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Effects of sensory manipulations on the dynamical structure of center-of-pressure trajectories of children with cerebral palsy during sitting

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ABSTRACT

Aim: To investigate the effects of manipulating visual information and the compliance of the support surface on the area of sway and dynamical trajectories of center-of-pressure (CoP) in children with CP and children with typical development during static sitting. Methods: 32 typical children, 14 children with mild CP and 12 with moderate-to-severe CP were tested for CoP sway during static sitting under four sensory conditions: (1) eyes open on a rigid surface; (2) eyes closed on a rigid surface; (3) eyes open on foam; (4) eyes closed on foam. Results: Children with moderate-to-severe CP showed greater regularity and local stability of dynamical CoP trajectories and lower complexity in their motor patterns than typical children and children with mild CP. Moreover, removing vision and sitting on a compliant surface reduced the regularity of CoP trajectories. Conclusion: Children with CP were able to adjust the structure and complexity of their postural control responses to sensory challenges, although the structure of their postural responses was poorer than in typical children.

1. Introduction

Children with cerebral palsy (CP) show deficits in mechanisms regulating postural control (Cascio, 2010; Ferdjallah, Harris, Smith, & Wertsch, 2002; Papadelis et al., 2014; Rose et al., 2002; Woollacott & Shumway-Cook, 2005), which require integration of visual, vestibular, and somatosensory information (Barela et al., 2011). These deficits are related to sensory processing impairments (Pavão & Rocha, 2017) and muscle incoordination affecting stability (Graaf-Peters et al., 2007; Nashner, Shumway-Cook, & Marin, 1983) and resulting in non-adaptive motor responses to the different tasks (Pavão, dos Santos, Oliveira, & Rocha, 2015). Chen and Woollacott (2007) reported that, compared to their typical peers, children with CP take a longer time to recover stability during sensory perturbations and show greater displacement of the center-of-pressure (CoP) to recover balance.

Although several studies have addressed postural control in children with CP and effects of sensory manipulations on their postural stability (Barela et al., 2011; Chen & Woollacott, 2007; Woollacott & Shumway-Cook, 2005; Rose et al., 2002; Nashner et al., 1983), most of them have tested children in the upright position (Barela et al., 2011; Chen & Woollacott, 2007), or during postural transitions (Pavão, Arnoni, & Rocha, 2017). Nevertheless, children with moderate-to-severe motor impairments have a limited ability to maintain the upright posture, thus remaining seated for long periods of time (Saavedra, Woollacott, & van Donkelaar, 2010).

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There are few studies testing the effects of altered sensory conditions on seated postural control in children with CP. Most studies manipulated the stability of the base of support by moving the surface (Brogren, Forssberg, & Hadders-Algra, 2001) or inclining the seat/trunk (Cherng, Lin, Ju, & Ho, 2009; Hadders-Algra et al., 2007; Saavedra et al., 2010).

Although the characteristics of the support surface influence seated postural control in children with CP (Cherng et al., 2009; Hadders-Algra et al., 2007), we did not find studies testing the effects of changes in the compliance of the support surface, or studies combining different types of sensory manipulations on seated posture in children with CP. In fact, it is important to investigate the role of sensory cues in seated postural control because functional tasks often place sensory threats, requiring adaptive postural responses. Combined changes in sensory information provide a chance to simulate daily environmental demands, as children often have to seat on different surfaces and with suboptimal visual conditions (i.e. sitting in bed during the night).

Recent studies have advocated the use of nonlinear techniques (i.e., analysis of CoP's dynamical trajectories) to analyze postural control data (da Costa, Batistão, & Rocha, 2013; Harbourne & Stergiou, 2009; Roerdink et al., 2006). According to these studies, linear analysis does not provide information about the structure and complexity of motor patterns, or about how the movement is controlled over time. Therefore, considering that neuromotor conditions reduce the complexity and variability of motor patterns (Harbourne, Willet, Kyvelidou, Deffeys, & Stergious, 2010), the use of nonlinear techniques analysis may be more sensitive to investigate the dynamical structure of CoP trajectories (da Costa et al., 2013).

Indeed, children with CP present higher regularity and lower complexity in CoP trajectories (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Pavão, Ledebt, Savelsbergh, & Rocha, 2017) than typical children, which indicates a rigid and predictable motor control system (Dusing & Harbourne, 2010). Studies addressing complexity and variability in the seated postural control of children with CP (Cignetti, Kyvelidou, Harbourne, & Stergiou, 2011; Deffeyes, Harbourne, Stuberg, & Stergiou, 2011; Kyvelidou, Harbourne, & Stergiou, 2010; Harbourne & Stergiou, 2003) did not address the effects of sensory changes on the dynamical structure of CoP trajectories in this population. In fact, we did not find any studies reporting the effects of sensory manipulations on the on variability and complexity of seated postural control of children with CP.

Understanding the response of CoP trajectories to the manipulation of sensory information may contribute to understand the complexity of motor patterns involved in seated postural control of children with CP. This may guide clinical professionals to offer appropriate stimuli during therapies in order to improve balance. Therefore, the aim of the present study was to investigate the effects of manipulating (1) visual information and (2) the compliance of the support surface on dynamical CoP trajectories in children with CP and children with typical development in the sitting posture.

According to Ulrich, Ulrich, Angulo-Kinzler, and Chapman (1997), the adaptability to changes in environmental contexts depends on: (1) the experience level of the subject; (2) the biomechanical characteristics of the task; and (3) the organization of these components, which should be sensitive to available information. Therefore, our initial hypothesis was that increased sensory threats, such as removing visual information and changing the compliance of the support surface, would affect CoP trajectories by increasing the area of CoP sway and the regularity of CoP trajectories, and decreasing the complexity of postural control, indicating rigidity and predictability of the system. Considering their neuromotor impairments (Woollacott & Shumway-Cook, 2005), we believe these changes will be more pronounced in children with CP.

2. Methods

2.1. Design

The present study had a cross-sectional design and was carried out at Child Movement Analysis Laboratory. All the participants were recruited in pediatric rehabilitation centers and/or regular schools.

2.2. Participants

A convenience sample of 58 children with ages between 5 and 15 years was evaluated. The participants were divided into three groups according to their gross motor abilities. The groups were age-matched ($F(2,2) = 0.160$; $p = 0.853$). All parents signed an informed consent prior to participation.

The first group consisted of 32 children with typical development all born full term and without any musculoskeletal disorders (18 males and 14 females; age (mean ± SD) = 9.12 ± 2.16 years). Participants with current lower limb injury or visual impairments, or who had any cardiovascular, pulmonary, neurological, or other systemic conditions that limited physical activity were excluded from the study.

The second and third groups comprised children with spastic CP classified according to their Gross Motor Function Classification System (GMFCS) levels as: mild motor impairment (GMFCS levels I and II ; n = 14; age [mean ± SD] = 9.07 ± 3.29 years) or moderate-to-severe motor impairment (GMFCS levels III and IV ; n = 12; age [mean ± SD] = 9.58 ± 2.81 years) (Chagas et al., 2008). GMFCS levels were rated by an experienced pediatric physical therapist. The sample characteristics are shown on Table 1.

Inclusion criteria for participants with CP were: (a) ability to follow simple instructions; (b) ability to independently keep sitting posture with arms free for 30 s, without the need for auxiliary devices; (c) attending physical therapy at least twice per week during the past six months; (d) absence of visual impairments not corrected by glasses or contact lenses. Exclusion criteria were: (a) presence of trunk deformities that could compromise the permanence in seated position; (b) orthopedic surgeries and chemical blockages in the previous 12 and 6 months, respectively; (c) hip subluxation above 30%; (d) trunk scoliosis with Cob angle above 40°; (e) visual impairments not corrected by glasses or contact lenses. The study was approved by the local Ethics Committee (CAAE: 04299912.6.0000.5504).

Table 1
Sample characterization according to the level of motor impairment following Gross Motor Function Classification System (GMFCS): Typical children, Cerebral Palsy GMFCS level I and level II/mild motor impairments, GMFCS III and IV/moderate-to-severe motor impairments.

	Sample Size	Age	Gender	GMFCS
Typical children	32	9.12 ± 2.12 years	18 males 14 females	–
CP mild impairments	14 subjects	9.07 ± 3.29 years	9 males 5 females	9 subjects level I 5 subjects level II
CP Moderate-to-severe impairments	12 subjects	9.58 ± 2.81 years	7 males 5 females	8 subjects level III 4 subjects level IV

The sample size calculation indicated the need of at least 8 to 10 children at each level of motor impairment to demonstrate statistically significant changes. The significance level used in the calculation was 5%, the statistical power was 0.80, and the expected effect (correlation coefficient r) was 0.8. The calculation was based on magnitude of effect obtained by means of a pilot study and based on differences in kinetic variables across GMFCS levels described in the literature (Corrêa, Corrêa, Franco, & Bigongiari, 2007; Ferdjallah et al., 2002; Nobre et al., 2010).

2.3. Procedures

Postural sway during quiet sitting was tested with participants seated on a force plate (Bertec400, sampling frequency 1000 Hz), which was positioned on a bench with adjustable height, so that the hips and knees joints remained at 90° of flexion (Ferrari, Tersi, Ferrari, Sghedoni, & Chiari, 2010). The buttocks and thighs were in contact with the force plate and the feet did not touch the floor. The participants remained seated without back support (Bigongiari et al., 2011; Ferrari et al., 2010; Ju, Hwang, & Chergn, 2012; Ju, You, & Cherng, 2010; Van der Heide et al., 2004).

Once seated on the platform, participants were instructed not to move or talk for 30 s while looking at a dot positioned at eye level 1 m in front of them. Then, participants performed three trials of each of the four study conditions: (1) stable condition with eyes open (sitting on a rigid surface); (2) stable condition with eyes closed (sitting on a rigid surface); (3) compliant condition with eyes open (sitting on a foam); (4) compliant condition with eyes closed (sitting on a foam). A rest period of 30 s was given between each attempt. The order of the conditions was randomized across participants by drawing lots.

Throughout the data collection the participant was seated on the force plate and the examiner remained at his/her side to avoid falls if any imbalance occurred during the test.

2.4. Data analysis

The signals of the force plate were processed and analyzed within MATLAB® (version 7.0.1., Math Works Inc., Natick, USA) using scripts specifically coded for this study. Data were normalized by the participants' body weight (Pavão et al., 2017).

In order to examine whether posture is actively controlled in the direction of largest postural sway (Roerdink et al., 2006), we analyzed both the registered X (medio-lateral) and Y (anterior-posterior) COP time-series. The time series were bidirectionally filtered (second-order low-pass Butterworth filter, cut-off frequency of 12.5 Hz) to eliminate low amplitude measurement noise. Then, we assessed COP dynamics by means of approximate entropy (ApEn) (Deffeyes et al., 2011), largest Lyapunov exponent (LyE), correlation dimension (COD) (Donker, Roerdink, Greven, & Beek, 2007; Roerdink et al., 2006).

2.5. Variables

Area of CoP sway corresponds to the dispersion of the oscillation considering the anterior-posterior (AP) and medial-lateral (ML) directions. This variable estimates the dispersion of CoP data by the calculation of the statokinesiogram area. The area was calculated through the statistical method of principal components analysis, which calculates an ellipse comprising 95% of the CoP data. The two axes of this ellipse are calculated from the measures of dispersion of CoP signals. The greater their values, the greater the balance deficits (Duarte & Freitas, 2010).

ApEn is a measure of "complexity" for time series data (Deffeyes et al., 2011), where "complexity" is defined as being low for time series with a repetitive pattern such as a sine function, high for a random variable, and intermediate for systems with chaotic dynamics. Alternatively, it can be described as a measure of "regularity" where time series data with repeated patterns have low approximate entropy and high regularity (Pincus & Goldberger, 1994). ApEn values range from 0, when the signal is predictable and regular, to a maximum value, when it is unpredictable and random. Small entropy values are frequently found when a regulatory mechanism takes priority over others, thus reducing control complexity. High entropy values are frequently found when several control mechanisms are present and do not interact with each other or are weakly coupled, thus increasing control complexity (Lipsitz, 2002). We calculated approximate entropy (ApEn) (Pincus, 1995) for anterior-posterior and medio-lateral axis.

LyE provides a local stability measure of a dynamical system, its sensitivity to initial conditions or its resistance to small internal perturbations, such as the small ones that occur while maintaining upright stance. LyE is negatively related with local stability of CoP trajectories (da Costa et al., 2013). Positive values indicate the presence of chaos, provided that the system stays in finite vicinity, implying that some attractor exists and reflecting local instability and lack of predictability. Lower LyE values are related to greater local stability of CoP trajectories, and hence, to greater predictability of the system (Roerdink et al., 2006). The calculation of LyE was based on Donker et al. (2007) and was determined for anterior-posterior and medio-lateral axis.

COD provides an index of the number of independent degrees of freedom (equations of motion) required to reproduce the time evolutionary properties of the CoP time series (Donker et al., 2007). It indexes the number of active dynamical degrees of freedom involved in postural control and, hence, its dimensionality (Roerdink et al., 2006). We highlight that no straightforward or uniform relation exists between the number of component degrees of freedom in motion and the dimension of the organizational dynamic in controlling those components (Donker et al., 2007). Its calculation was performed following Grassberger and Procaccia (1983) by conducting a phase space reconstruction of the COP dynamics. Lower values of COD indicate more rhythmic time series with a rigid behavior (Donker et al., 2007). We calculated COD for anterior-posterior and medial-lateral axes.

For all dependent variables the average of the three performed trials in each of the four sensory conditions was determined to conduct statistics.

2.6. Statistical analysis

Statistical analyses were performed in SPSS (version 17.0). Repeated-measures ANOVA with sensory conditions as a within-subject factor (four levels: eyes open on a rigid surface; eyes closed on a rigid surface; eyes open on an compliant surface; eyes closed on a compliant surface) and Group as a between-subject factor (three levels: typical, mild CP and moderate-to-severe CP) was applied to all dependent variables (Area of CoP sway, LyE AP, LyE ML, ApEn AP, ApEn ML, COD AP and COD ML). For main effects of Group, Tukey post hoc tests were performed. Effect sizes for main and interaction effects are reported as partial eta squared ($\eta 2p$). Significance was set at $p < 0.05$. Assumptions for the specific analyses were satisfied.

3. Results

Statistical test ANOVA of repeated measures showed main effects of group ($F = 8.462$; $p < 0.05$; $n^2p = 0.547$) and condition ($F = 2.172$; $p < 0.05$; $n^2p = 0.566$), without significant interactions group*condition.

Group effects were observed for all the dependent variables, with exception of ApEn AP. Post-hoc tests showed that children with moderate-to-severe CP presented greater values of Area of CoP sway ($p < 0.05$), lower values of, LyE AP ($p < 0.05$), LyE ML ($p < 0.05$), ApEn ML ($p < 0.05$), COD AP ($p < 0.05$) and COD ML ($p < 0.05$) than children with typical development. Children with mild CP presented lower LyE ML ($p = 0.010$), COD AP ($p < 0.05$) and COD ML ($p < 0.05$) than children with typical development. Children with mild CP presented lower Area of CoP sway ($p < 0.05$), greater values of COD ML than children with moderate-to-severe CP ($p < 0.05$), and both children presented lower values of COD ML than typical children ($p < 0.05$ and $p < 0.05$, respectively).

Condition effects were found for ApEn AP ($F = 6.217$; $p < 0.05$). Post-hoc tests showed that in the sensory condition of eyes closed on a compliant surface children showed lower values compared to the conditions eyes open on a rigid surface ($p < 0.05$) and eyes closed on a rigid surface ($p < 0.05$).

The values of the mean and interactions effects of each analyzed variable are expressed in Table 2.

The graphical representations of the performance of the children on the variables in each group and each sensory condition are expressed in Figs. 1–4.

4. Discussion

We aimed to investigate the effects of manipulating visual information and the compliance of the support surface on the area of CoP sway and dynamical trajectories of CoP in children with CP and children with typical development during sitting. The results partially confirmed our initial hypothesis that combined sensory manipulations would increase the regularity of CoP trajectories and decrease the complexity of postural control. Unexpectedly, the effects were not more pronounced in children with CP than in typical children, since we did not find group/condition interactions.

The use of nonlinear techniques to analyze dynamical CoP trajectories provides information about the quality and structure of the variability in these trajectories (da Costa et al., 2013; Harbourne & Stergiou, 2009). Previous studies used nonlinear techniques to analyze CoP data in CP (Deffeyes et al., 2011; Donker et al., 2008; Pavão et al., 2017). Nevertheless, the major novelty of our study was using them to investigate the effects of sensory manipulations on the dynamical structure of CoP trajectories.

In daily routine, we are commonly exposed to postural challenges that often combine more than one sensory modality, such as visual deprivation while maintaining postures over unstable support surfaces. For example, if one wakes up during the night (with suboptimal visual conditions) and needs to remain seated on a mattress while drinking water. Thus, it is important to understand how these challenges may influence the structure of motor patterns in children with CP (da Costa et al., 2013), as this may provide clinical professionals with tools to offer appropriate training aimed at improving sitting balance in daily life situations.

In this study, children with CP showed greater body sway and lower complexity in motor patterns than typical children, and children with moderate-to-severe CP showed lower complexity than children with mild CP.

We found that children with mild and moderate-to-severe CP showed lower LyE than typical children. LyE is negatively related to local stability of CoP trajectories (Donker et al., 2007). The greater the stability of the CoP trajectories, the greater the system resistance to low internal perturbations. Thus, the lower values of LyE in children with mild and moderate-to-severe CP indicate an inflexible and predictable motor system (Roerdink et al., 2006), which might determine less adaptable motor responses during unexpected perturbations.

Table 2
Mean and standard deviation, main and interaction effects of Group (between-subject factor, three levels: typical children (TC), cerebral Palsy GMFCS level I and level II/mild impairment and GMFCS III and IV/moderate to severe impairment and Condition (within-subject factor, four levels: 1. eyes open rigid surface (EOR); 2. eyes closed rigid surface (ECR); 3. eyes open compliant surface (EOC); 4. eyes closed compliant surface (ECC)) on Area of CoP sway, Lyapunov Exponent in anterior-posterior axis and medio-lateral one (LyE AP and LyE ML, respectively), Approximate Entropy in anterior-posterior axis and medio-lateral one (ApEn AP and ApEn ML, respectively), Correlation Dimension Entropy in anterior-posterior axis and medio-lateral one (COD AP and COD ML, respectively).

		GROUP						
EOS	TC	Mild	Moderate-to-severe	*F (1, 67)*	*p*	η_p^2	EOR	ECR
Area (cm)	0.056 ± 0.035	0.115 ± 0.053	0.437 ± 0.057	16.455	p < 0.05	0.374	0.194 ± 0.027	0.191 ± 0.027
LyE AP	0.046 ± 0.001	0.042 ± 0.002	0.040 ± 0.002	5.409	p < 0.05	0.164	0.042 ± 0.001	0.045 ± 0.001
LyE ML	0.046 ± 0.001	0.041 ± 0.001	0.038 ± 0.002	12.079	p < 0.05	0.305	0.040 ± 0.001	0.043 ± 0.001
ApEn AP	0.373 ± 0.007	0.383 ± 0.011	0.349 ± 0.011	2.449	0.096	0.082	0.378 ± 0.007	0.376 ± 0.007
ApEn ML	0.461 ± 0.013	0.427 ± 0.020	0.366 ± 0.021	7.220	p < 0.05	0.208	0.429 ± 0.014	0.414 ± 0.012
COD AP	3.706 ± 0.029	3.539 ± 0.044	3.414 ± 0.048	15.157	p < 0.05	0.355	3.535 ± 0.034	3.553 ± 0.034
COD ML	3.706 ± 0.035	3.334 ± 0.053	3.071 ± 0.057	49.988	p < 0.05	0.645	3.398 ± 0.043	3.380 ± 0.042

		USE OF PEDIASUIT®					INTERACTION	
EOS	EOC	ECC	*F (1, 67)*	*p*	η_p^2	*F (1, 67)*	*p*	η_p^2
Area (cm)	0.218 ± 0.038	0.209 ± 0.034	0.576	0.632	0.010	0.959	0.455	0.034
LyE AP	0.042 ± 0.002	0.043 ± 0.002	0.910	0.437	0.016	1.210	0.303	0.042
LyE ML	0.041 ± 0.002	0.042 ± 0.001	1.378	0.251	0.024	0.665	0.678	0.024
ApEn AP	0.362 ± 0.007	0.356 ± 0.006	6.217	p < 0.05	0.102	0.127	0.993	0.005
ApEn ML	0.412 ± 0.012	0.417 ± 0.013	1.118	0.386	0.018	0.980	0.440	0.034
COD AP	3.524 ± 0.039	3.600 ± 0.030	1.343	0.262	0.024	0.827	0.551	0.029
COD ML	3.306 ± 0.046	3.397 ± 0.041	1.369	0.254	0.024	0.592	0.736	0.021

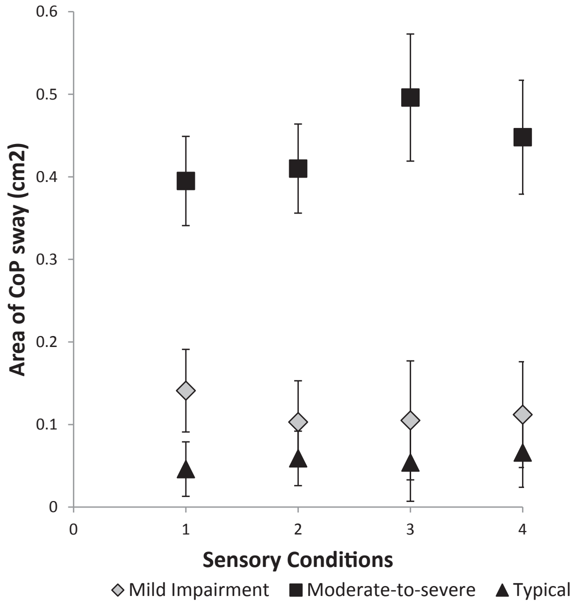

Fig. 1. Graphical representation as a function of group (TC: typical children; children with mild CP and children with moderate-to-severe CP) and sensory condition (1. Eyes open on stable surface; 2. Eyes closed on a stable surface; 3. Eyes open on an unstable surface; 4. Eyes closed on an unstable surface) for the Area of CoP sway.

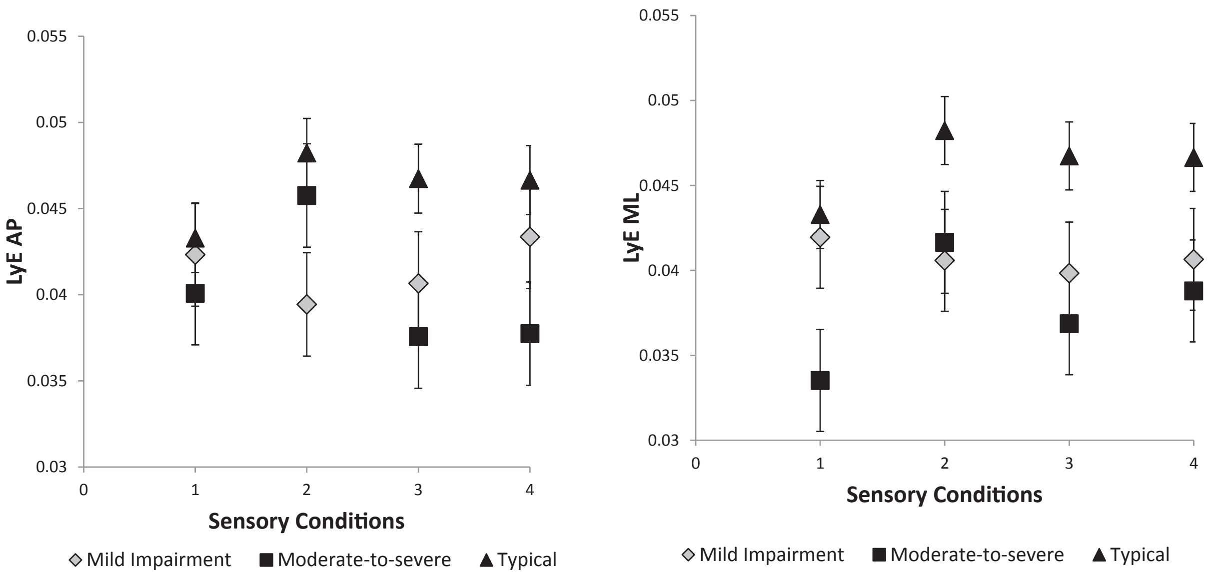

Fig. 2. Graphical representation as a function of group (TC: typical children; children with mild CP and children with moderate-to-severe CP) and sensory condition (1. Eyes open on stable surface; 2. Eyes closed on a stable surface; 3. Eyes open on an unstable surface; 4. Eyes closed on an unstable surface) for the variables Largest Lyapunov Exponent on anterior-posterior axis (LyE AP) and Largest Lyapunov Exponent on medial-lateral axis (LyE ML).

Children with moderate-to-severe CP also showed lower ApEn ML than typical children. ApEn is negatively related with the regularity of CoP trajectories (Donker et al., 2011a). Lower values of ApEn represent lower complexity of the motor system to perform actions and high regularity in CoP sway indicating a stereotyped motor behavior (Donker et al., 2008). Although previous studies have reported a more regular pattern of CoP sway in children with CP while standing (Donker et al., 2008; Pavão et al., 2017), the present results show that even in the seated posture, which demands less postural adjustments than standing, children with CP show a high regularity of CoP sway. Moreover, considering the established relationship between regularity of CoP sway and amount of attention invested in posture (Roerdink, Hlavackova, & Vuillerme, 2011a), our results may indicate that sitting demands greater investment of attention for children with moderate-to-severe CP than for typical children, since their ApEn was lower than their typical peers.

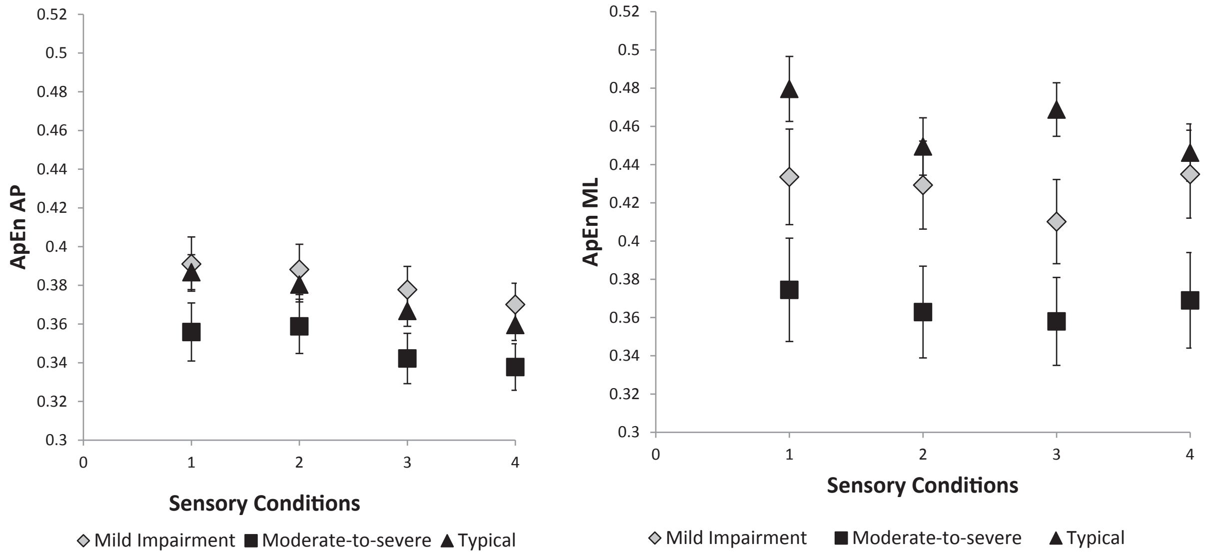

Fig. 3. Graphical representation as a function of group (TC: typical children; children with mild CP and children with moderate-to-severe CP) and sensory condition (1. Eyes open on stable surface; 2. Eyes closed on a stable surface; 3. Eyes open on an unstable surface; 4. Eyes closed on an unstable surface) for the variables Approximate Entropy on anterior-posterior axis (ApEn AP) and Approximate Entropy on medial-lateral axis (ApEn ML).

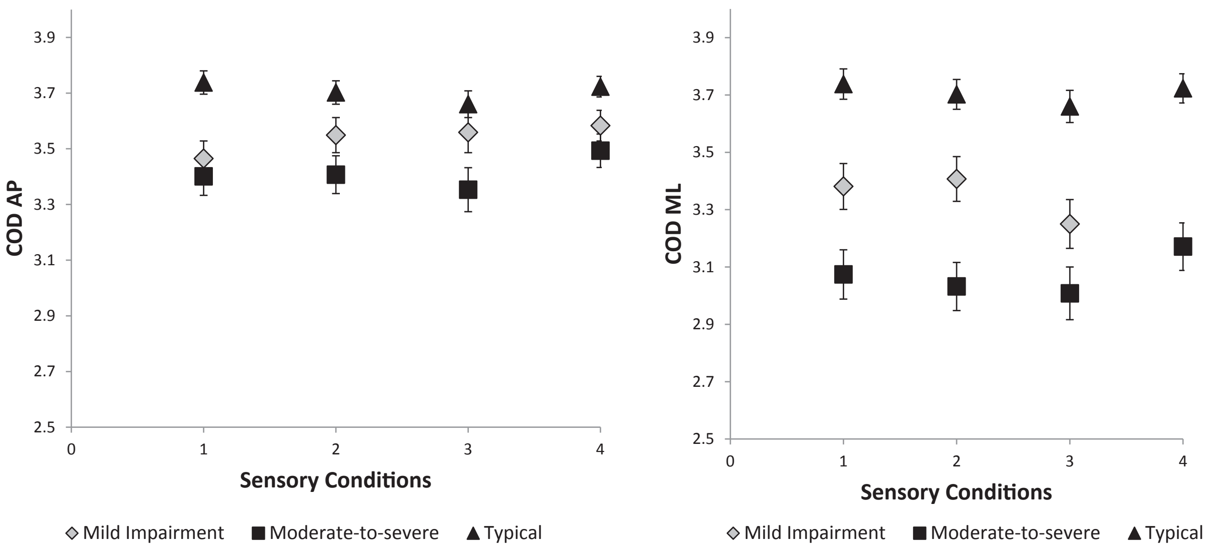

Fig. 4. Graphical representation as a function of group (TC: typical children; children with mild CP and children with moderate-to-severe CP) and sensory condition (1. Eyes open on stable surface; 2. Eyes closed on a stable surface; 3. Eyes open on an unstable surface; 4. Eyes closed on an unstable surface) for the variables Correlation Dimension on anterior-posterior axis (COD AP) and Correlation Dimension on medial-lateral axis (COD ML).

Lastly, children with mild and moderate-to-severe CP showed lower COD (AP and ML) than typical children. COD is a measure of the complexity of vital process studied. It indicates the number of active dynamical degrees of freedom involved in postural control. Lower values of COD in children with CP indicate that they recruited lower control processes (degrees of freedom) to maintain the seated posture than typical children (Donker et al., 2007; Roerdink, Hlavackova, & Vuillerme, 2011b). This was more remarkable in the group with more severe impairment, which highlights the role of the neuromotor condition.

Taken together, the results demonstrated that even while sitting children with CP show a less complex and more predictable motor system than typical children, which may limit their motor responses to unexpected perturbations (da Costa et al., 2013). According to Harbourne and Stergiou (2009), temporal variations in movement trajectories exhibit deterministic patterns, which have been defined as chaotic. In this sense, chaotic regimes allowing a healthy system to have a wide range of potential behaviors and an optimal state of variability renders the system more flexible and adaptable; the opposite should be expected when regular behaviors are expressed. Our finding may therefore be aligned to the notion of pathological regularity versus healthy complexity (da Costa et al., 2013). According to Donker et al. (2008), a less 'complex' or more 'regular' physiological time series reflect less effective physiological control.

In fact, the seated posture involves a wide base of support with low biomechanical demands to keep stability (Liao & Hwang, 2003). Nevertheless, although sitting maintenance might be considered a simple motor task, its maintenance seems to be especially challenging for individuals with CP, since their motor control system present lower complexity, high levels of predictability and requiring greater investments of attention in postural control regulation (Roerdink et al., 2011a).

The sensory manipulations used in this study only disturbed the dynamical patterns of CoP trajectories in the most challenging test condition (eyes closed on a compliant surface). In this condition, all groups reduced their ApEn AP. The combination of withdrawing vision with sitting on a complying support surface increased the task demands (Harbourne & Stergiou, 2009), resulting in a more regular pattern of CoP sway. Moreover, considering the relationship between regularity of CoP sway and investment of attention in postural control, this increase in the regularity of CoP trajectories may also be explained by increased attention demands (Roerdink et al., 2011a). These results demonstrate that multimodal sensory challenges disturb the structure of CoP behavior both in CP and in typical children, reducing the automatism of postural control.

We did not find any differences in the complexity of CoP trajectories neither when visual information, nor when somatosensory information was individually manipulated. Similarly, Cherng, Su, Chen, and Kuan (1999) and Donker et al. (2008) did not find differences in the postural stability of children with CP while manipulating visual information in isolation. Postural instability was only increased for subjects with CP when the vision was withdrawn and participants were over a compliant support surface (Cherng et al., 1999). Barela et al. (2011) found that children with spastic hemiplegia during upright stance show adaptive sensorimotor coupling in a moving room, although their coupling had smaller magnitude that the one observed in typical children.

Together, the aforementioned studies and our results suggest that in children with CP and typical children the perturbation of an isolated sensory system might be compensated by sensory inputs provided by other systems, especially in the seated posture, which involves low biomechanical complexity (Harbourne & Stergiou, 2003). Therefore, we can infer that the dynamical structure of CoP trajectories in children with CP is only altered under high sensory threats.

Different from our expectations, the decreased values of ApEn during sensory challenges was not higher in children with CP than in typical children. Children with CP show important deficits in sensory processing (Pavão & Rocha, 2017), determining poorer postural control strategies than typical children (Pavão et al., 2015), lower complexity in motor strategies of postural control system and greater regularity in dynamical CoP trajectories. Nevertheless, in spite of their neuromotor condition, they were able to deal with sensory challenges with CoP trajectories behaving similar to typical children.

The main clinical implications of our results are that multimodal sensory challenges should be trained in rehabilitation programs aiming to improve postural control in children with CP. Multimodal sensory changes such as the ones used in the present study may be used in therapy to challenge the postural the control system, possibly leading to gains in flexibility and complexity. Nevertheless, further studies should address the impact of sensory training on postural balance of children with CP

We cannot fail to consider that the absence of interaction effects may be a result of the small sample size of the groups with CP. However, we have followed the assumptions of the minimal sample size to ensure the statistic power of the tests.

5. Conclusion

Children with CP show greater body sway and more regular, predictable and less complex pattern of CoP trajectories while sitting than their typical peers. The combination of multimodal sensory challenges disturbed CoP trajectories' behavior, resulting in greater regularity of CoP sway in all groups. According to the results, although children with mild and moderate-to-severe motor impairments showed differences in the dynamical structure of CoP trajectories, they were able to adjust the structure and complexity of their postural control responses to sensory challenges.

Declaration of interest

The authors report no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2018.11.003.

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