



Full Length Article

How do children aged 6 to 11 stabilize themselves on an unstable sitting device? The progressive development of axial segment control

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ABSTRACT

Postural control continues to develop during middle childhood as shown by the decrease in body sway in stance between the ages of 5 and 11. Although head and trunk control is crucial for balance control during both static and dynamic activities, evaluating its specific development and its contribution to overall postural control is methodologically challenging. Here, we used an unstable sitting device adapted to ensure that only the axial segments could control the balance of the device and thus the balance of the upper body. This study aimed to assess the development of the postural stabilization of axial body segments during middle childhood. Thirty-six children (in three age groups: 6-7yo, 8-9yo, and 10-11yo) and 11 adults sat on the unstable sitting device and had to stabilize their axial segments under several conditions: a moderate vs. high level of balance challenge, and eyes open vs. eyes closed. Upper-body postural sway (area, mean velocity and root mean square (RMS) of the center of pressure (CoP) displacement) decreased progressively with age (6-7yo > 8-9yo > 10-11yo > adults), and this effect was accentuated when the balance challenge was high (for CoP area) or in the “eyes closed” condition (for CoP area and RMS). The stabilization strategies were assessed by anchoring indexes computed from three-dimensional kinematics. A progressive shift was showed, from an “en bloc” pattern at 6–7 years of age toward a more articulated (i.e. adult-like) pattern at 10–11. A head-on-space stabilization strategy first emerged at the age of 8–9. Middle childhood is an important period for the development of axial segment stabilization, which continues to mature until adulthood. This development might be related to the introduction and progressive mastery of feedforward sensorimotor processes and might contribute strongly to the development of overall postural control.

1. Introduction

Postural control involves both balance (i.e. whole body stabilization) and the orientation and stabilization of body segments, in order to interact with the environment during (for example) a voluntary movement (Shumway-Cook & Woollacott, 2007). Although children are able to stand independently and counteract balance disturbances early in childhood (Hadders-Algra, 2005), the various

Abbreviations: AI, anchoring index; ANOVA, analysis of variance; CNS, central nervous system; CoP, center of pressure; DoF, degree of freedom; EC, eyes closed; EO, eyes open; HSD, honestly significant difference; HSSS, head-in-space stabilization strategy; RMS, root mean square; TSSS, trunk-in-space stabilization strategy

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components of postural control continue to develop through childhood and into adolescence (Assaiante, 2012; Verbecque, Vereeck, & Hallemans, 2016). In particular, overall postural sway during quiet stance decreases between the ages of 5 and 10–11 (Hsu, Kuan, & Young, 2009), and there are still differences between adolescents and adults (Ferber-Viart, Ionescu, Morlet, Froehlich, & Dubreuil, 2007; Verbecque et al., 2016). Moreover, this developmental effect appears to be even more pronounced when control of balance is challenged by (i) experimental sensory manipulations, such as a lack of vision (Ferber-Viart et al., 2007; Wolff et al., 1998) or vibration-induced proprioceptive disturbance (Cuisinier, Olivier, Vaugoyeau, Nougier, & Assaiante, 2011), and (ii) postural task demands, such as oscillation (Mallau, Vaugoyeau, & Assaiante, 2010) or sudden displacements of the support (Forsberg & Nashner, 1982). These observations suggest that the ability to stabilize the body develops progressively and significantly during middle childhood (i.e. between 5 and 12 years of age).

In static and dynamic situations, balance requires coordinated control of the different body segments' positions and the resulting center of mass (CoM) (Massion, Popov, Fabre, Rage, & Gurfinkel, 1997). The axial segments can be functionally divided into a head module (head + neck), a trunk module (thorax + abdomen), and a pelvis module, which can be moved relative to each other. Together, the trunk and pelvis modules have a key role in balance because of their high mass (60% of the total body mass, cf. Winter, 1995). Indeed, small trunk deviations can strongly impact the position of the CoM and thus destabilize the body. Axial segment control is essential (from infancy onward) for several motor activities such as sitting, walking, reaching and grasping (Assaiante, 2012; Rachwani, Santamaria, Saavedra, & Woollacott, 2015). Moreover, the trunk serves as a means of organizing postural control (Assaiante, McKinley, & Amblard, 1997). For example, although the head is often selected as the reference frame (probably because it contains the visual and vestibular receptors), its position is determined by the central nervous system (CNS) with respect to space and to the coordinates of the supporting trunk. Moreover, the trunk has a key role in reducing head oscillations because it acts as a low-pass filter and thus stabilizes the visual field and facilitates the integration of vestibular information (Kavanagh, Barrett, & Morrison, 2004). Therefore, trunk stabilization is essential for controlling the head's position in space. The trunk is also an egocentric reference for planning and controlling movements of the upper and lower limbs (Mouchnino, Aurenty, Massion, & Pedotti, 1993; Roncesvalles, Schmitz, Zedka, Assaiante, & Woollacott, 2005). Indeed, trunk stabilization is closely linked to the performance and accuracy of reaching movements (Flatters et al., 2014; Saavedra, Joshi, Woollacott, & van Donkelaar, 2009).

Efficient stabilization of the axial segments is crucial for postural control. It is based on the articulated control of the joints that connect the pelvis to the trunk and the trunk to the head. It is not clear how this motor ability develops because the CNS has to cope with redundancy in the degrees of freedom (DoF), due to the multisegment control of posture and to complexity of the neuromusculoskeletal system. As suggested by Bernstein (1967) and as reported for the development of other motor skills, the development of axial postural control might be driven by the CNS via (i) the freezing of certain joints in order to lower the number of simultaneously controlled DoF, and (ii) the gradual release of these previously frozen DoF when this skill has developed sufficiently with age, practice and/or expertise. Anchoring index (AI), introduced by Assaiante and Amblard (1995), is a kinematic method allowing to compare the stabilization of a given body segment with respect to both external space and the underlying anatomical segment. This approach has been used in developmental studies in order to determine when the children would release their DoF during the development of locomotion. They showed that children used an “en bloc” stabilization strategy when they begin to walk, with the head and trunk stabilized on their underlying segments (the trunk and pelvis, respectively). With age and walking experience, the children progressively move to articulated head-in-space and trunk-in-space stabilization strategies (HSSS and TSSS, respectively) (Assaiante & Amblard, 1995). Even though this articulated mode of control between the head and trunk usually appears at about 7 years of age for locomotion, the stabilization of axial segments (and especially the trunk) nevertheless continues to mature until adolescence. More specifically, children may return to an “en bloc” control of the head with respect to the trunk during difficult tasks, due to changes in the sensory context or under more challenging balance conditions (Assaiante, 1998).

Axial segment coordination and stabilization are crucial for static and dynamic postural control. These processes continue to develop during middle childhood and depend on the difficulty of the postural challenge. However, to the best of our knowledge, the axial segments' specific contribution to the development of postural control has not been directly evaluated. This may be because quantifying each body segment's contribution to the control of posture (i.e. separating the trunk's contribution from the limbs' contribution) is methodologically challenging. Nevertheless, researchers have recently developed unstable sitting devices (half-sphere or ball-bearing systems) that isolate the upper body and thus serve as tools for challenging the balance of axial segments during a seated postural task (Cholewicki, Polzhofer, & Radebold, 2000; Larivière, Mecheri, Shahvarpour, Gagnon, & Shirazi-Adl, 2013). As shown by Larivière et al. (2013), classical posturographic variables (see Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996) can be computed for seated postural control on these unstable platforms, just as they can be for standing posture. Moreover, Larivière et al. (2013) also introduced a calibration procedure that standardized the stabilization task's level of difficulty as a function of the seated participant's anthropometric characteristics. Consequently, the task's level of difficulty can be incremented in the same way for all participants.

Given that (i) postural control continues to develop throughout childhood; and (ii) the stabilization of axial body segments (the head, trunk, and pelvis) is crucial for the control of posturokinetic activities, the objective of the present study of typically developing children aged between 6 and 11 was to assess the effect of age on the postural stabilization of axial body segments. To this end, three age groups of children and a control group of adults were studied during a postural task on an unstable sitting device requiring the specific use of the axial segments to maintain balance. We hypothesized that postural sway would decrease with age and that this developmental effect would be accentuated by the task difficulty (i.e. the degree of balance challenge) and the visual condition (eyes open vs. eyes closed). Hence, we expected that head and trunk stabilization in the younger children would be more affected by a difficult balance challenge. This age effect might be based on the use of different segment stabilization strategies for the head and the trunk, as a function of the age. We further hypothesized that the younger children would rely on “en bloc” segmental stabilization

Table 1Characteristics of the study subgroups. Data are quoted as the mean \pm SD.

Group	Age (years)	Height (cm)	Weight (kg)	Sex ratio (F/M)
6-7yo (n = 13)	6.7 \pm 0.7	124 \pm 1.3	26.7 \pm 3.5	6/7
8-9yo (n = 12)	9.1 \pm 0.5	136.5 \pm 2.1	31.2 \pm 2.1	7/5
10-11yo (n = 11)	10.8 \pm 0.6	143.1 \pm 3.3	38.4 \pm 4.2	6/5
Adults (n = 11)	20.9 \pm 4.2	172 \pm 0.8	68 \pm 12.2	6/5

strategies (with the head and the trunk stabilized on their underlying segments, and especially when the balance task was difficult), whereas older children and adults would use articulated head-in-space and trunk-in-space stabilization strategies.

2. Experimental procedures

2.1. Participants

Eleven adults (6 females and 5 males) and 36 children (19 females and 17 males) were included in the study. To assess the development of postural control during middle childhood, the children were separated into three age groups: 6–7 years old (yo) ($n = 13$), 8–9yo ($n = 12$) and 10–11yo ($n = 11$). Characteristics of studied groups are reported in Table 1.

The main exclusion criteria were a history of neurologic or musculoskeletal disorders, acute or chronic low back pain, and uncorrected vision defects. The study was performed in compliance with the tenets of the Declaration of Helsinki. All the adult participants and the children's parents gave their written, informed consent to participation before the study.

2.2. The unstable sitting device

The unstable sitting device (Fig. 1) was a prototype based on the wobble chair system developed earlier by Larivière et al. (2013). The seat area was built from a flat plate (length: 35 cm, width: 70 cm, height: 5 cm) with an anti-slip coating. The plate's center (pivot point) was fitted with a cardan joint with two degrees of freedom (DoF) and four springs (maximum distance from the pivot point: 22.5 cm; stiffness: 3062.5 N.m⁻¹; height: 10 cm) arranged around the cardan joint (two on the anteroposterior axis and two on the

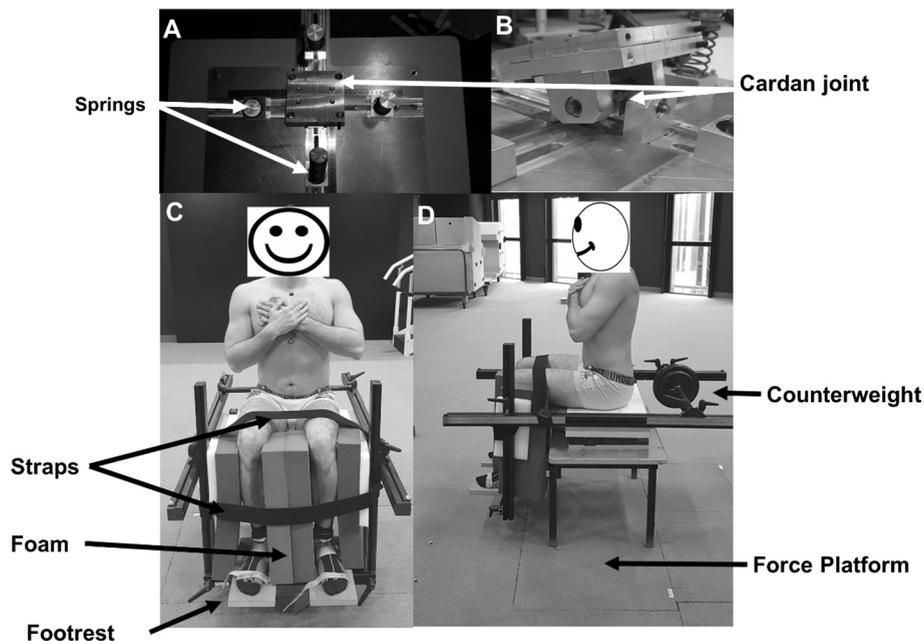


Fig. 1. The tilt mechanism of the unstable sitting device and the set-up for the postural task. (A) A view of the underside of the seat, showing the cardan joint and the four springs. The distance between the springs and the cardan joint (placed at the pivot point) could be modulated, in order to graduate the instability of the seat and make the difficulty of the postural task independent of the participant's anthropometric characteristics. The greater the distance between the spring and the central pivot, the more it opposes a tilt of the seat. (B) A side view of the cardan joint. The joint allowed the seat to tilt on the mediolateral and anteroposterior axes around a pivot point in a frictionless manner and with a maximum tilt angle of 12°. Frontal (C) and sagittal (D) views of the set-up used in the seated postural tasks. In these photos, the participant stabilized himself in an upright upper body posture.

mediolateral axis). The cardan joint allowed the seat to tilt in a frictionless manner along both axes, with a maximum tilt of 12°. The distance between the pivot point and the springs could be adjusted so as to modulate the seat's degree of instability and therefore the difficulty of the unstable sitting postural task: the further the springs were from the cardan joint, the greater the leverage and thus the easier it was for the springs to resist any tilting. Conversely, the closer together the springs were, the less they were able to resist the tilting of the seat. In order to maintain the device motionless when necessary, each of the two DoF of rotation could be locked with chocks.

The seat device was fitted with an adjustable footrest (for height and depth) so that the degree of flexion at the hip, knee and ankle joint was kept constant (90°) during movements of the seat. This ensured that only the axial segments could control the balance of the device and thus the balance of the upper body. Moreover, movements of the lower limbs were restricted by foam blocks strapped between and around them. Thus, a tilt of the unstable sitting device and stabilization of the axial segments could not be counter-balanced by the action of the lower limbs. The potential role of the upper limbs was also cancelled out by asking the participants to keep their elbows by their side and their arms crossed on the chest. The participant's position on the seat (with the ischial tuberosities centered on the flat support) was checked using visual cues. Lastly, weights were placed on a bar at the back of the seat, in order to counterbalance the load constituted by the participant's lower limbs and the foot-rest at the front; hence, the seat remained horizontal at rest. The whole unstable sitting device was centered on top of a four-leg table, which in turn stood on a three-dimensional (3D) force platform (AMTI, Advanced Mechanical Technology, Inc., Watertown, MA, USA) with a sampling rate of 1000 Hz. Hence, the forces were transmitted from the surface of the seat to the ground through the four springs and the pivot, and then the four legs of the table. During preliminary technical tests, we made sure that the displacement of a weight placed on the device over a given length would result in a CoP displacement of the same length on the force platform. The calibration procedure developed by Larivière et al. (2013) was used to make the balance task's level of difficulty independent of the individual participant's anthropometric characteristics. For each participant, the calibration procedure involved determining the minimal spring-pivot distance for which the system could be considered as neutrally stable for the subject, relative to his/her anthropometric characteristics (see Larivière et al., 2013 for more details). In preliminary experiments, we checked that a distance corresponding to 80 or 90% of that calculated in the calibration procedure was an acceptable level of difficulty for the balance task, while ensuring that the task could be achieved by children aged between 6 and 11 years. Preliminary experiments also showed that bringing the springs progressively closer to the pivot (in increments of 10% of the distance calculated in the calibration procedure) was sufficient to obtain significant differences in the CoP variables.

2.3. Tasks and data acquisition

Trunk and head postural control was assessed using the unstable sitting device described above (Fig. 1). The participant was seated on the unstable sitting device, in order to perform unstable sitting postural trials with two levels of difficulty. For the medium level of difficulty, the springs were set to 90% of the distance calculated during the calibration procedure. For the high level of difficulty, the springs were set to 80% of the calibration distance. At each level of difficulty (medium or high), the participant performed three trials with the eyes open (the EO condition), and three with the eyes closed (the EC condition). Participants were asked to remain as stable as possible and to adopt an upright upper body posture, with their arms crossed on the chest. Each trial lasted 30 s. Trials in EO or EC conditions with a medium or high level of difficulty were intermixed and presented in random order. During a 1-min rest period being trials, the participant remained on the seat (with the latter being locked in a static position).

2.4. Data recording and processing

CoP trajectories on the 3D force platform were recorded at a frequency of 1000 Hz. Raw data were filtered by a low-pass Butterworth filter (order: 4; cut-off: 12 Hz). Next, the CoP displacements were analyzed as the mean of three postural variables: (i) the CoP area (mm²), computed from the 95% confidence ellipses of the CoP displacement; (ii) the CoP mean velocity (mm.s⁻¹); and (iii) the root mean square (RMS) of the CoP displacements (mm). The CoP area evaluates the accuracy of the postural control and the CoP RMS its variability. Lastly, the CoP mean velocity is considered as the most reliable parameter to show age effects on postural control (Prieto et al., 1996). Moreover, these parameters are not influenced by body mass (Chiari, Rocchi, & Cappello, 2002). Since destabilization was induced along both pitch and roll axes, RMS and mean velocity were computed from the resultant displacement of the CoP.

Angular displacements of the head, trunk and pelvis were measured with a 9-camera 3D optoelectronic motion capture system (VICON, Oxford Metrics, Oxford, UK). The marker set (Fig. 2) was a simplified Plug-in Gait set-up (Oxford Metrics), with four markers on the head (two on the left and right of the forehead, and two on the left and right of the back of the head), one on the right acromion, one on the left acromion, five on the trunk (the spinous process of the 7th cervical vertebrae, the spinous process of the 10th thoracic vertebrae, the suprasternal notch of the manubrium, the xiphoid process of the sternum, and middle of the right scapula), and three on the pelvis (on the left and right anterior superior iliac spine, and the sacrum).

The markers' trajectories (sampling rate: 100 Hz), the synchronization with CoP data, and the marker labels were determined using VICON Nexus software (version 1.8.5, Oxford Metrics). The raw data were filtered with a low-pass Butterworth filter (order: 4; cut-off: 12 Hz). On the basis of these kinematic data, anchoring indexes were computed for the head and the trunk in the sagittal, frontal and transversal planes. The AI provides information on the segmental stabilization strategy used by a subject in a particular plane. It is defined as the ratio between the relative angular dispersion of a given body segment to the relative angular dispersion of the underlying segment and the total angular dispersion of the two segments, according to the equation $AI_{\text{segment}} = (\sigma_r^2 - \sigma_a^2) / (\sigma_r^2 +$

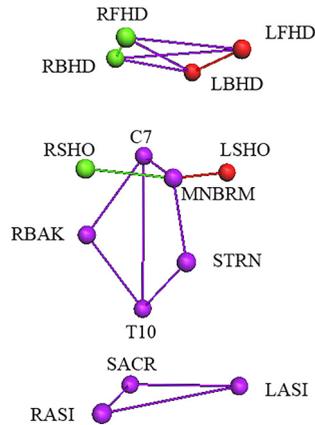


Fig. 2. A simplified Plug-in-Gait marker-set with 14 reflective markers. LFHD and RFHD: left and right forehead; LBHD and RBHD: left and right back of the head; LSHO and RSHO: left and right acromion; C7: spinous process of the 7th cervical vertebrae; T10: spinous process of the 10th vertebrae; MNBRM: the suprasternal notch of the manubrium; STRN: the xiphoid process of the sternum; RBAK: middle of the right scapula; LASI and RASI: left and right anterior superior iliac spine; SACR: the sacrum.

σ_a^2), where σ_a and σ_r are respectively the standard deviation (SD) of the absolute segment's angular displacement and the SD of the relative segment's angular displacement (with respect to the underlying segment). A significantly positive AI_{head} or AI_{trunk} indicates that an articulated control strategy, i.e. respectively that an HSSS or a TSSS is being used. Conversely, a significantly negative AI_{head} or AI_{trunk} indicates the operation of an “en bloc pattern” control strategy for each segment (i.e. with the head stabilized on the trunk or with the trunk stabilized on the pelvis, respectively). Lastly, an AI that does not differ significantly from zero indicates that a mixed (articulated + “en bloc”) strategy is being used. All data processing was carried out using MATLAB R2017 software (MathWorks, Inc., Natick, MA, USA).

2.5. Statistical analyses

Quantitative data were expressed as the mean \pm SD. Postural sway during unstable sitting was analyzed with separate mixed-design analyses of variance (ANOVA) for the CoP area, mean velocity, and RMS. For each of these variables a $4 \times 2 \times 2$ three-way ANOVA was performed with the “age group” as the between-subject factor (6-7yo; 8-9yo; 10-11yo; adults) and the “vision condition” (EO; EC) and the “level of difficulty” (medium; high) as within-subject factors. Tukey's honestly significant difference (HSD) test was used for post-hoc comparisons, when necessary. The threshold for statistical significance was set to $\alpha = 0.05$. Size effects were reported with partial eta² statistics (η_p^2).

To examine the changes with age in segmental strategies, the mean \pm SD values of AI_{head} and AI_{trunk} were computed for the sagittal, frontal and transversal planes for each age group, at each level of difficulty of the unstable sitting postural task (medium; high) and in EO and EC conditions. Two-tailed one-sample *t*-tests were used to determine whether AI_{head} and AI_{trunk} differed significantly from zero, with a threshold for statistical significance of $\alpha = 0.05$.

3. Results

3.1. Postural sway analyzed with the CoP area, CoP velocity and CoP RMS

Unsurprisingly, a higher level of difficulty was associated with a greater CoP area [$F(1,43) = 415.1, p < .001, \eta^2 = 0.91$], mean velocity [$F(1,43) = 59.6, p < .001, \eta^2 = 0.58$] and RMS [$F(1,43) = 222.3, p < .001, \eta^2 = 0.84$]. Moreover, the overall degree of sway was greater in the EC condition than in the EO condition, with a main effect of vision on the CoP area [$F(1,43) = 408.2, p < .001, \eta^2 = 0.90$], mean velocity: [$F(1,43) = 97.3, p < .001, \eta^2 = 0.69$], and RMS [$F(1,43) = 123.2, p < .001, \eta^2 = 0.74$]. Hence, the participants were globally less stable when a higher level of difficulty was combined with the EC condition, as attested to by the significant level of difficulty \times vision interaction observed for the CoP area [$F(1,43) = 17.6, p < .001, \eta^2 = 0.29$], mean velocity [$F(1,43) = 8.14, p = .01, \eta^2 = 0.15$], and RMS [$F(1,43) = 6.28, p = .016, \eta^2 = 0.13$].

One key objective of the present study was to investigate the effect of age on the postural sway measured in an unstable sitting condition that requires the use of axial segments alone for stabilization. As depicted in Fig. 3, we observed a developmental hierarchy (6-7yo > 8-9yo > 10-11yo > adults) for postural sway, with a significant main effect of age reported for the CoP area [$F(3,43) = 86.2, p < .001, \eta^2 = 0.86$], mean velocity [$F(3,43) = 77.34, p < .001, \eta^2 = 0.84$] and RMS [$F(3,43) = 121.6, p < .001, \eta^2 = 0.89$]. Moreover, post-hoc comparisons of successive pairs of age groups showed that in each case, the older of the two groups was significantly more stable (i.e. had lower mean values of the CoP variables) than the younger age group ($p < .001$ for all post-hoc pairwise comparisons and all dependent variables).

The age effect depended significantly on the level of difficulty for the CoP area [$F(3,43) = 5.82, p = .002, \eta^2 = 0.29$] but not for

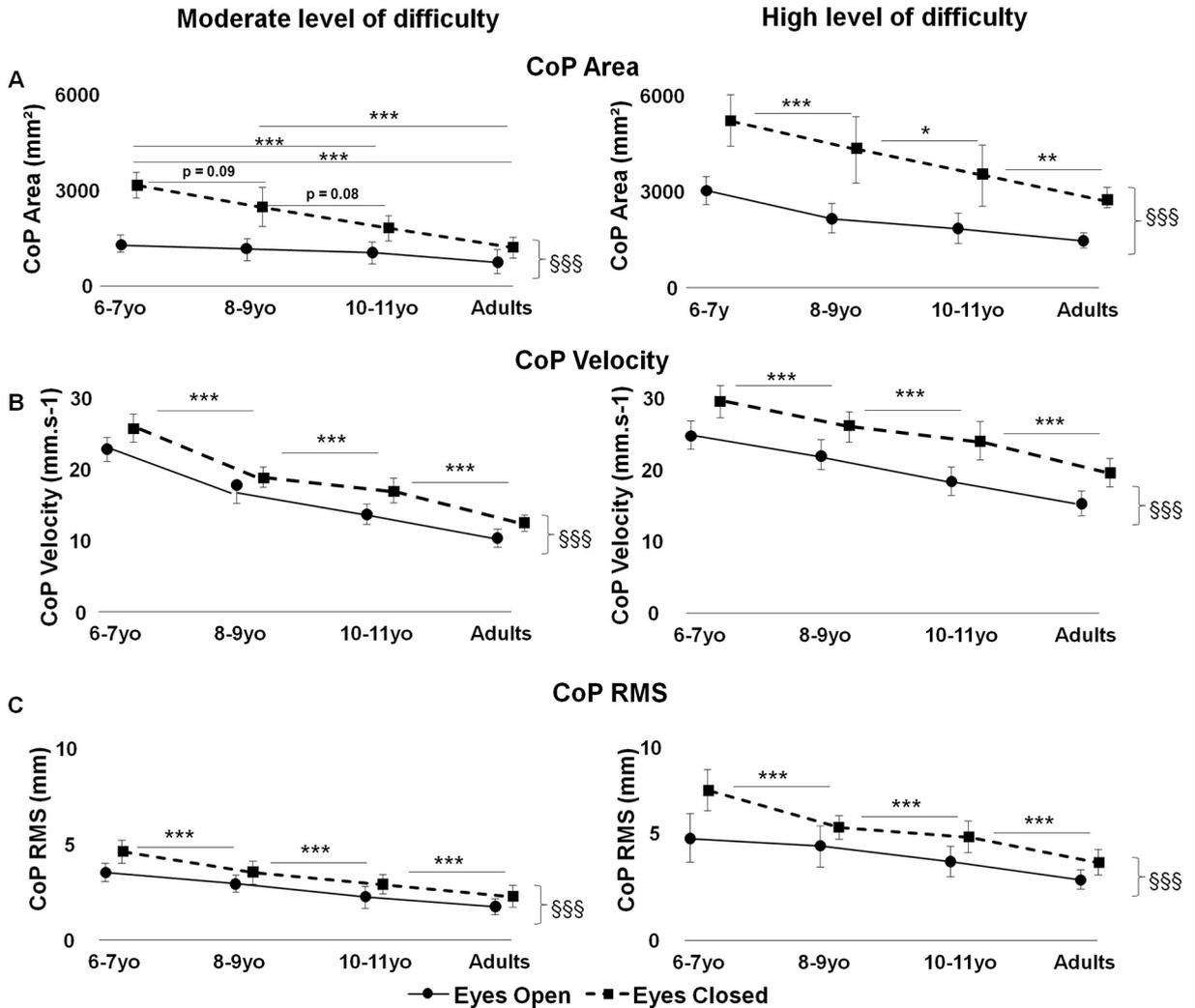


Fig. 3. Upper-body postural sway assessed with CoP variables in unstable sitting. (A) The mean 95% confidence ellipse for the CoP area (in mm²), (B) the mean CoP velocity (in mm.s⁻¹), and (C) the mean RMS of the CoP displacement (in mm) at a moderate level of difficulty (left side) and a high level of difficulty (right side) in unstable sitting, in the eyes-open condition (EO - circles and solid line) and the eyes-closed conditions (EC - squares and dashed line). The error bars correspond to ± 1 SD. Consecutive significant differences between age groups are indicated by asterisks (* $p < .05$; ** $p < .01$; *** $p < .001$). It should be noted that these asterisks refer to post-hoc tests of the main effect of age on the CoP velocity and the CoP RMS, because the Age \times level of difficulty interaction was not significant for these two variables. The symbol § on the right side of the plots refers to a significant main effect of vision (§§§ $p < .001$), and the post-hoc differences between the EO and EC conditions were significant for each age group and all three CoP variables. See the text for more details on the significant vision \times age interaction for CoP area and RMS.

the CoP mean velocity [$F(3,43) = 0.5, p = .69$] or RMS [$F(3,43) = 1.43, p = .25$]. The relative decrease in the CoP area with increasing age was greater at a high level of task difficulty (Fig. 3A), and all pairwise comparisons of age groups at this level were significant (all $p < .05$). At the medium level of difficulty, the overall age hierarchy for the mean CoP area was also 6-7yo > 8-9yo > 10-11yo > adults; however, the differences between adults and the 10-11yo group ($p = .23$), between the 10-11yo and 8-9yo groups ($p = .079$), and between the 8-9 and 6-7yo groups ($p = .091$) did not reach the significance level. The other differences between older and younger groups of participants were significant ($p < .001$).

Furthermore, the absence of vision affected the CoP area and RMS to a larger extent in the younger groups of children than in the older and in the adults (Fig. 3A and C), as confirmed by the significant interactions between age and vision [$F(3,43) = 13.3, p < .001, \eta^2 = 0.48$ for CoP area; $F(3,43) = 7.07, p < .001, \eta^2 = 0.33$ for CoP RMS]. It should be noted that this interaction was not significant for the CoP mean velocity [$F(3,43) = 0.1, p = .97$]. Tukey HSD post-hoc analyses showed that the mean CoP area and CoP RMS were always significantly greater in the EC condition than in the EO condition for each age group (all $p < .05$). It is noteworthy that the difference between EO and EC conditions was particularly marked in the 6-7yo group (see the area and RMS data in Fig. 3A and C) and substantial for 10-11yo group (see the area data in Fig. 3A). Lastly, we noted that the three-way age \times vision \times level of difficulty interactions were not significant for the CoP area [$F(3,43) = 0.61, p = .61$], mean velocity [$F(3,43) = 0.03$,

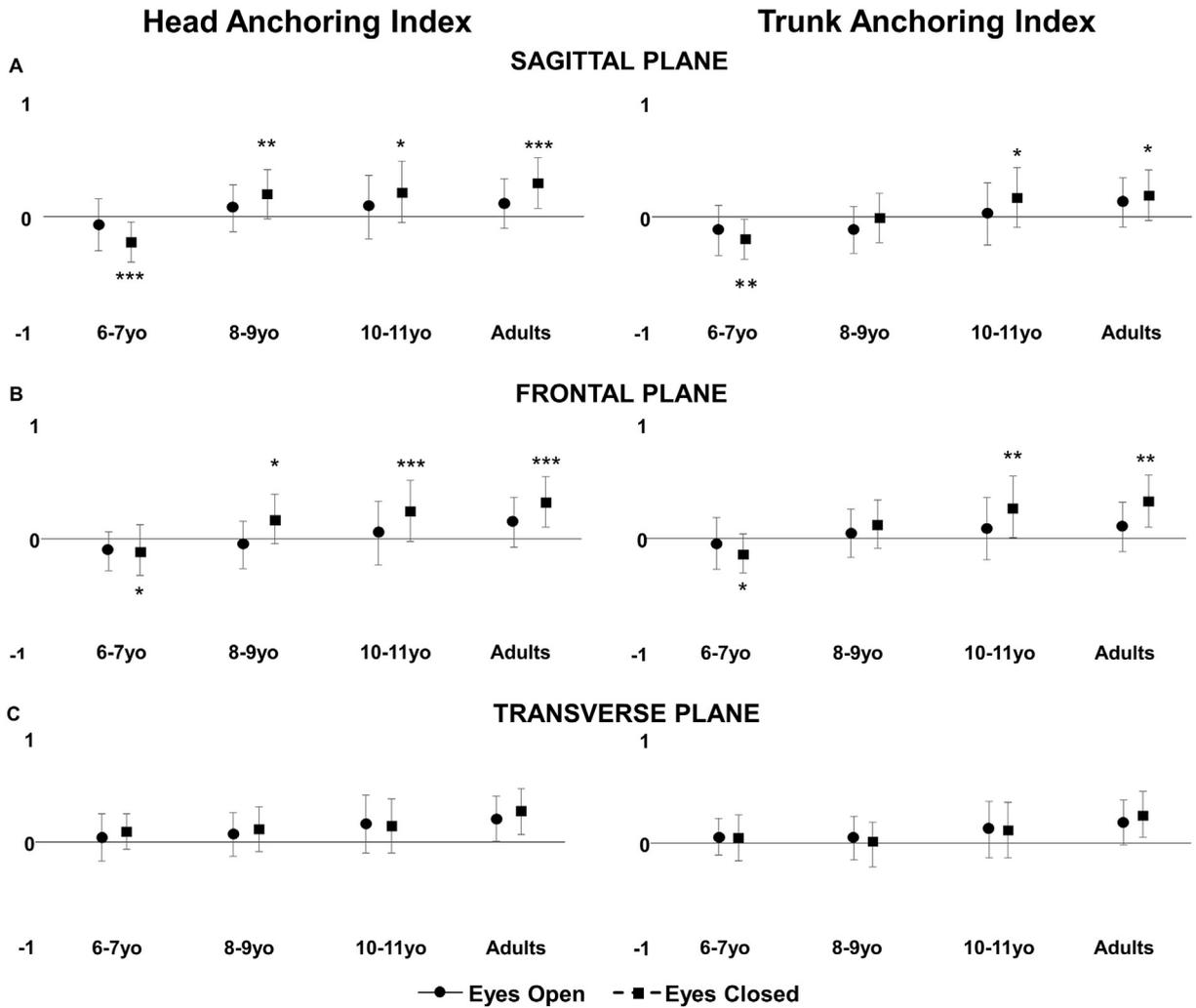


Fig. 4. Anchoring indexes calculated at the medium level of difficulty. The figure shows the mean AIs for the head (left panel) and the trunk (right panel) in each age group, in the sagittal (A), frontal (B) and transversal (C) planes and under eyes-open (EO – black circles) and eyes-closed (EC – black squares) conditions. Error bars indicate ± 1 SD. Significant differences from 0 are indicated by asterisks (* $p < .05$; ** $p < .01$; *** $p < .001$).

$p = .99$] and RMS [$F(3,43) = 0.98, p = .41$].

3.2. Stabilization strategies

The AIs for the head and trunk in all planes during unstable sitting are displayed in Fig. 4 (for a medium level of difficulty) and Fig. 5 (for a high level of difficulty). Firstly, one can note that the AI in the transverse plane was never significantly different from zero, regardless of the level of difficulty, vision condition, and group ($p > .05$ for all). This might be an inherent feature of the task; indeed, the postural disturbance caused by the tilt of the seat involved displacements along the anteroposterior and mediolateral axes but never involved axial rotation. Interestingly, similar patterns were observed in the sagittal and frontal pattern for each group and in each experimental condition.

In the 6-7yo group, the mean values of AI_{head} and AI_{trunk} in both the sagittal and frontal planes were negative under all experimental conditions. In the EC condition, AI_{head} and AI_{trunk} for both planes were significantly negative at the medium level of difficulty ($AI_{head}: p < .001$; $AI_{trunk}: p < .01$; Fig. 4) and the high level of difficulty ($p < .05$); this indicated the use of head-on-trunk and trunk-on-pelvis stabilization strategies with the eyes closed. This was also the case in the EO condition at the high level of difficulty for AI_{head} ($p < .05$), whereas AI_{trunk} did not differ significantly from zero ($p > .05$). At the medium level of difficulty (Fig. 4) and the EO condition, the values of AI_{head} and AI_{trunk} were also negative but did not differ significantly from zero ($p > .05$); this suggested the use of a mixed stabilization strategy when the postural challenge was less difficult.

In the 8-9yo group, AI_{head} in both sagittal and frontal planes was significantly positive at the moderate level of difficulty with EC

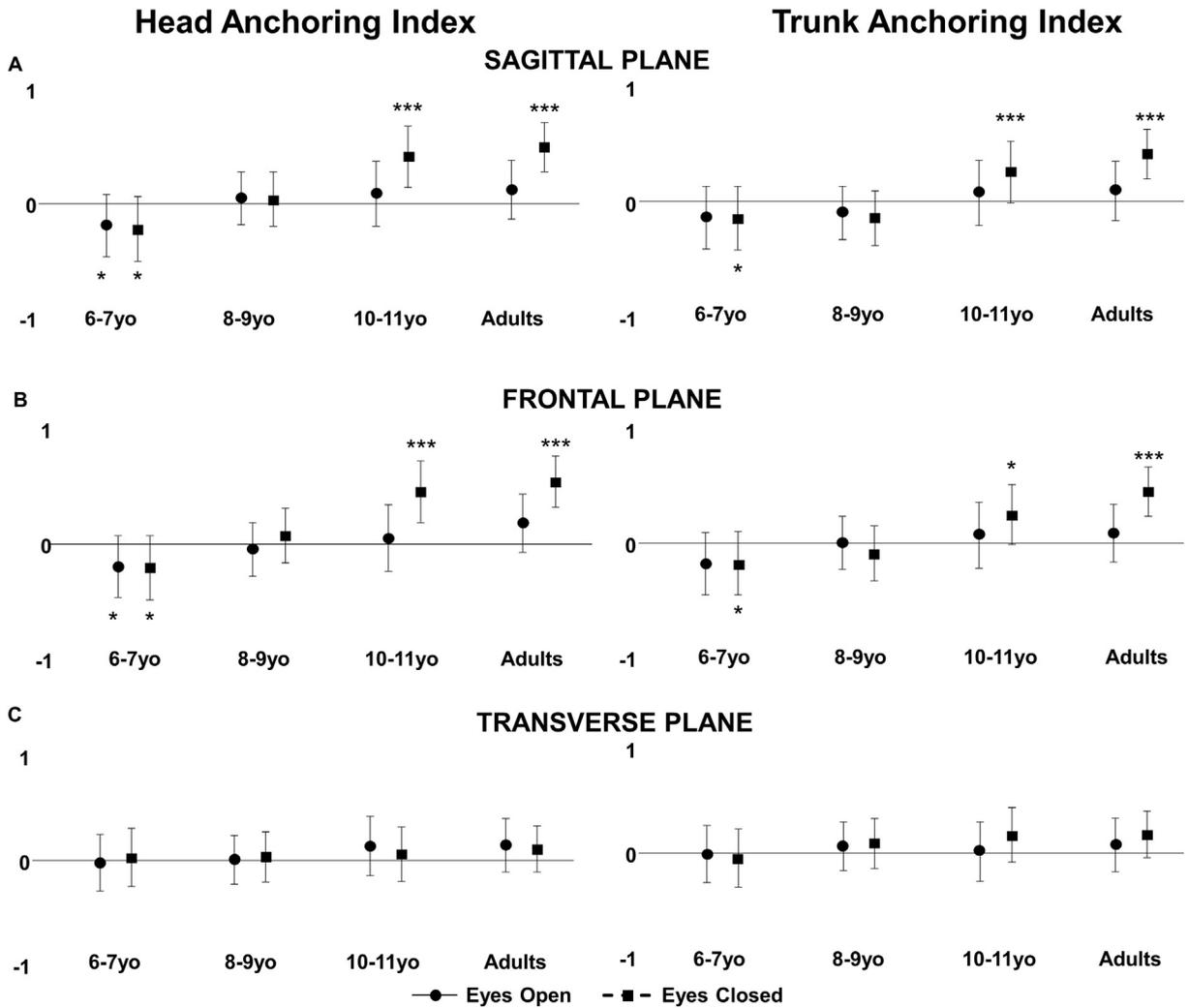


Fig. 5. Anchoring indexes calculated at the high level of difficulty. The figure shows the mean AIs for the head (left panel) and the trunk (right panel) in each age group, in the sagittal (A), frontal (B) and transversal (C) planes and under eyes-open (EO – black circles) and eyes-closed (EC – black squares) conditions. Error bars indicate ± 1 SD. Significant differences from 0 are indicated by asterisks (* $p < .05$; ** $p < .01$; *** $p < .001$).

($p < .01$ and $p < .05$ respectively; Fig. 5); this clearly demonstrated the emergence of a HSSS in this condition. However, for both planes and in all other experimental conditions, AI_{head} and AI_{trunk} did not differ significantly from zero ($p > .05$), suggesting that mixed strategies were being used to stabilize the head and trunk.

Lastly, very similar patterns of results were observed for sagittal and frontal AI_{head} and AI_{trunk} in the 10-11yo group and in the adult groups, whatever the experimental condition. In both groups, all the mean values of AI_{head} and AI_{trunk} were positive. Moreover, AI_{head} and AI_{trunk} in frontal and sagittal planes were significantly positive in the EC condition with a moderate level of difficulty (Fig. 4; sagittal plane: $p < .05$ in all cases except $p < .001$ for the adult group's AI_{head} ; frontal plane: $p < .001$ for AI_{head} and $p < .01$ for AI_{trunk} in both 10-11yo and adults groups) and with a high level of difficulty (Fig. 5; $p < .001$ in all cases except $p < .05$ in the frontal plane for AI_{trunk} in the 10-11yo group). These results indicated that the 10-11yo group and adults were using an HSSS and a TSSS when deprived of vision. In the EO condition, the positive mean values of AI_{head} and AI_{trunk} in both the 10-11yo and adult groups did not differ from zero, regardless of the level of difficulty ($p > .05$ for all); this indicated that mixed strategies were used when vision was available.

4. Discussion

In the present study, we assessed the development of the postural stabilization of axial body segments in children aged 6–11 and in adults (as controls) performing a postural task on an unstable sitting device under EO or EC conditions and with a moderate or high level of balance challenge. As we had initially hypothesized, postural sway (evaluated from the area, velocity or RMS of the CoP)

gradually decreased with the age group (6–7yo > 8–9yo > 10–11yo), and there were still differences between the 10–11yo group and the adults. This progressive effect of age on postural sway was accentuated when balance was especially challenging, due either to a lack of vision (for CoP Area and CoP RMS) or a high level of postural task difficulty (for CoP Area). Furthermore, the development of axial stabilization was characterized by progressive changes in the segmental strategies used between 6 and 11 years of age, with a move from an “en bloc” pattern at 6–8yo to HSSS and TSSS at 10–11yo. In fact, the head and trunk anchoring indexes were significantly negative in the EC condition or at a high level of difficulty in the 6–7yo group but started to become positive in 8–9yo group (IA_{head} at a moderate level of difficulty). Behavior in the 10–11yo and adult groups was qualitatively similar, with positive anchoring indexes for the head and the trunk. Interestingly, the indexes did not differ significantly from zero in the EO condition at both levels of difficulty, indicating the use of a mixed strategy. In contrast, the 10–11yo and adult groups used HSSS/TSSS in the EC condition.

4.1. A progressive improvement in axial segment stabilization between 6 and 11 years of age

With the exception of the CoP area measured at a moderate level of difficulty with EO (where only trends were present), we observed significant main effects of age and significant differences between pairs of successive age groups for all the CoP variables. This indicated a progressive improvement in axial segment stabilization between the ages of 6 and 11. This decrease in postural sway was associated with the progressive acquisition and mastery of adult-like stabilization strategies for the head and the trunk. Indeed, when the balance task was difficult (i.e. EC at the moderate level of difficulty and EC and EO at the high level of difficulty), the negative anchoring indexes clearly showed that younger children used “en bloc” stabilization strategies, with the head and the trunk respectively stabilized over their underlying segments (the trunk and the pelvis).

Next, from the age of 8 onwards, the anchoring indexes did not differ significantly from zero -suggesting that the “en bloc” stabilization strategies had disappeared even when the task was difficult. Conversely, “in-space” strategies started to emerge progressively (when the postural challenge was moderate) in this age group. However, a trunk-in-space stabilization strategy was still absent, as indicated by the not significantly positive anchoring indexes for the trunk at both levels of difficulty and under both visual conditions. The age of 8 thus appears to be pivotal; adult-like segmental stabilization strategies start to emerge, although stabilizing the head in space during a difficult task remains challenging - as also previously reported during locomotion (Assaiante & Amblard, 1995). Our findings are also in line with Roncesvalles et al.'s (2005) report on a transition phase around the ages of 7–9, as characterized by a shift from an egocentric frame of reference to an exocentric frame of reference (with segments oriented with respect to the gravity). Moreover, this emerging strategy in the 8–9yo group was efficient for the postural control of axial segments, since a significant decrease (relative to children aged 7) in body sway during postural tasks was observed in the present study and in the literature (Olivier, Cuisinier, Vaugoyeau, Nougier, & Assaiante, 2010). Some researchers consider that these clear changes around the age of 8 (observed in this instance during quiet standing or during dynamic activities such as walking) evidence the “non-linear” development of postural control; in relative terms, they report that the postural sway decreases significantly to the age of 8, does not change between 8 and 11, and then decreases further after the age of 11 (Assaiante & Amblard, 1995; Cuisinier et al., 2011; Forsberg & Nashner, 1982; Kirshenbaum, Riach, & Starkes, 2001; Olivier et al., 2010). These researchers have suggested that there is a turning point in the sensory integration process, with a shift from visual dependence to adult-like postural control based on a combination of visual and proprioceptive feedback (Shumway-Cook & Woollacott, 1985). However, our results show that the age of 8–9 years corresponds to the progressive, essentially linear development of axial control, rather than a “turning point”. Although new stabilization strategies appeared at this age, the decreases in postural sway during unstable sitting were quite similar before (vs. 6–7yo) and again (vs. 10–11yo). Similarly, the EC vs. EO differences in postural sway decreased (at least for CoP Area and CoP RMS) not only from 6–7yo to 8–9yo but also from 8–9yo to 10–11yo and again from 10–11yo to adulthood.

Ultimately, from the age of 10 onwards, the children became able to use an HSSS and a TSSS even when the task was difficult. The mastery of an articulated strategy at the trunk is especially important for the development of dynamic balance because it can attenuate head sway during balance tasks - as previously reported for locomotion (Kavanagh, Barrett, & Morrison, 2006). Overall, the gradual changes in the AIs (from negative to positive) between the 6–7yo and 10–11yo groups and the decrease in postural sway appeared to be in line with Bernstein's DoF theory; one or more previously frozen DoF (i.e. spatially constrained joints) are progressively released during the development of axial segment stabilization (Bernstein, 1967). These fundamental changes in the stabilization of axial segments during middle childhood emphasize the importance of the segments' contribution to the development of overall postural control.

4.2. The shift from reactive axial segment control to proactive axial segment control, and its contribution to postural control

In the present study on an unstable seated postural task, we observed developmental differences in postural sway over the 6–11 age range. These changes were related to the postural control of the trunk and head. Similar developmental changes during middle childhood have also been shown for standing tasks (Ferronato & Barela, 2011; Hsu et al., 2009; Stambolieva, Marinov, Kolev, & Gatev, 2012). These findings raise the question of how the development of axial segment control specifically contributes to changes in postural sway observed during ontogenesis – changes that might also be due to maturation of the CNS's control processes. Age-related improvements in postural control are often considered as a reflect of the maturation of the CNS in general and sensorimotor processes in particular, resulting in postural control that is more accurate (i.e. small CoP sway area) and efficient (i.e. small RMS and slow CoP displacements) (Kirshenbaum et al., 2001; Rival, Ceyte, & Olivier, 2005). More precisely, the researchers argued that the high velocity of CoP displacements at the age of 6–7 and the progressive decrease in this velocity with age until adulthood is the sign of a transition from a reactive control strategy (with fast correction of the CoP's position based on sensory feedback) to a more proactive

strategy (with a combination of feedforward and feedback control of the CoP displacement) (Ferronato & Barela, 2011; Rival et al., 2005; Stambolieva et al., 2012). Our present results showed that the velocity of the CoP displacement decreased with age during an unstable sitting postural task, indicating that the same improvement in the child's postural control strategy applied to axial segments. In the present study, the ability to remain stable on the unstable sitting device relied on the participant's ability to anticipate movements of the seat. In some cases, these movements were initiated by movements of the participant's axial segments. Hence, stability should depend on anticipatory control and feedforward mechanisms. Several studies (Assaiante, Barlaam, Cignetti, & Vaugoyeau, 2014; Barela, Jeka, & Clark, 2003; Barlaam, Fortin, Vaugoyeau, Schmitz, & Assaiante, 2012; Cignetti, Caudron, Vaugoyeau, & Assaiante, 2013) have found that feedforward postural control mechanisms are closely linked to construction of the body schema and to internal models of action. The fact that the construction of the body schema and refinements of the internal model (both of which are involved in the anticipatory control of posture) mature slowly throughout childhood (Barlaam et al., 2012; Choudhury, Charman, Bird, & Blakemore, 2007; Cignetti, Caudron, et al., 2013) may explain (i) the progressive development of axial segment postural control observed between 6 and 11 years of age, and (ii) the differences between older children and adults. We hypothesize that the improvement of postural control reported in the literature throughout middle childhood is strongly influenced by the development of axial segment stabilization, as described in the present study. Indeed, given that (i) the trunk represents a child's first frame of reference for postural orientation, balance control and posturokinetic activities (Assaiante, 2012; Roncesvalles et al., 2005), (ii) head stabilization facilitates the sensory integration of the visual and vestibular inputs involved in postural control, and (iii) axial segments account for a large proportion of the total body mass (Massion, Popov, Fabre, Rage, & Gurfinkel, 1995; Winter, 1995), a low level of head and trunk stability (induced by weaker axial segment control) in the youngest children might lead to more frequent deviations of the CoP – and thus broader and faster corrections of the CoP – during static or dynamic postural control in stance.

4.3. *The development of postural control of axial segments continues from 11 years old to adulthood*

Although we found that children in the 10-11yo group were able to use the same segmental stabilization strategies as adults, the postural sway was less accurate, faster, and more variable in the children than in the adults. This is in line with previous suggestions whereby postural control in general and trunk stabilization in particular continue to develop during adolescence (Assaiante, 2012; Cignetti, Chabeauti et al., 2013; Cignetti, Caudron et al., 2013). As suggested above, these changes might also be linked to the updating of internal models of action and the refinement of feedforward control mechanisms that occur during adolescence (Choudhury et al., 2007). Nevertheless, at the age of 11, our results show that the head and the trunk can be stabilized with respect to space in an adult-like manner - even when balance is challenged.

Unexpectedly, we found that the HSSS and TSSS were reinforced under EC conditions both in 10-11yo children and in adults, whereas the same mixed strategy was used with eyes open by the two populations. There are several possible explanations for this finding. Firstly, (Fitzpatrick & McCloskey, 1994) suggested that proprioceptive information is heavily involved in detecting body postural sway. Moreover, movement of the pelvis appears to trigger postural adjustments during sitting (Forssberg & Hirschfeld, 1994). Therefore, it is possible that proprioceptive information may be used less when vision is available and, conversely, that the removal of visual information (under EC conditions) allows more effective use of the pelvis's proprioceptive information for stabilization of the trunk and therefore the head with respect to space. The better use of proprioceptive information may be enabled by attentional refocusing on pelvis movements when the eyes are closed. According to Cuisinier et al. (2011), this ability to reweight sensory information may be not available in early middle childhood and might only reach an adult-like level at around 11 years of age. If so, this could explain why only the 10-11yo children and the adults were able to use an HSSS and a TSSS in the EC condition, whereas the youngest children — more depending on visual information (Ferber-Viart et al., 2007) — used an “en bloc” strategy for the head and the trunk. Furthermore, previous studies have reported that an HSSS is the most appropriate strategy for balance control under difficult conditions (Nadeau, Amblard, Mesure, & Bourbonnais, 2003). Thus, older children and adults reinforce their use of the available in-space stabilization strategy under EC conditions because the CNS detects the more challenging situation and then applies the most effective balance strategy. Lastly, this principle of effectiveness may be supplemented by a principle of efficiency; in the EO condition, a mixed stabilization strategy was enough to efficiently deal with this less challenging balance task. Given that only small postural corrections were required, the latter could have been produced by slight movements of the pelvis, trunk and/or head as part of a low-costly segmental stabilization strategy for the CNS. In contrast, more demanding (EC) conditions required children in the 10-11yo group and the adults to use the pelvis to minimize the postural sway by combining an HSSS and a TSSS. The ability to use this potentially more costly strategy would avoid large trunk adjustments that could be hazardous for stability in a more challenging balance task.

4.4. *Limitations: the age effect was studied with a cross-sectional design, without assessing gender differences*

Our study assessed the effects of age on postural parameters in four different groups in a cross-sectional manner, rather than using a 6-year longitudinal follow-up cohort. Although we reported robust age effects (considering strong effect sizes), conclusions drawn from these group data regarding general developmental trajectories should be taken with appropriate caution. In addition, our methodology and sample sizes were not designed to study gender differences in the stabilization of axial segments. However, known differences occur in the development of postural control between young girls and young boys. Specifically, boys around the age of 9 years sway more and show larger age-related differences than girls. These differences may indicate a slight delay in the development of postural control in young boys, and some authors suggest the use of different postural strategies, particularly with boys

who potentially rely more on somatosensory feedback (Nolan, Grigorenko, & Thorstensson, 2005; Smith, Ulmer, & Wong, 2012). Therefore, it would be interesting to explore gender differences in the development of postural control of the axial segments further. Indeed, it is of particular interest to determine whether the same differences (girls vs. boys) will occur around the age of 9–10.

5. Conclusion

To the best of our knowledge, the present study is the first to have assessed the effect of age on the postural stabilization of axial body segments in children aged from 6 to 11 years and in adults. When an unstable sitting device required the specific use of the axial segments to maintain balance, the postural sway gradually decreased with age (6-7yo > 8-9 yo > 10-11yo > adults). The age-related decrease was even more marked under more challenging conditions (i.e. EC and the hardest level of balance difficulty). The development of the axial segment control was also characterized by progressive changes in segmental stabilization strategies, with a move from an “en bloc” pattern at 6-7yo to the ability to select head and trunk in-space strategies when necessary at 10-11yo (as in adults). We suggest that the development of axial segment control contributes to the overall development of postural control observed between 6 and 11 years of age; this might be explained by the progressive emergence of feedforward mechanisms. The present study introduced a novel method and provided normative data on the specific use of axial segments to control posture during middle childhood. The novel method might (i) highlight impairments in axial postural control in children with medical conditions (e.g. children with cerebral palsy), (ii) serve as a tool for physical rehabilitation, and (iii) help to evaluate the efficacy of treatments that specific target axial body segments.

Author statements

Jonathan Pierret, Christian Beyaert, Jean Paysant and Sébastien Caudron conceived and designed research.

Jonathan Pierret, Christian Beyaert and Sébastien Caudron performed experiments.

Jonathan Pierret and Sébastien Caudron analyzed data.

Jonathan Pierret and Sébastien Caudron performed the statistical analysis.

Jonathan Pierret, Sébastien Caudron and Christian Beyaert interpreted results of experiments.

Jonathan Pierret prepared figures.

Jonathan Pierret, Sébastien Caudron and Cristian Beyaert drafted the manuscript.

Jonathan Pierret, Christian Beyaert, Jean Paysant and Sébastien Caudron approved final version of submitted manuscript.

Declaration of Competing Interest

None.

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