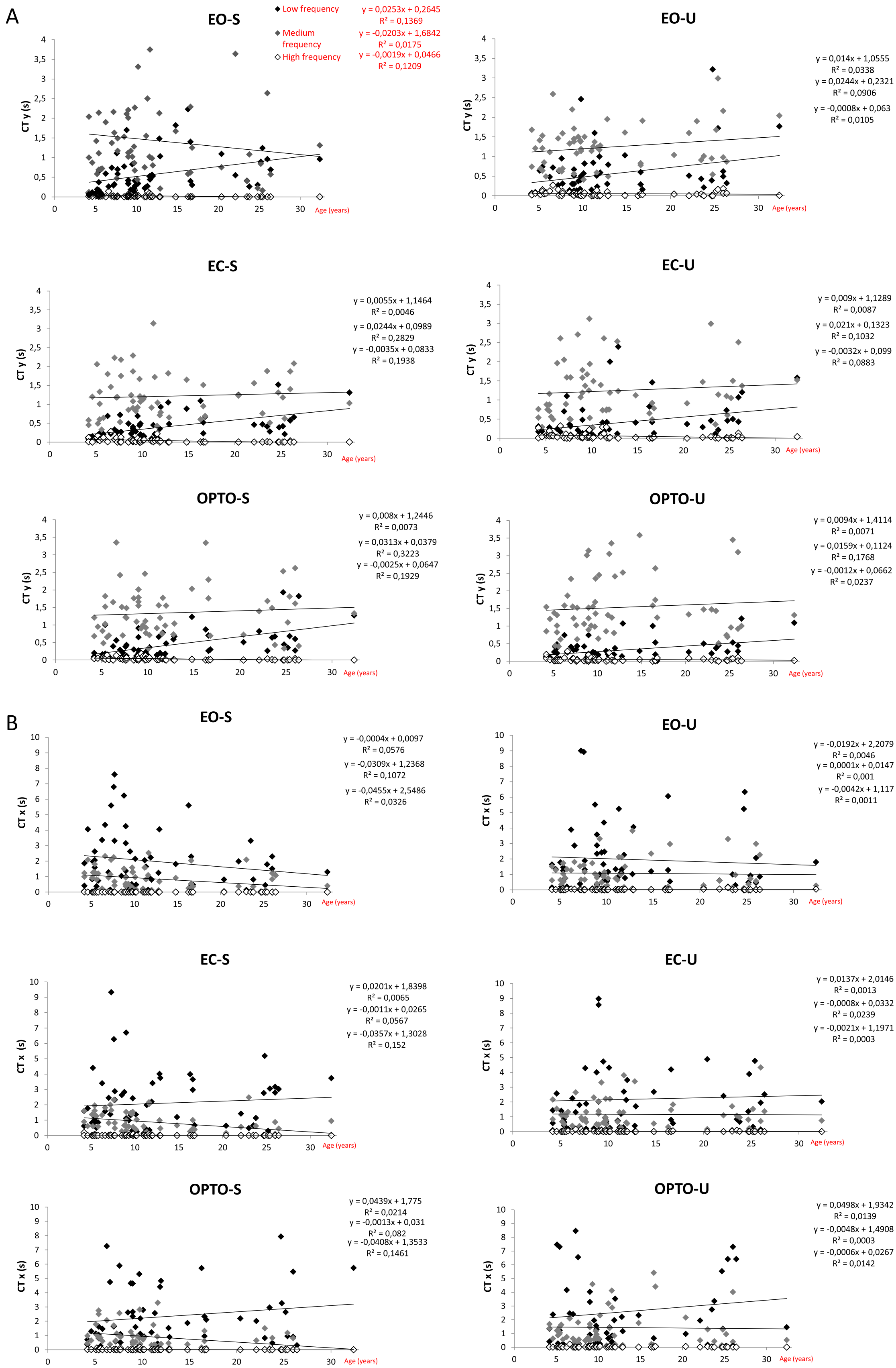

Fig. 4. Canceling time in antero-posterior direction (A) and in medio-lateral direction (B) (respectively CT*y* and CT*x*), for each frequency (L, low, M, medium and H, high) in all conditions tested (EO-S, EC-S, OPTO-S, EO-U, EC-U and OPTO-U), for each subject tested. Line represents the corresponding regression.

4.1. Spatial domain analysis showed a decrease of surface and mean velocity of the CoP with increase of subject's age

This study enlarges previous studies already cited in the introduction, exploring the development of postural control in healthy children and showing a significant decrease of the surface and mean velocity of CoP with age (Forssberg and Nashner, 1982; Shumway-Cook and Woollacott, 1985; Harbourne and Stergiou, 2003; Hong et al., 2008; Cuisinier et al., 2011; Ajrezo et al., 2013; Barozzi et al., 2014). Moreover, the study by Faigenbaum et al. (2014) showed that the dynamic postural control analysis is useful for the study of feasibility and reproducibility of postural measurements. Indeed, these authors reported low variability between different measurements in 188 healthy children from 6.9 to 12.1 years. This study suggested that analyses of dynamic postural capabilities could bring important information on the development of postural control in healthy children.

The surface area and the mean velocity of CoP decreased significantly as the age of the children increased in the majority of the conditions tested (except for EO-U conditions). Our results are similar to those obtained by Ionescu et al. (2006). Moreover, these findings are in line with the study of Rival et al. (2005), showing a significant decrease of surface and mean velocity of CoP with age, and suggesting that the processes controlling postural stability are not yet developed during childhood. Furthermore, we also reported that there is no decrease of the surface or mean velocity of CoP in eyes open condition on unstable support; recall that in this condition visual inputs are available and somesthesic information are misled. Thus, we can suggest that quite early, already at 4 years of age, visual inputs are efficiently used and developed enough for the child to obtain postural stability.

The surface and mean velocity of CoP changed significantly depend to postural condition. Indeed, the surface and mean velocity are significantly smaller in stable than in unstable condition. The unstable support mislead somesthesic inputs, which is why we can suggest that the latter are involved in controlling the surface and mean velocity of CoP. Thus, with age, children learn how to achieve a postural control in perturbed conditions also.

4.2. The PI in both directions decreased significantly with increasing age of children

For the first time we showed that the spectral power indices recorded in both medio-lateral and antero-posterior directions decreased significantly with age, suggesting an improvement of postural control during childhood – in line with the work of Dumistrescu and Lacour (2006) and Bernard-Demanze et al. (2009) showing that the smaller the spectral power index, the better the postural control. Interestingly, such decrease has been observed for all frequency bands at least in all stable conditions. In line with the hypothetical physiological significance of the different bands of frequencies (Nashner, 1979; Kohen-Raz et al., 1996; Paillard et al., 2002; Lacour et al., 2008; Bernard-Demanze et al., 2009), our data suggest that visual, vestibular, cerebellar and proprioceptive inputs develop with age, thus providing a better postural stability control. Recall that Steindl et al. (2006) have shown that proprioceptive function seemed to be mature at 3–4 years of age, while visual and vestibular afferents reached adult level at 15–16 years only. Based on our findings, we could assume that proprioceptive functions and vestibular information are not completely developed in younger children and seem to improve until adult life.

In contrast, on unstable support the spectral power index in antero-posterior direction did not decrease significantly with age. Recall that Hong et al. (2008) suggested that postural control develops more rapidly in the antero-posterior than in the medio-lateral direction due to gait development, which is mature early in a child's life (normally, after the first year of life). Thus, given that all the subjects tested in the present study were walkers and already well-trained to motor experiences, they did not show any developmental improvement in such direction.

Finally the spectral power index in antero-posterior direction was significantly smaller when subjects could use the visual inputs (in eyes open condition more than in eyes closed or with perturbed vision condition), suggesting that visual capabilities are used as spatial referential.

4.3. The CT in antero-posterior direction only increased with age

The CT, in antero-posterior direction only, increased significantly with the age of the tested subjects, suggesting an improvement with age in sensorial integration, which is responsible for obtaining postural stability. This finding is in line with several developmental studies that have already been cited (Forssberg and Nashner, 1982; Shumway-Cook and Woollacott, 1985; Cuisinier et al., 2011; Barozzi et al., 2014) and that show the difficulty for young children to reweigh sensorial input, most likely due to the immaturity of their adaptive processes (Barela et al., 2003; Peterson et al., 2006). Moreover, the study by Looper et al. (2006) suggested that the adult pattern of gait develops with motor training and experiences: the more children grow up, the more they increase their motor experiences and achieve efficient postural control of their body. This hypothesis is also in line with the study of Ulrich et al. (2001), showing that training on the treadmill increases motor experiences of children, leading them to achieve efficient postural control independently of environmental conditions. Thus, our subjects improved their postural control in antero-posterior direction with age, most likely due to training of motor capabilities during their daily life.

Furthermore, we did not find a significant increase with age of canceling time in medio-lateral direction. In this direction, postural control is not much used in everyday life; we could therefore suggest that in this direction, subjects are less stimulated and the developmental improvement is not relevant.

There is also a significant effect of visual condition on the canceling time in medio-lateral direction. Indeed, the canceling time in medio-lateral direction is significantly shorter in eyes open than in perturbed vision condition. In eyes open condition, visual inputs are available, which is not the case with perturbed vision.

5. Conclusion

Our current findings show an improvement of postural control during childhood. This improvement could be due to a better use of sensorial input (namely visual and vestibular information) and a better cerebellar integration, which allows children to achieve a good postural stability independently of environmental conditions. Finally, these parameters based on both spatial and temporal analysis of the CoP could be used as a reference for further studies dealing with pathologic motor development in children.

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Competing interests

The authors have declared that no conflicting interests exist.

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