



# Development of postural stability limits: Anteroposterior and mediolateral postural adjustment mechanisms do not follow the same maturation process

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## ABSTRACT

There is increasing evidence that indicates a critical transition period for the maturation of postural control from the ages of 6–7 years. Some studies suggest that this transitional period may be explained by a change from a ballistic toward a sensory strategy, but the cause remains unknown. The purpose of this study was to investigate the influence of the transition period on dynamic postural control in a natural self-initiated leaning task under different sensory conditions. We evaluated the center of pressure (COP) displacement during maximum leaning in four directions (forward, backward, rightward, leftward) under three sensory conditions (eyes open, eyes closed and eyes closed standing on a foam). Three groups were tested: young children (4 years old), older children (8–10 years old) and adults (21–42 years old). The maximum COP excursion along the anteroposterior and mediolateral axes and the COP amplitude were analyzed. Young children showed smaller maximum anteroposterior and mediolateral COP excursion than other groups. Older children also exhibited a significantly smaller maximum excursion along the mediolateral direction but performed similar to adults along the anteroposterior direction. In a similar manner, the analysis of the COP amplitude did not indicate any differences between the groups along the anteroposterior axis. In contrast, along the mediolateral axis, the results showed developmental differences. Furthermore, the effect of sensory conditions was similar across the children's groups. Our results suggest an important plasticity period for the maturation of postural control mechanisms. Notably, our findings support the idea that the postural mechanisms controlling the anteroposterior axis reach maturity before the mechanisms involved in controlling the mediolateral axis.

## 1. Introduction

Postural control is a fundamental component of movement development and movement control that involve both the ability to recover from instability (in response to an external perturbation) and the ability to anticipate and move to avoid instability (in response to an internal perturbation or self-initiated movement) (Bartlett & Birmingham, 2003). Postural control requires that the center of pressure (COP) be maintained within the base of support delimited by the feet. The maximal COP displacement within the base of support before stepping or falling is namely the limits of stability. From the age of 7, humans are using 70% of their base of

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support along both the anteroposterior (AP) and mediolateral (ML) axes. In contrast, younger children from 4 to 6 years of age, used only 44% of their support base (Riach & Starkes, 1993). This non-monotonic development pattern, i.e. a sudden rather than a gradual change with age in the parameters of movement and postural control have been also reported in many studies (Riach & Starkes, 1994; Kirshenbaum, Riach, & Starkes, 2001; Rival, Ceyte, & Olivier, 2005; Assaiante, 2012) and in studies assessing reactive postural adjustments (Shumway-Cook & Woollacott, 1985), postural control adjustments during self-initiated unloading (Hay & Redon, 1999), goal-directed arm movements (Sigmundsson, Whiting, & Loftesnes, 2000) and quiet standing tasks (Verbecque, Vereeck, & Halleman, 2016; Riach & Starkes, 1994; Kirshenbaum et al., 2001; Rival et al., 2005; Figura, Cama, Capranica, Guidetti, & Pulejo, 1991). Of particular interest, several ontogenetic studies investigating postural control suggested that this transition period takes place around 6–7 years of age and is characterized by a sudden decrease in COP velocity, slower anticipatory postural adjustments, greater variability and amplitude of the COP excursion as well as mentioned above, an abrupt increase in the limits of stability along both AP and ML directions (Riach & Starkes, 1993; Riach & Starkes, 1994; Kirshenbaum et al., 2001; Assaiante, 2012, Shumway-Cook & Woollacott, 1985; Figura et al., 1991).

One important hypothesis that has been proposed to explain these sudden changes in movement and postural control during the transition period are nervous system adaptations in which the effectiveness of the processing and integration of multimodal sensory information increase and evolve from a ballistic toward a sensory strategy (Kirshenbaum et al., 2001; Rival et al., 2005; Assaiante, 2012). The ballistic strategy also named open loop, primary variability or bloc strategy is the first stage of postural control development in which young children until the age of 5 years make large COP corrections with a high COP velocity (Kirshenbaum et al., 2001; Assaiante, 2012). The use of sensory feedback may produce a more accurate targeting of COP within the base of support but this stage involves honing of the ballistic response and children have to use an egocentric reference to control their posture (Roncesvalles, Schmitz, Zedka, Assaiante, & Woollacott, 2005; Assaiante, 2012) since they have limited use of the online sensory information (Kirshenbaum et al., 2001). The sensory strategy is the second postural strategy stage also named close loop, secondary variability or multiarticulated strategy that appears around the age of 8 years old. It could be reflected by smaller and slower COP displacements compared to the first stage. The sensory information may be used to expand the range of quiet stance stability and allow deviation from the desired position. This step increases the degrees of freedom which improves the multisensory calibration and promotes greater sensorimotor integration skills required for adaptable function in a changing environment (Kirshenbaum et al., 2001; Hadders-Algra, 2010; Assaiante, 2012). This is an important period in which children master an internal representation of their body scheme and use an exocentric reference (with respect to environmental landmarks) to position their body segments in space under gravitational and destabilizing torques (Roncesvalles et al., 2005; Assaiante, 2012; Blanchet, Marchand, & Cadoret, 2012). Between these postural strategy stages, a recalibration period is required; this is the transition period. At the age of 6 to 7 years old, the transition period appears to be a critical period in postural control development to improve the integration of sensory information for postural control especially those from external sources such as environmental and external forces (Roncesvalles et al., 2005; Assaiante, 2012; Hay & Redon, 1999; Kirshenbaum et al., 2001).

However, most studies supporting this view have used experimental paradigms involving either fast unpredictable surface tilts or quiet standing tasks performed under limited sensory conditions (Riach & Starkes, 1994; Kirshenbaum et al., 2001; Rival et al., 2005; Shumway-Cook & Woollacott, 1985). The purpose of the present study was to investigate the influence of the transition period on dynamic postural control in a natural self-initiated leaning task under different sensory conditions. To do so, a group of young children (4 to 5 years of age) was compared to a group of older children (8 to 10 years of age) and a group of adults (21 to 42 years of age) to test the hypothesized transition period of 6 to 7 years of age during a task at the limit of stability. Furthermore, to investigate whether sensory strategy is a major factor that can explain the hypothesized transition period, all subjects were tested in three sensory conditions. If the transition period is primarily explained by a sensory strategy, then younger children will show significant changes in postural control compared to older children and adults in specific sensory conditions.

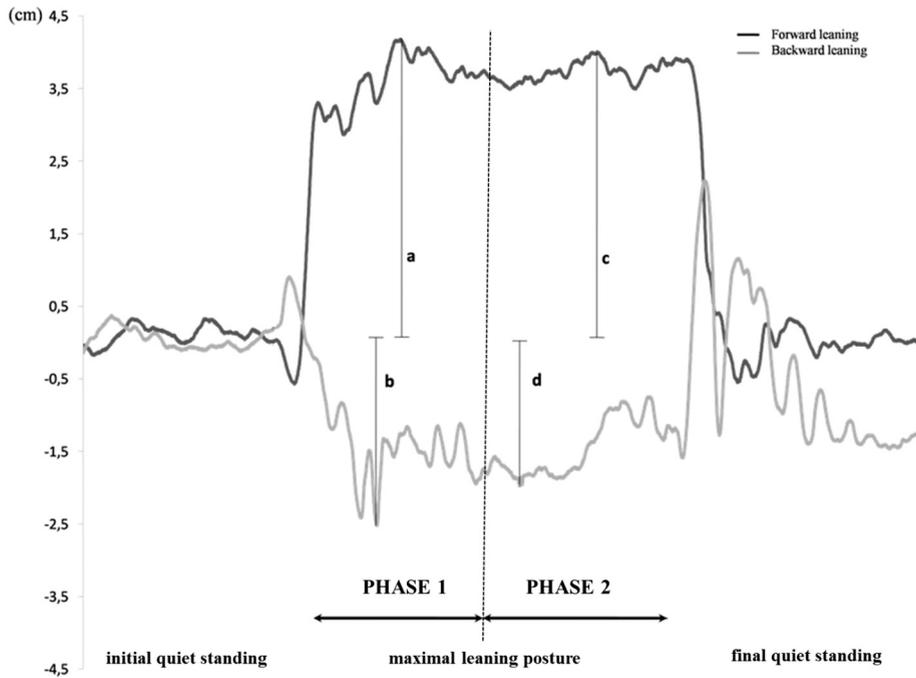
## 2. Methods

### 2.1. Participants

The participants were 10 “young children” (YC) aged from 4 to 5 years ( $4.2 \pm 0.3$  years old; 4 boys and 6 girls), 11 “older children” (OC) aged from 8 to 10 years ( $8.6 \pm 0.7$  years old; 4 boys and 7 girls), and 10 adults aged from 21 to 42 years ( $30.7 \pm 7.4$  years old; 4 men and 6 women). The adults sample age varies from 21 to 42 years in order to represent a normal adult population. Exclusion criteria were a history of orthopedic or neurologic disorders, recent surgical procedures and drug use, as reported by the subjects or their parents. All participants were recruited from the same social environment. This study was approved by the university ethics committee, and informed consent was obtained from each participant or the children’s parents prior to the study.

### 2.2. Experimental setup and procedures

At the beginning of a trial, participants stood barefoot on a force plate. Participants were asked to maintain upright quiet standing position until an auditory cue (5 s) instructed the participants to lean as far as possible in a different directions for each trial (forward, backward, rightward or leftward) and to maintain this maximum leaning position. After 10 s, a second auditory cue instructed the subject to return to the initial quiet standing position (7 s). During the experimental task, participants were asked to keep their body straight without moving or lifting their feet or flexing their hips or knees (Blanchet, Prince, Chouinard, & Messier, 2014; Bartlett &



**Fig. 1.** The parameters considered in the data analysis are shown. The signal was collected from a representative adult subject. The black line represents the COP excursion during a complete trial of maximal leaning task in the forward direction (AP axis). The gray line represents the backward trial (AP axis). The analysis of the maximal leaning posture was subdivided into two phases. The start of phase 1 was determined by the first time that the COP moved in the opposite direction to the voluntary leaning movement (end of reaching stability limits), and the total duration of this phase was at the first 5 s of maintaining the maximal leaning position. We also analyzed phase 2, i.e., the COP displacement during the last 5 s of maintaining the maximal leaning position. The lines a, b, c, and d represent the maximum COP excursion relative to the mean position of COP during initial quiet standing. The summation of the values of the lines a and b (phase 1) and the lines c and d (phase 2) represent the total maximum COP excursions along the AP axis (cm). The same calculation was executed for the ML axis (summation of the maximum COP excursion values between the rightward and leftward directions (ML axis)).

Birmingham, 2003). This experimental task imitates functional daily living tasks and when compared to quiet standing, it increased the external gravitational torque and muscular demand as the orientation of the participant's body changed from the vertical axis (Viel, Vaugoyeau, & Assaiante, 2009; Blanchet et al., 2012). Moreover, our self-initiated leaning task allows time for planning the forthcoming perturbations based on sensory signals.

This experimental task was performed under three sensory conditions: a) eyes open (EO), b) eyes closed (EC) and c) eyes closed while standing on a foam (EC + F). The compliant foot support was a 5.5 cm-thick medium density open cell foam. One trial was performed under each condition for each of the four directions. Before data collection: a) the experimenter demonstrated the task, b) YC were asked to reformulate instructions, c) all subjects performed a practice trial and d) after each trial, all subjects were asked to confirm that they reached their maximum leaning.

### 2.3. Data collection and data analysis

Ground reaction force data were collected at 200 Hz using an AMTI force platform and the Balance Clinic software. The amplitudes (cm) of the COP excursions along the AP and ML axes during forward, backward, rightward and leftward leaning were analyzed. The leaning trials were subdivided in two phases (Fig. 1). The beginning of phase 1 was defined as the first time the COP moved in the opposite direction of the voluntary leaning movement and ended at the 5th second of maximum leaning. This initial portion of the maximal leaning may reflect, in part, planning mechanisms or anticipation. An additional external force creating a destabilizing torque initiate the leaning movement in this phase. Phase 2 occurs during the last 5 s of maximum leaning. This second phase may reflect the contribution of an on-line postural control mechanism (Blanchet et al., 2014).

The amplitudes (cm) of the maximum COP excursions were calculated using the mean COP position during initial quiet standing and the maximum value reached during maximum leaning (Fig. 1). The range between the forward and backward values represents the total maximum COP excursion along the AP axis and the range of the leftward and rightward values represents the total maximum COP excursion along ML axis (Blanchet et al., 2014; Bartlett & Birmingham, 2003). Larger COP excursions during the maximal leaning represented greater balancing ability by increasing the limits of stability. These measures have shown moderate-to-excellent test-retest reliability in children (Bartlett & Birmingham, 2003). The computation of these variables were made for both phases. These values were normalized by foot length and foot width and expressed as a percentage of the base of support along the AP and ML

axes.

The root mean square (RMS) amplitude of the COP (cm) was a variable largely used in postural control analysis (Wickstrom, Stergiou, & Kyvelidou, 2017; Palluel, Nougier, & Olivier, 2010). Also named standard deviation, the RMS values represent the variability of COP displacements. This parameter is independent of the effect of biomechanical factors such as weight that change rapidly throughout development (Wickstrom et al., 2017). The AP and ML RMS values allow to estimate overall postural performance (Palluel et al., 2010). A reduction of these parameters was often considered as an improvement of stability (Palluel et al., 2010). The reliability and validity of the parameters for clinical quantification of postural control has been already demonstrated (Pinsault & Vuillerme, 2010; Palluel et al., 2010; Wickstrom, Stergiou, & Kyvelidou, 2017; Blanchet et al., 2014). The RMS were calculated for the axis of leaning movement (AP axis for forward and backward leaning and ML axis for rightward and leftward leaning) and for the opposite axis of movement (ML axis for forward and backward and AP axis for rightward and leftward). The analyses of the RMS amplitude of the COP for the opposite axis during the voluntary movement are reported to illustrate lateral postural adjustments or asymmetries (Mancini, Rocchi, Horak, & Chiari, 2008).

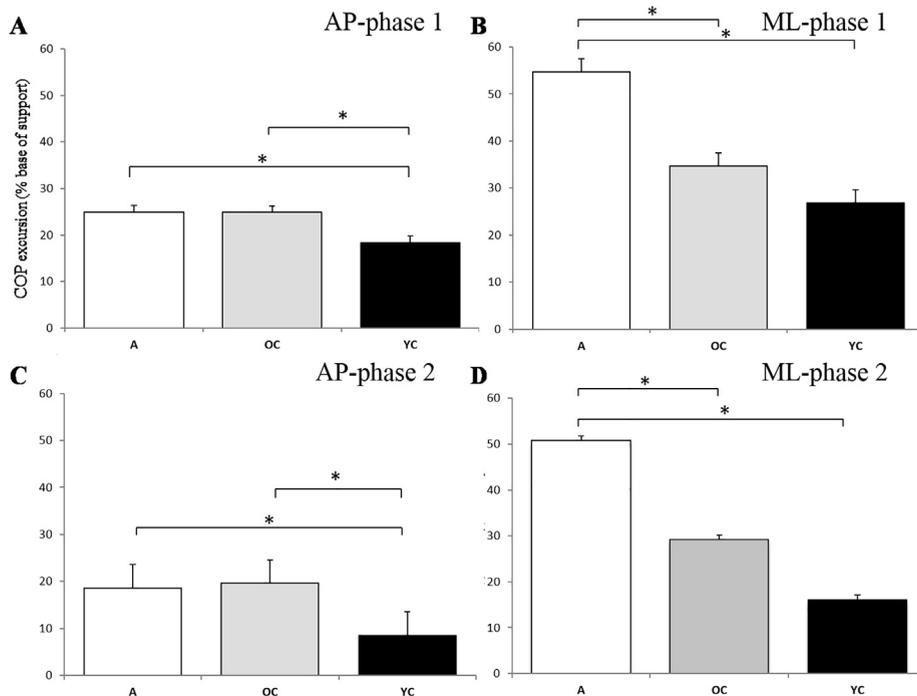
#### 2.4. Statistical analysis

A three-factor repeated-measures ANOVA (3 age groups  $\times$  3 sensory conditions  $\times$  4 directions: forward, backward, rightward, leftward) was applied on RMS amplitude of COP. For the maximum COP excursion data, a separate three-factor repeated-measures ANOVA (3 age groups  $\times$  3 sensory conditions  $\times$  2 directions: AP and ML) was conducted. These analyses were performed for leaning phase 1 and phase 2. Statistically significant difference was set at  $p < 0.05$  and post-hoc pair-wise comparisons were made using Bonferroni adjustments.

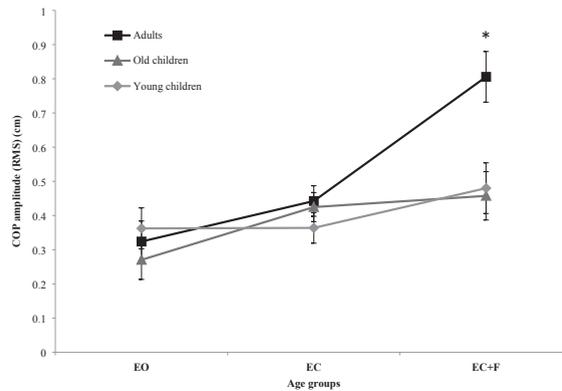
### 3. Results

#### 3.1. Maximum COP excursion

The ANOVA performed on the maximum COP excursions revealed both a significant age effect (phase 1:  $F(2,28) = 20.36$ ,  $p < 0.05$ ); phase 2:  $F(2,28) = 45.91$ ,  $p < 0.05$ ) and an age by direction interaction (phase 1:  $F(2,28) = 24.97$ ,  $p < 0.05$ ); phase 2:  $F(2,28) = 33.11$ ,  $p < 0.05$ ). As seen in the Fig. 2, for the AP axis, post-hoc analyses indicated that the maximum COP excursions of YC were significantly smaller than those of OC (phase 1 and phase 2;  $p < 0.05$ ) and adults (phase 1 and phase 2;  $p < 0.05$ ). However, there was no difference between maximum COP excursions of OC and adults in both phases. For the ML axis, post-hoc tests



**Fig. 2.** Mean amplitude of the maximum center of pressure (COP) excursion along anteroposterior (AP) directions (AP axis) (A and C) and mediolateral (ML) directions (ML axis) (B and D) during the phase 1 (A and B) and the phase 2 (C and D) of the maximal leaning for the three groups (adults (A), old children (OC (8 to 10 years of age)) and young children (YC (4 to 5 years of age))). The \* indicated the significant difference between groups. The vertical bars represent the standard errors.



**Fig. 3.** Mean root mean square (RMS) center of pressure (COP) amplitude during the phase 1 of the maximal leaning under each sensory condition (eyes open (EO), eyes closed (EC) and eyes closed while standing on a foam (EC + F)) for the three age groups. The \* indicates that there was a significant difference between adults and both children's groups in the EC + F condition. The vertical bars represent the standard errors.

revealed no difference in maximum COP excursions between the children groups for phase 1. However, YC exhibited significantly smaller maximum COP excursions than OC in phase 2 ( $p < 0.05$ ). Furthermore, in contrast to the AP axis, the maximum COP excursions of both children groups were significantly smaller than those of adults in ML axis (phase 1 and phase 2;  $p < 0.05$ ) (Fig. 2).

### 3.2. RMS amplitude of COP along the axis of the leaning movement

For phase 1, the ANOVA applied on the RMS of the amplitude of COP along the axis of the leaning movement showed a significant interaction effect between age and condition ( $F(4,56) = 4.41$ ,  $p < 0.05$ ). As seen in Fig. 3, under the EO and EC conditions, post-hoc analyses indicated no difference among the participant's groups. However, under the EC + F condition, while no difference was found between both children groups, YC and OC displayed significantly smaller RMS amplitudes than adults ( $p < 0.05$ ) as seen in the Fig. 3.

In phase 2, there was no interaction between age and condition (not illustrated in the figures). However, the ANOVA showed a significant age by direction interaction ( $F(6,84) = 5.39$ ,  $p < 0.05$ ). Similarly, as the results showed for the maximal COP excursions, the post-hoc analyses revealed that in the AP axis (forward and backward directions), the RMS values were not different between the three groups. By contrast, along the ML axis, post-hoc tests indicated that RMS amplitudes of YC and OC were higher than those of adults ( $p < 0.05$ ), but no difference was found between the children groups in rightward direction. For the leftward direction, RMS amplitudes of YC were greater than those of OC and adults ( $p < 0.05$ ). Moreover, RMS amplitudes of OC and adults were similar.

### 3.3. RMS amplitude of COP along the opposite axis of the leaning movement

The ANOVA performed on RMS amplitude of COP along the opposite axis of the leaning movement showed a significant age effect for both leaning phases (phase 1 ( $F(2,28) = 4.44$ ,  $p < 0.05$ ); phase 2 ( $F(2,28) = 21.34$ ,  $p < 0.05$ )) as well as an age by direction interaction (phase 1 ( $F(6,84) = 4.25$ ,  $p < 0.05$ ); phase 2 ( $F(6,84) = 4.51$ ,  $p < 0.05$ )). For the AP axis (rightward and leftward leaning), no difference was found among the three groups in both the phase 1 and the phase 2 as seen in the Fig. 4.

By contrast, for the ML axis, while no difference was identified between the children groups during phase 1, RMS amplitudes of YC were higher than those of adults (forward and backward) ( $p < 0.05$ ). Furthermore, OC exhibited larger RMS amplitudes than adults ( $p < 0.05$ ) in phase 1 during backward leaning. In phase 2, both children groups displayed greater RMS amplitudes than adults ( $p < 0.05$ ) during forward leaning. In phase 2, however, significant differences were found among all groups ( $p < 0.05$ ) (Fig. 4).

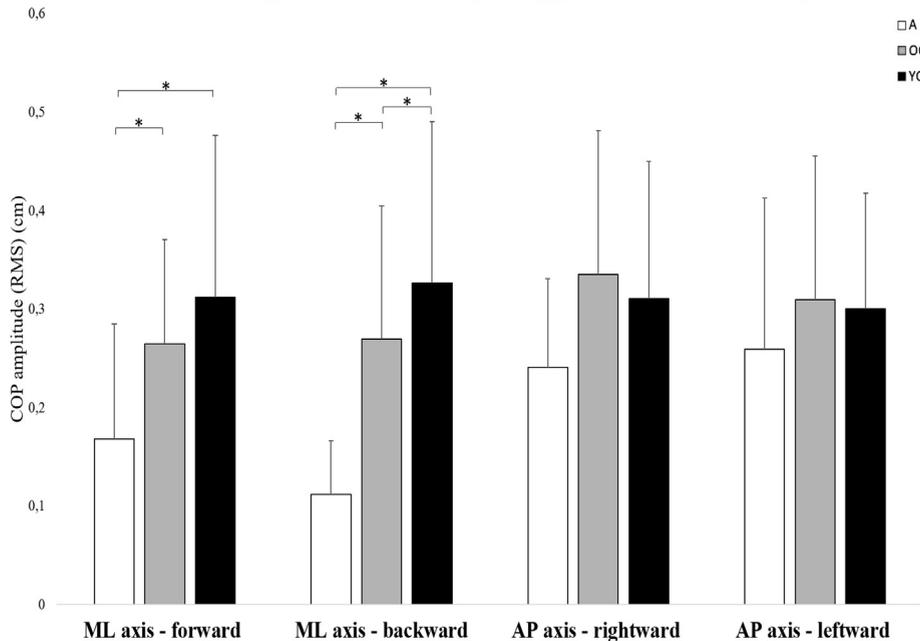
### 3.4. Condition effects

For conciseness, only main effects and interactions including the factor group will be reported for all analyses of variance in our results. However, it is important to note that in both phases, for all variables, the ANOVA showed a significant effect of condition. The maximum COP excursion (phase 1: ( $F(2,56) = 11.67$ ,  $p < 0.05$ ) phase 2: ( $F(2,56) = 41.07$ ,  $p < 0.05$ )), the RMS amplitude of COP along both the axis of leaning movement (phase 1: ( $F(2,56) = 47.08$ ,  $p < 0.05$ ) phase 2: ( $F(2,56) = 47.43$ ,  $p < 0.05$ )) and the opposite axis of leaning movement (phase 1: ( $F(2,56) = 47.21$ ,  $p < 0.05$ ) phase 2: ( $F(2,56) = 71.37$ ,  $p < 0.05$ )) analysis indicated that the postural performance decreased with the reduction of sensory information for all three groups.

## 4. Discussion

For the first time, we assessed how different sensory conditions affect postural performance before and after the critical transition

### Phase 2- RMS of the amplitude of COP along the opposite axis of the leaning movement



**Fig. 4.** Mean root mean square (RMS) center of pressure (COP) amplitude along the opposite axis of the leaning movement during the phase 2 of the maximal leaning under each direction (forward, backward, rightward and leftward) for three age groups. The \* indicates that there was a significant difference. The vertical bars represent the standard errors.

period. There were two main findings. First, during maintain maximum leaning, younger children were not differentially affected by sensory conditions than older children. The postural performance decreased with the reduction of sensory information for all three groups. Second, the results revealed axis-dependent differences among the groups in postural control. These findings are discussed in the following section.

#### 4.1. Postural control under different sensory conditions

Our findings indicate that sensory conditions did not affect the children's postural performance differently before and after the critical transition period. Therefore, this study provides evidence that the sensory strategy is mature later than 10 years old in our experimental task.

In contrast to ballistic strategy, the mature healthy postural control system is known to have the ability to explore all degrees of freedom (Hadders-Algra, 2010). This may explain why adults increased their RMS values relative to both children groups along the axis of the leaning movement during phase 1, especially in the EC + F condition (Fig. 3). Both children groups showed the same trends and this could be interpreted by immature sensory strategy. Future studies combining postural, kinematic and EMG analyses are needed to determine whether such adult-like pattern is an important developmental feature in the context of our dynamic postural task.

Barela and collaborators (2003) suggested that inferior postural control performance in children may result not from sensory feedback processing but from children's inability to form a precise internal model of body orientation (Barela, Jeka, & Clark, 2003). Likewise, other studies have proposed an inaccurate internal representation in 4- to 5-year-old children (Assaiante, 2012, Roncesvalles et al., 2005). The internal model is an internal representation of body geometry, of the forces exerted on the ground and of the orientation of the subject's body in relation to the vertical pull of gravity (Viel et al., 2009). It is noteworthy that reaching and maintaining stability limits largely depend on such accurate perceptions. In this light, it is possible that the observed significantly smaller maximum COP excursions along both movement axes in younger children compared to adults in all sensory conditions is explained by an imprecise internal body representation.

The internal representation is closely linked to the reweighting mechanisms, i.e., the modulation of the relative contribution of each sensory system in response to the internal perception and to the continuously changing environment (Assaiante, 2012; Bair, Kiemel, Jeka, & Clark, 2007; Mallau, Vaugoyeau, & Assaiante, 2010). Several studies suggested that reweighting mechanisms are less efficient in younger children than older children (Bair et al., 2007; Mallau et al., 2010; Rinaldi, Polastri, & Barela, 2009) and that it can improve sensory calibration (Assaiante, 2012). With the improvement of sensory calibration, children become better to estimating where they are relative to the balance point of center of mass projection and at incorporating the sensory-feedback mode of response (Kirshenbaum et al., 2001). Therefore, the smaller maximum COP excursions found in younger children compared to adults might also be explained, in part, by an inferior ability in young children to dynamically reweight sensory information according to

the postural task contingencies. This hypothesis was supported by Hay and Redon (1999) who demonstrated the improvement of feedforward mechanisms and coordination with feedback mechanisms during the transition period.

#### 4.2. Developmental differences in postural control along the different axes

A recent study suggested that it is necessary to determine relevant age-specific reference values for postural control (Verbecque et al., 2016). A major finding of the present study is that both children groups displayed significant difference relative to adults along the ML axis, but very similar performance along the AP axis (Figs. 2 and 4). This observation suggests that postural control along the AP and ML axes have different sensitive developmental periods.

Very few studies have examined the ontogenetic profile of postural control along both the AP and ML axes (Wolff, Rose, Jones, Bloch, & Oehlert, 1998; Cherng, Lee, & Su, 2003; Lebedowska & Syczewska, 2000). The results of some quiet standing studies are consistent with ours (Cherng et al., 2003; Lebedowska & Syczewska, 2000). However, using a frequency median spectral frequency, Cherng and their colleagues (2003) reported the opposite trend. These different results could be explained by the postural parameters chosen and by the fact that they normalized their data using body height and foot length only along the AP axis.

Using a dynamic task, Riach and Starkes (1993) reported no developmental difference in the maximum COP excursions between the AP and ML axes. Once again, differences in postural tasks and analysis procedures may have had an impact on results. The participants in this study were asked to lean as far as possible two times in the same trial (forward, backward, leftward and rightward). Each extreme position was held for 2 s (Riach & Starkes, 1993). There were several motor control requirement differences in our protocol. For example, the subjects maintained the maximum leaning position during a much longer period (10 s). The duration of the postural task is very important in ontogenetic studies, especially when investigating the sensory systems. Children are known to have a longer delay for sensory processing (Rinaldi et al., 2009), slower adaptation to postural responses (Rinaldi et al., 2009), less anticipation of the consequences of leaning (Assaiante, 2012; Blanchet et al., 2012) as well as inferior abilities to correct the destabilizing postural torque (Blanchet et al., 2012). Additionally, in contrast to the report by Riach and Starkes (1993), each leaning movement in the present study was initiated from a quiet standing position. In this context, children up to 10 years of age did not reach an adult-like performance level along the ML axis, suggesting that this age is a sensitive period in which children fine-tuned postural control along the ML axis.

The different development rates observed in postural adjustments along the AP and ML axes in this study could be explained by several reasons. First, genetically, the normal rate of development of postural control is known to mature earlier for the antigravity muscles (including gastrocnemius) responsible for AP postural control (Hadders-Algra, 2010). Second, motor development is largely affected by experience. In daily life, the majority of functional activities are executed along the AP axis e.g., reaching for an object, opening doors. These experiences could improve the development of AP mechanisms. Third, the body weight transfer using both abductors and adductor hips muscles (load/unload mechanism) required along the ML axis may be more demanding and more complex for immature postural systems than the weight transfer required along the AP axis, in which balance is under ankle muscles (plantar/dorsiflexor) control (Winter, Prince, Frank, Powell, & Zabjek, 1996). Fourth, compared to ML axis, toes could allow additional fine-tuned adjustments along the AP axis. In sum, our results suggest that the ankle strategy might mature earlier than the hip strategy (Kirshenbaum et al., 2001). However, our experimental paradigm needs to be tested with two force platforms with larger children groups to further investigate this novel hypothesis.

The significant difference between the maximum COP excursions of YC and OC along the AP axis is consistent with previous studies proposing that a transition period in postural control take place around 6–7 years of age (Riach & Starkes, 1993; Riach & Starkes, 1994; Kirshenbaum et al., 2001; Rival et al., 2005; Assaiante, 2012; Roncesvalles et al., 2005; Figura et al., 1991). More importantly, the results suggest that this age represent a sensitive period for the fine tuning of the amplitude of stability limits along the AP axis. In striking contrast, significant differences between both children groups compared to adults for the RMS and maximum COP excursion values along ML axis suggests a sensitive developmental period for this postural control mechanism. It was demonstrated that increasing sensorimotor experience during sensitive developmental period will have a differential effect on motor behavior (Penhune & Steele, 2012). Interestingly, in a sport increasing body weight transfers (ML COP displacements) experience such as soccer, 13 years old soccer player's athletes had a significant better postural control in ML axis compared to control group (Biec & Kuczynski, 2010). This result could supported our sensitive period for ML postural control hypothesis. Other studies are required to investigate this hypothesis. However, the present study highlights two important sensitive periods for AP and ML postural control development. It is well known that the sensitive periods are crucial for proper brain development. Suboptimal sensorimotor inputs during these developmental stages can cause neurodevelopmental problems with lifelong consequences (Sommeijer et al. (2017)). Our results suggest that specific stimulation programs of AP and ML postural control should be included at specific stages in children and adolescents rehabilitation programs, in teaching physical education, in neuromuscular training and in athletes training. The identification of sensitive periods in postural control adds new and important knowledge to better understand the effects of sensitive periods in sensorimotor development (Hensch, 2004) like in language development (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005).

## 5. Conclusion

The sensory conditions did not affect the children's postural performance differently before and after the critical transition period. Thus, our results suggested that the efficient sensory strategy is not mature at 10 years old. Interestingly, however, the present study provides important evidence for a different maturation process in the sensorimotor pathway responsible of COP adjustments along the AP and ML axes. Our results also indicated that until the age of 10, children do not reach a mature ability to control COP

adjustments along the ML axis. Conversely, our results support the idea that the ability to control COP adjustments along the AP axis is already developed at 4 years of age, but reached the adult level after the transition period.

### Conflict of interest

The authors declare that they have 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.2018.11.016>.

### References

- Assaiante, C. (2012). Action and representation of action during childhood and adolescence: A functional approach. *Clinical Neurophysiology*, *42*, 43–51.
- Bair, W. N., Kiemel, T., Jeka, J. J., & Clark, J. E. (2007). Development of multisensory reweighting for posture control in children. *Experimental Brain Research*, *183*, 435–446.
- Barela, J. A., Jeka, J. J., & Clark, J. E. (2003). Postural control in children: Coupling to dynamic somatosensory information. *Experimental Brain Research*, *150*, 434–442.
- Bartlett, D., & Birmingham, T. (2003). Validity and reliability of a pediatric reach test. *Pediatric Physical Therapy*, *15*, 84–92.
- Biec, E., & Kuczynski, M. (2010). Postural control in 13-year-old soccer players. *European Journal of Applied Physiology*, *110*, 703–708.
- Blanchet, M., Marchand, D., & Cadoret, G. (2012). Postural control adjustments during progressive inclination of the support surface in children. *Medical Engineering & Physics*, *34*, 1019–1023.
- Blanchet, M., Prince, F., Chouinard, S., & Messier, J. (2014). Postural stability limits in manifest and premanifest Huntington's disease under different sensory conditions. *Neuroscience*, *279*, 102–112.
- Cherng, R. J., Lee, H. Y., & Su, F. C. (2003). Frequency spectral characteristics of standing balance in children and young adults. *Medical Engineering & Physics*, *25*, 509–515.
- Figura, F., Cama, G., Capranica, L., Guidetti, L., & Pulejo, C. (1991). Assessment of static balance in children. *The Journal of Sports Medicine and Physical Fitness*, *31*, 235–242.
- Hadders-Algra, M. (2010). Variation and variability: Key words in human motor development. *Physical Therapy*, *90*, 1823–1837.
- Hay, L., & Redon, C. (1999). Feedforward versus feedback control in children and adults subjected to a postural disturbance. *Experimental Brain Research*, *125*, 153–162.
- Hensch, T. K. (2004). Critical period regulation. *Annual Review Neuroscience*, *27*, 549–579.
- Kirshenbaum, N., Riach, C. L., & Starkes, J. L. (2001). Non-linear development of postural control and strategy use in young children: A longitudinal study. *Experimental Brain Research*, *40*, 420–431.
- Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early Speech Perception and Later Language Development: Implications for the “Critical Period”. *Journal Language Learning and Development*, *1*, 237–264.
- Lebiedowska, M. K., & Syczewska, M. (2000). Invariant sway properties in children. *Gait & Posture*, *12*, 200–204.
- Mallau, S., Vaugoyeau, M., & Assaiante, C. (2010). Postural strategies and sensory integration: No turning point between childhood and adolescence. *PLoS ONE*, *5*, 1–13.
- Mancini, M., Rocchi, L., Horak, F. B., & Chiari, L. (2008). Effects of Parkinson's disease and levodopa on functional limits of stability. *Clinical Biomechanics*, *23*, 450–458.
- Palluel, E., Nougier, V., & Olivier, I. (2010). Postural control and attentional demand during adolescence. *Brain Research*, *1358*, 151–159.
- Penhune, V. B., & Steele, C. (2012). Parallel contributions of cerebellar, striatal and M1 mechanisms to motor sequence learning. *Behavioral Brain Research*, *226*, 579–591.
- Pinsault, N., & Vuillerme, N. (2010). Vestibular and neck somatosensory weighting changes with trunk extensor muscle fatigue during quiet standing. *Experimental Brain Research*, *202*, 253–259.
- Riach, C. L., & Starkes, J. L. (1993). Stability limits of quiet standing postural control in children and adults. *Gait & Posture*, *1*, 105–111.
- Riach, C. L., & Starkes, J. L. (1994). Velocity of center of pressure excursions as an indicator of postural control systems in children. *Gait & Posture*, *2*, 167–172.
- Rinaldi, M. N., Polastri, P. F., & Barela, J. A. (2009). Age-related changes in postural control sensory reweighting. *Neuroscience Letters*, *467*, 225–229.
- Rival, C., Ceyte, H., & Olivier, I. (2005). Developmental changes of static standing balance in children. *Neuroscience Letters*, *376*, 133–136.
- Roncesvalles, M. N., Schmitz, C., Zedka, M., Assaiante, C., & Woollacott, M. (2005). From egocentric to exocentric spatial orientation: Development of posture control in bimanual and trunk inclination tasks. *Journal of Motor Behavior*, *37*, 404–416.
- Shumway-Cook, A., & Woollacott, M. H. (1985). The growth of stability: Postural control from a development perspective. *Journal of Motor Behavior*, *17*, 131–147.
- Sigmundsson, H., Whiting, H. T. A., & Loftesnes, J. M. (2000). Development of proprioceptive sensitivity. *Experimental Brain Research*, *135*, 348–352.
- Sommeijer, J. P., Ahmadlou, M., Saiepour, M. H., Seignette, K., Min, R., Heimel, J. A., et al. (2017). Thalamic inhibition regulates critical-period plasticity in visual cortex and thalamus. *Nature Neuroscience*, *20*, 1715–1721.
- Viel, S., Vaugoyeau, M., & Assaiante, C. (2009). Adolescence: A transient period of proprioceptive neglect in sensory integration of postural control. *Motor Control*, *13*, 25–42.
- Verbecque, E., Vereeck, L., & Hallemans, A. (2016). Postural sway in children: A literature review. *Gait & Posture*, *49*, 402–410.
- Wickstrom, J., Stergiou, N., & Kyvelidou, A. (2017). Reliability of center of pressure measures for assessing the development of sitting postural control through the stages of sitting. *Gait Posture*, *56*, 8–13.
- Winter, D. A., Prince, F., Frank, J. S., Powell, C., & Zabjek, K. F. (1996). Unified theory regarding A/P and M/L balance in quiet stance. *Journal of Neurophysiology*, *75*, 2334–2343.
- Wolff, D. R., Rose, J., Jones, V. K., Bloch, D. A., & Oehlert, J. W. E. (1998). Gamble JG. Postural balance measurements for children and adolescents. *Journal of Orthopaedic Research*, *16*, 271–275.