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Anticipatory postural adjustments associated with a forward leg raising in children: Effects of age, segmental acceleration and sensory context

Estelle Palluel [a,*], Hadrien Ceyte [b], Isabelle Olivier [a], Vincent Nougier [a]

[a] *Laboratoire TIMC-IMAG, Equipe " Santé, Plasticité, Motricité", UMR 5525, Université Joseph Fourier-CNRS, Grenoble, 38 706 La Tronche cédex, France*
[b] *Equipe ACCORPS/Archives H. Poincaré-LHPS, UMR 7117 CNRS/Nancy-Université, France*

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ABSTRACT

Objective: The purpose of this study was to determine the influence of age, segmental acceleration and sensory context on anticipatory postural adjustments (APAs) in a forward leg raising task.

Methods: Three groups of 11 children, aged 8, 10 and 12, and 12 adults, aged 20 to 26, were instructed to perform this movement at maximal (*MAXIMAL*) and sub-maximal segmental accelerations and in normal (*CONTROL*), no vision (*NV*) and perturbed proprioception conditions (*VIB*). The generation and calibration of APAs were examined through the centre of foot pressure displacements: The onset, duration and amplitude of APAs were particularly explored. The EMG activity of the tibialis anterior (TA_{stance}) and gastrocnemius medialis (G_{stance}) of the stance leg was also recorded.

Results: Two phases were clearly identified on the ML axis: A thrust and an unloading phase. *Effect of age*: At 8 and 10, (1) the unloading duration was shorter, and (2) the onset of APAs on the ML axis appeared later than in 12-year-old children and in adults. *Effect of the segmental acceleration*: (1) a greater amplitude of the thrust and unloading phases, (2) a shorter unloading duration, and (3) a later onset of ML APAs and of the TA_{stance} activity were observed at maximal acceleration in all groups. *Effect of the sensory context*: No difference was found between the *CONTROL* and *NV* conditions. When the proprioceptive feedback was altered, (1) the thrust and unloading durations increased, and (2) the onset of the APAs on the ML axis occurred earlier.

Conclusion: All children exhibited an anticipatory behaviour, but the adults' behaviour was reached at 12 only. Our results also indicated a change in the generation and calibration of APAs in the *VIB* condition, suggesting that proprioceptive information is essential for both dimensions of the APAs.

Significance: The development of the APAs was not related to the segmental acceleration and to the sensory context of the forthcoming movement in children aged 8–12. It is very likely that the participants built up an internal representation of this movement.

1. Introduction

Voluntary movements involve postural adjustments that precede, support and follow them. The regulations occurring before movement onset are commonly named anticipatory postural adjustments (APAs). It is now well established that these APAs are centrally programmed and depend on the characteristics of the forthcoming movement (Bouisset, 1991; Bouisset and Zattara, 1981). Two functions have been attributed to the APAs since Belenkii et al.'s experiments (1967): The minimization and optimization of the centre of foot pressure (CoP) displacements. Previous findings related to APAs in children reported that this population is able to produce anticipatory activities in arm raising (Hay and Redon, 2001; Riach and Hayes, 1990), tiptoe standing (Haas et al., 1989), and gait initiation (Assaiante et al., 2000; Ledebt et al., 1998; Malouin and Richards, 2000). The APAs are not innate in gait initiation and must undergo development before being systematic and functional (Hayes and Riach, 1989). According to these authors, the feedforward control is fully developed approximately at 7 years old. Hay and Redon (1999) showed that the contribution of the feedforward processes to postural control evolve non-monotonically between 3 and 10 years old. Although postural responses of 6-year-old children were almost similar to those of adults, the feedforward control appeared to be less efficient for the 9- to 10-year-old children. Other studies indicate that at eight, the adult-like control has not been achieved yet (Schmitz et al., 2002) and still develops in the mid-childhood (McFadyen et al., 2001; Vallis and McFadyen, 2005). The ability to predict, evaluate and compensate for the disequilibrium resulting from a voluntary movement

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* Corresponding author. Tel.: +33 4 76 63 75 46; fax: +33 4 76 63 51 00.
E-mail address: estelle.palluel@ujf-grenoble.fr (E. Palluel).

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improves with the experience of the task and with the development (Hirschfeld and Forssberg, 1992).

Since the APAs are movement specific and because movement speed increases with age, we investigated the influence of the acceleration of the moving segment on the generation and modulation of the APAs. Previous studies showed that the APAs are programmed according to the parameters of the voluntary movement. Their amplitude is pre-set according to the expected perturbation induced by the forthcoming movement (Crenna and Frigo, 1991; Pedotti et al., 1989). The APAs cannot be triggered when the movement is too slow (Lee et al., 1987), and increase in amplitude as the movement becomes faster (Bouisset, 1991; Horak et al., 1984). In gait initiation, both APAs amplitude and timing can be consistently modulated by the dynamic parameters of the movement (Crenna and Frigo, 1991). For example, according to Ledebt et al. (1998), the amplitude of the backward displacement associated with gait initiation varies according to the velocity reached at the end of the first step, especially in children younger than 6.

In deafferented adults, Forget and Lamarre (1990) investigated the weight of the sensory context on APAs. Although these patients had no proprioceptive feedback (i.e., touch, pressure, statesthetic or kinaesthetic sensations) in both arms, they were able to generate APAs. Other studies focused on the effects of tendon vibration on APAs. They showed that vibration distorted the perception of static joint angle and involved a modification of posture and of the APAs timing (Kasai et al., 2002). Vibration applied to the tibialis anterior entailed an earlier anticipatory behaviour but APAs appeared later when the vibration was applied to the soleus. Therefore, if APAs can be generated without proprioceptive feedback their modulation is linked to it. However, we still do not know to which extent the sensory context influences the generation of APAs in children.

Performing a leg raising movement involves the transition from a bipodal to a one-leg stance. Several authors examined APAs in a series of forward-oriented motor tasks, including stepping forward and initiating gait (Crenna and Frigo, 1991; Haas et al., 1989). Mouchnino et al. (1992a,b) showed that a lateral leg raising movement to an angle of 45 deg was linked to CoP displacements towards the moving leg. Two phases were clearly identified on the medio-lateral axis: (1) A thrust phase initiated by the extensors and corresponding to a CoP shift towards the moving leg, and (2) an unloading phase corresponding to a CoP shift towards the supporting leg. The thrust always started before movement onset because it was essential to create the necessary dynamic conditions to execute the movement. According to the authors, the purpose of APAs associated with a lateral leg raising movement was threefold: (1) Displacing the CoP towards the supporting leg, (2) performing a leg raising movement, and (3) stabilizing the position of the moving leg.

Most of the experiments conducted with children focused on gait initiation. We chose the forward leg raising movement because it is an unusual movement: Therefore, in this particular task, the performance did not depend on the participants' experience and allowed to investigate their ability to perform this movement and their adaptation to different task constraints according to their age. Thus, the purpose of the present study was to investigate the effects of (1) age, (2) segmental acceleration of the moving leg, and (3) sensory context on the generation and calibration of the anticipatory behaviour associated with a forward leg raising movement both in children and in adults.We know that the age range of the children groups (8–12) will undergo huge developmental changes. Although adult-like strategies may be set fairly early in the childhood, it was hypothesized that adult-like anticipatory behaviour would not be achieved at 8. More specifically, we tried to identify whether this behaviour became mature between 8 and 12 years old and whether the development of APAs during the ontogenetic period depended on both segmental acceleration and sensory context.

2. Method

2.1. Participants

Three groups of 11 children, aged 8 (mean age = 7.9 years old ±5.2.months; mean height = 128 ± 5 cm; mean weight = 28.6 ± 4.2 kg), 10 (mean age = 10.0 years old ±3.4 months; mean height = 142 ± 3 cm; mean weight = 33.1 ± 2.3 kg) and 12 (mean age = 12.4 years old ±6.1.months; mean height = 151 ± 6 cm; mean weight = 41.2 ± 5.4 kg), and a group of 12 adults, aged 20-26 (mean age = 23.8 years old ±2.2 years; mean height = 172 ± 5 cm; mean weight = 67.5 ± 4.4 kg), took part in the experiment. Informed consent was obtained from each participant as required by the Helsinki declaration (1964). All participants were right-footed (this preference corresponding to the limb used when kicking), and were naive to the purpose of the experiment. They were recruited on a voluntary basis and were schoolboys/girls with a normal scholastic level. Informed consent was provided by their parents and teachers.The adults were students without any known neurological disorder.

2.2. Tasks and procedures

The participants stood barefoot on a force platform (AMTI ORI6-7) in a comfortable position with their arms at their sides and feet abducted at 30 deg with the medial borders of the heel separated by 10 cm. The participants were asked to raise their right leg forward towards a circular target (10 cm of diameter) placed at knee height and 150 cm in front of them: The height of the target was adjusted for each participant. This pointing movement consisted of a hip flexion with knee in complete extension (i.e., with an alignment of the ankle, knee and hip joints). The right leg was the moving leg, whereas the left leg was the supporting leg. The participants self-initiated their movement after hearing a signal and the final position was maintained for 2 s at least (see Fig. 1).

Each participant was exposed to four different experimental conditions manipulating the segmental acceleration and sensory information available: (1) maximum acceleration (i.e., in which the participants were asked to move as quickly as possible) with normal vision and proprioception (*MAXIMAL*), (2) sub-maximal acceleration with normal vision and proprioception (*CONTROL*), (3) sub-maximal acceleration without vision (*NV*), and (4) sub-maximal acceleration with perturbed proprioception (*VIB*). In the latter condition, the ankle proprioception was disturbed by applying a vibratory stimulation of 80 Hz on the antagonist muscles of the supporting leg. Two vibrators were thus fixed on the tendons of the soleus and tibialis anterior muscles. The sub-maximal acceleration was determined – during the pre-test – as the acceleration that could easily be reached, reproduced and well performed by children and adults when all the sensory information was available: It was set at 16 ms^{-2}. An accelerometer (ENTRAN RO4401) was fixed at the shank level of the moving leg (5 cm above the ankle joint). The order of presentation of the conditions was counterbalanced among the participants. 11 trials were completed per condition. After each condition, the participants took a 2 min rest in order to avoid fatigue.

2.3. Dependent variables

CoP motion was recorded for 3 s starting from the auditory signal. Kinetic analysis was performed by calculating the CoP displacements on both the AP (AP APAs) and ML (ML APAs) axes. Data were sampled at 100 Hz. Movement onset (t_0) corresponded to the acceleration onset of the moving leg. Thus, the APAs corresponded to the postural responses occurring before t_0. Two phases were clearly identified on the ML axis: (1) a *thrust phase* and (2) an

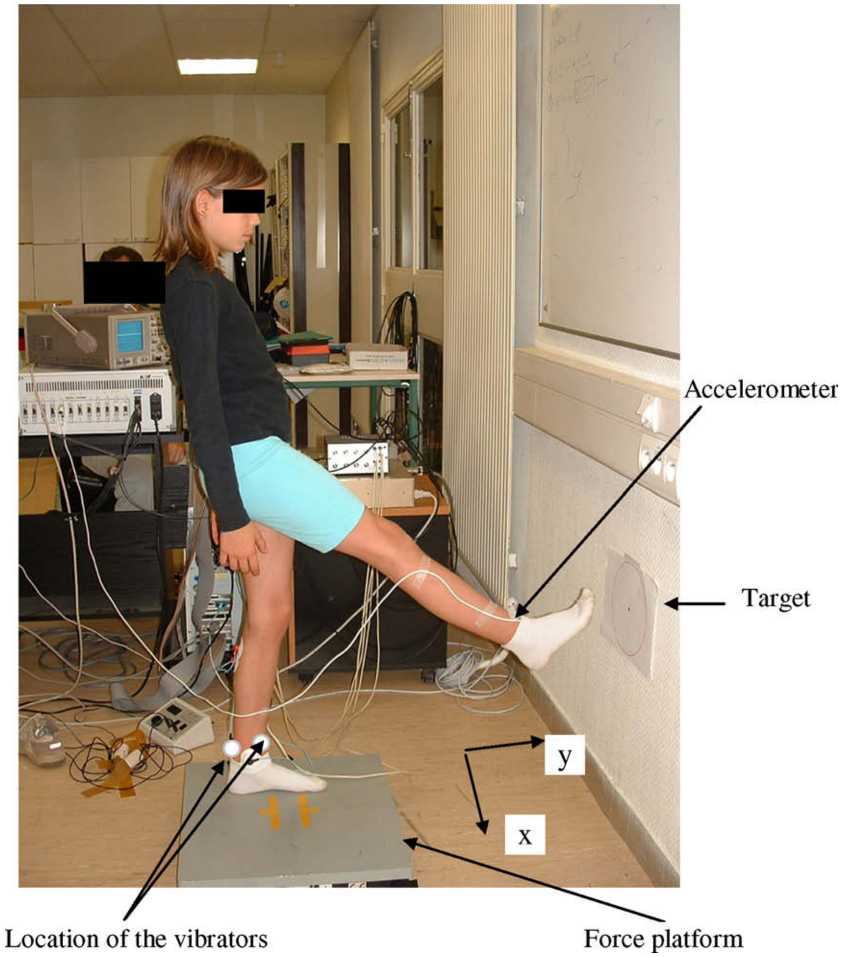

Fig. 1. Experimental set-up.

unloading phase. The thrust phase corresponded to a CoP shift towards the moving leg that was essential to initiate the CoP displacement towards the supporting leg while maintaining balance. The unloading phase was defined by a CoP shift towards the supporting leg (Mouchnino et al., 1922a,b). The amplitude (in mm) and duration (in ms) of both phases were calculated. The onset (in ms before t_0) of the ML and AP APAs was also identified (see Fig. 2). The EMG activity of the tibialis anterior (TA_{stance}) and gastrocnemius medialis (G_{stance}) was recorded unilaterally (stance leg). EMG data were sampled at 1000 Hz, filtered at 100 Hz and rectified. Onset latencies were determined by the time when the EMG activity was greater than two standard deviations above the mean baseline activity. The latter was measured in each trial, and it corresponded to the first 100 ms of recording. The muscle onset latency was calculated relative to t_0; a negative value indicated an anticipatory burst.

2.4. Statistical analysis

Different factors were analysed: Age (8, 10, 12 and adults), Segmental acceleration (*MAXIMAL* and *CONTROL*) and Sensory condition (*CONTROL*, *NV* and *VIB*). Two separate analyses of variance (ANOVA) with repeated measures on the last factor were performed to identify either the effects of the segmental acceleration (two-way ANOVA: Age × Segmental acceleration) or the effects of the sensory condition (two-way ANOVA: Age × Sensory conditions) on the APAs. The ANOVA Age × Segmental acceleration was applied (1) to check whether the maximal acceleration increased with age, (2) to check if the segmental acceleration had an effect on the amplitude, duration, and onset of the APAs, and (3) to determine whether a development process of the APAs was observed between 8 and 12. The purpose of the ANOVA Age × Sensory conditions was to investigate (1) whether the amplitude, duration and onset of the ML APAs were sensory condition-related, and (2) whether a development process of the APAs was observed between 8 and 12. Post hoc analyses (Tukey HSD) were used whenever significant effects needed further investigation. The level of significance was set at $\alpha = 0.05$.

3. Results

As the characteristics of APAs can be influenced by the initial position of the CoP, we first checked whether this position varied between groups of participants and conditions. The initial position was the position recorded at the onset of a trial. The two ANOVAs were separately applied to the initial position of the CoP and revealed no significant difference.

3.1. Effects of the segmental acceleration

3.1.1. Maximal acceleration

Results showed a significant interaction of age × segmental acceleration ($F(3,41) = 3.45$, $p < 0.05$). Planned comparisons revealed a significant difference of maximal acceleration between (1) 8 and 12 ($p < 0.01$), (2) 8 and adults ($p < 0.05$), (3) 10 and 12 ($p < 0.01$) and (4) 10 and adults ($p < 0.05$), with lower values occur-

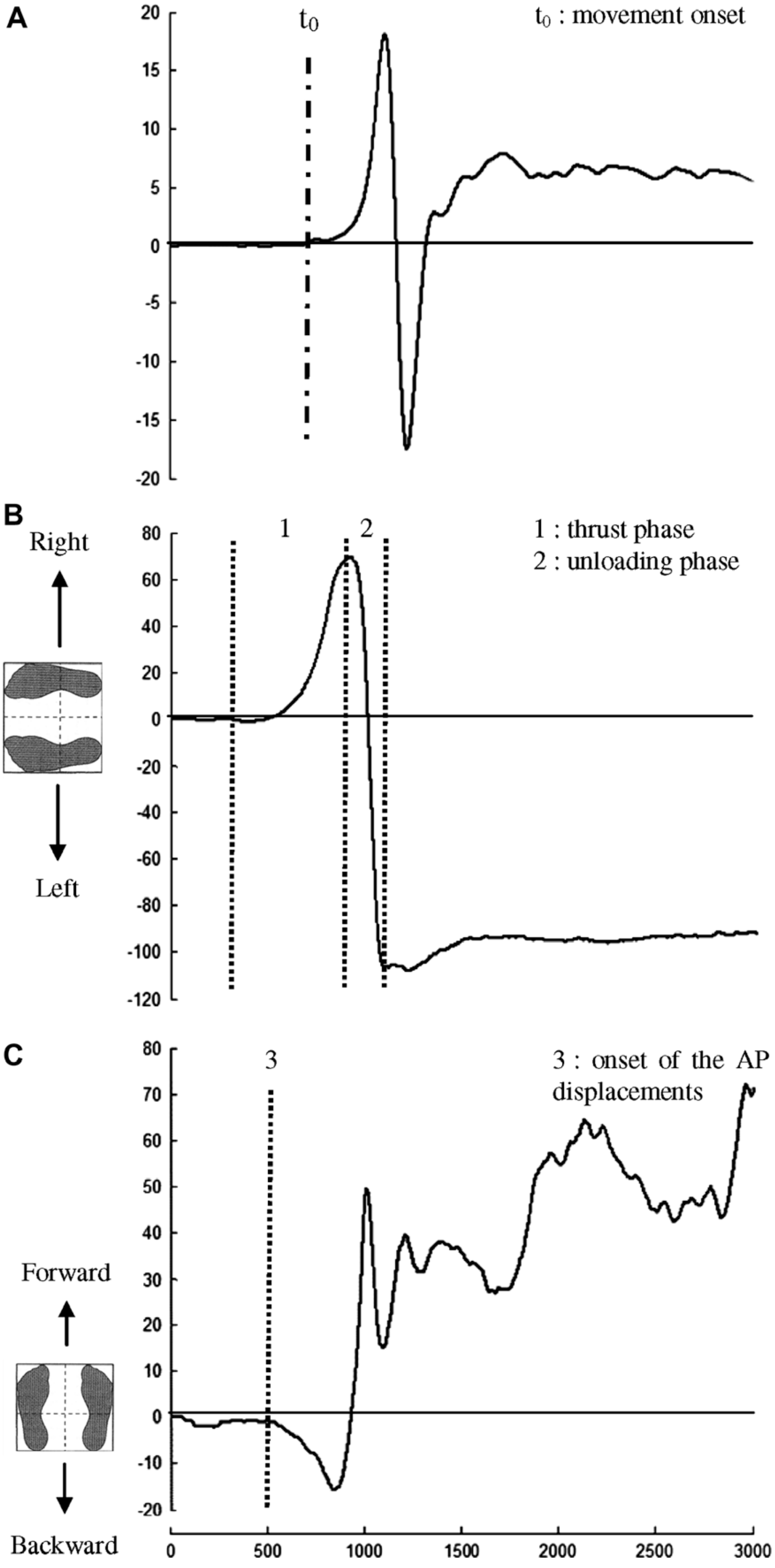

Fig. 2. Segmental acceleration and CoP displacements on the ML and AP axes recorded during one trial. (A) Segmental acceleration (ms^{-2}). (B) CoP shift on the ML axis (mm) characterized by a thrust and an unloading phase. (C) CoP shift on the AP axis (mm).

ring in the younger groups (at 8 years old, mean = 29.6 ± 9.1 ms^{-2}; at 10 years old, mean = 30.8 ± 10.1 ms^{-2}; at 12 years old, mean = 45.6 ± 9.8 ms^{-2} and in adults, mean = 42.1 ± 16.3 ms^{-2}). No significant difference was found between (1) 8 and 10 ($p > 0.05$) and (2) 12 and adults ($p > 0.05$).

3.1.2. Amplitude, duration and onset of the ML (i.e., thrust and unloading phases) and the AP APAs

The statistical analysis revealed no significant interaction of age × segmental acceleration for the amplitude, duration, and onset of the ML APAs ($p_s > 0.05$). There was also no effect on the AP APAs ($p > 0.05$). The main effect of age was observed for the unloading duration ($F(3,41) = 3.08$, $p < 0.05$) and for the onset of the ML APAs ($F(3,41) = 4.28$, $p < 0.05$) (Fig. 3). The main effect of segmental acceleration was found for the amplitude of the thrust and unloading phases ($F(1,41) = 91.35$, $p < 0.01$ and $F(1,41) = 90.34$, $p < 0.01$, respectively), for the duration of the unloading phase ($F(1,41) = 73.68$, $p < 0.01$), and for the onset of the ML APAs ($F(1,41) = 30.09$, $p < 0.01$). Performing a leg raising movement at maximal acceleration involved a greater amplitude of the thrust and unloading phases, and a shorter unloading phase and a later onset of ML APAs in all groups. The unloading phase was shorter at 8 (328.2 ± 104.3 ms) and 10 (318.6 ± 90.0 ms) than in adults (413.8 ± 132.8 ms) ($p_s < 0.05$). The difference was almost significant between (1) 8- and 12- ($p = 0.09$), and (2) 10- and 12-year-old children ($p = 0.06$). The onset of these ML APAs occurred earlier in the 12-year-old children and in adults than in the 8- ($p_s < 0.05$) and 10-year-old children ($p_s < 0.05$) (see Fig. 4).

3.1.3. EMG activity

No significant effect or interaction was found for the G_{stance} activity ($p_s > 0.05$). However, the analysis indicated the main effect of segmental acceleration for the TA_{stance} ($F(1,41) = 6.19$, $p < 0.05$) with greater APAs observed in the *CONTROL* (−262.9 ± 145.0 ms) than in the MAXIMAL condition (−206.3 ± 141.9 ms) (see Fig. 5).

3.2. Effects of the sensory condition

The statistical analysis revealed neither significant interaction of age × sensory condition nor main effect of age for the amplitude, duration, and onset of the ML APAs ($p_s > 0.05$) and for the onset of the AP APAs ($p > 0.05$). However, the main effect of sensory condition was observed for the duration of the unloading phase ($F(2,82) = 5.31$, $p < 0.01$) and for the onset of the ML APAs ($F(2,82) = 6.31$, $p < 0.01$). Post hoc analysis showed that the duration of the unloading phase was significantly longer in the *VIB* than in the *CONTROL* condition ($p < 0.01$). The onset of the ML APAs occurred earlier in the *VIB* than in the *CONTROL* or *NV* conditions in all groups ($p < 0.01$ and $p < 0.05$, respectively) (see Fig. 6).

3.2.1. EMG activity

No significant main effect and no interaction were found for the G_{stance} and the TA_{stance} activities ($p_s > 0.05$).

4. Discussion

The purpose of this study was to investigate whether the APAs generated in a forward leg raising movement became mature between 8- and 12-year-old children as compared to adults, and whether these APAs were influenced by the segmental acceleration of the moving leg and the sensory inputs available. The present results provided evidence that all children exhibited an anticipatory behaviour in a forward leg raising movement and that the adults' behaviour was reached at 12 only. In fact, comparison between the *MAXIMAL* and *CONTROL* conditions showed the main effect of age: (1) movement speed increased between 10 and 12, (2) there was an earlier onset of APAs on the ML axis at 12 and in adults, and (3) the unloading duration was shorter at 8 and 10 than at 12 and in adults. The generation and calibration of APAs, illustrated in the two older groups by an earlier onset of APAs and a slower unloading phase, respectively, varied thus with age. Whereas the 12-year-old children exhibited the same behaviour as adults, our

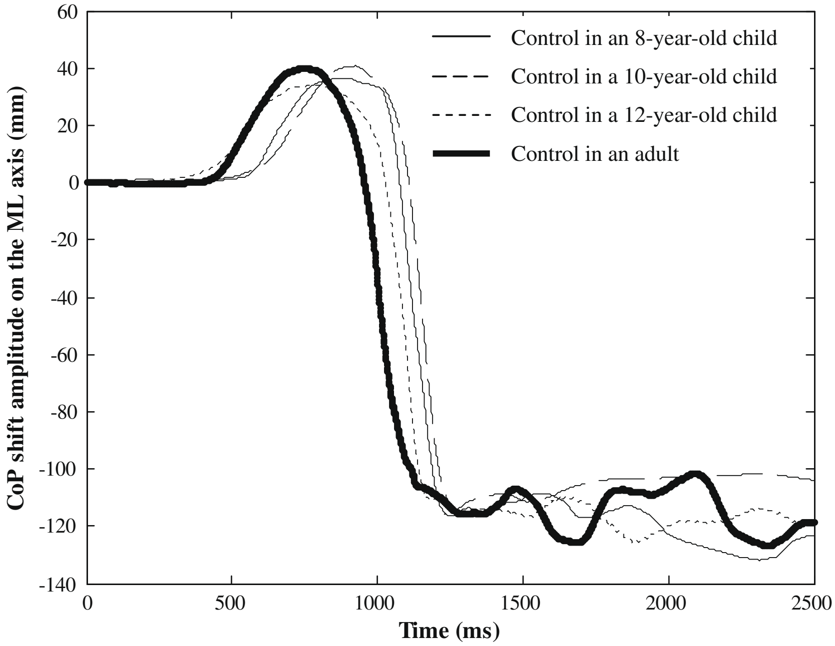

Fig. 3. Example of the age-related difference observed between the 8-, 10- and 12-year-old children and the adults for the CoP shift amplitude on the ML axis in the *CONTROL* condition. The onset of the movement was set at 900 ms. The 8-year-old and 10-year-old children exhibited a shorter unloading duration and a later onset of APAs on the ML axis.

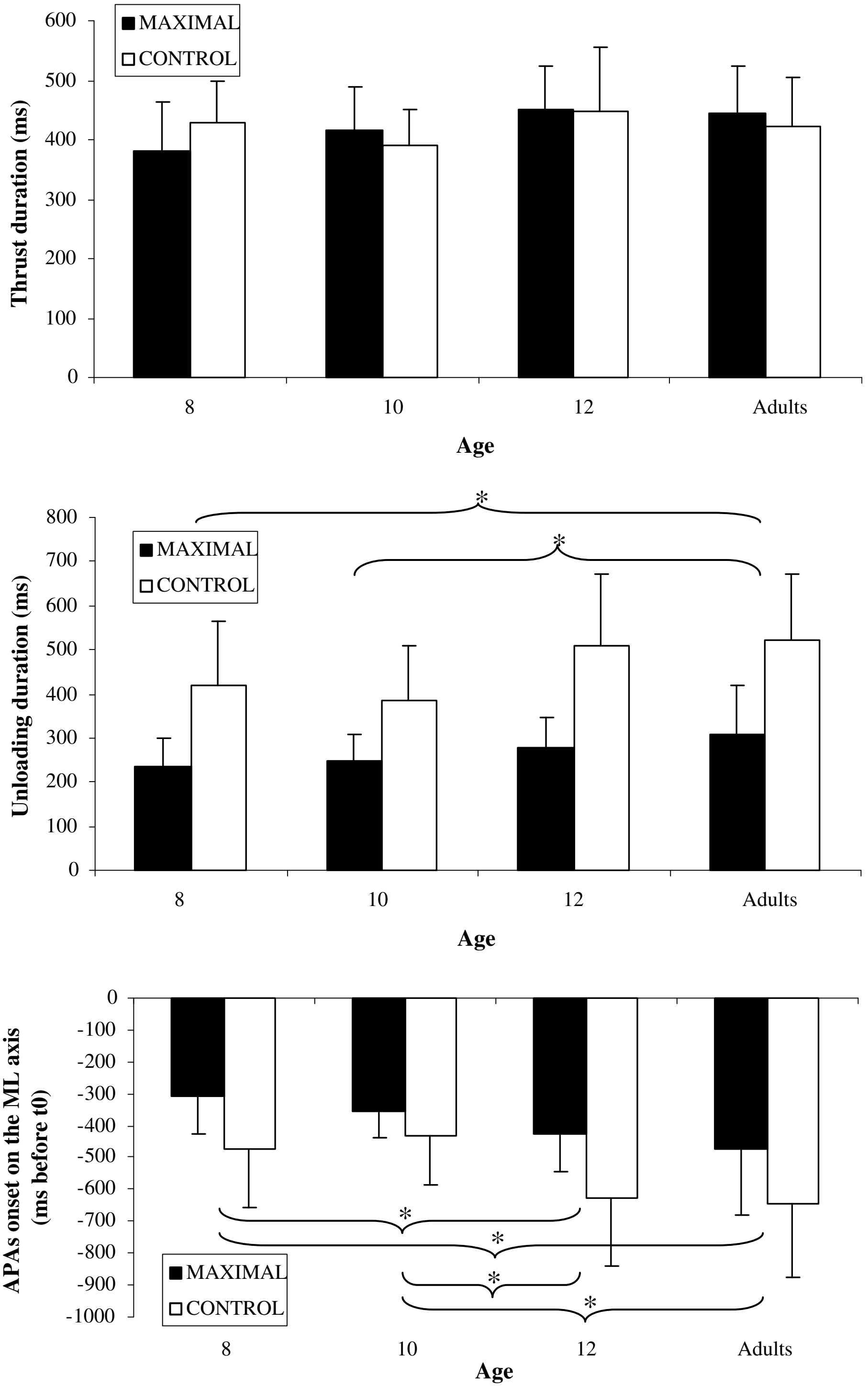

Fig. 4. CoP shift duration (ms) of the thrust and unloading phases, onset on the ML axis (ms before t_0) in the *CONTROL* and *MAXIMAL* conditions according to age. The significant values are reported ($^{*}P < 0.05$).

results clearly demonstrated that there was less anticipatory activity on the ML axis at 8 and 10 than at 12 or in adults. Although children aged 8 and 10 exhibited some adult-like strategies (i.e., amplitudes of the thrust and unloading phases, duration of the thrust phase, onset of the AP APAs), they did not totally exhibit the movement pattern observed in adults. Two factors may explain this observation: The younger children had a less stable initial posture and/or a lack in cognitive control of the movement. Our results confirmed previous findings indicating that (1) the expression of anticipatory postural adjustments was still developing during mid-childhood and (2) the adult-like pattern was not reached at 8 (Hay and Redon, 1999; McFadyen et al., 2001; Schmitz et al., 2002).

Since several studies demonstrated a clear relationship between the programming of APAs and the spatio-temporal parameters of the movement (Bouisset, 1991; Horak et al., 1984; Lee et al., 1987), we expected that performing a leg raising movement at two different segmental accelerations (maximal and sub-maximal)

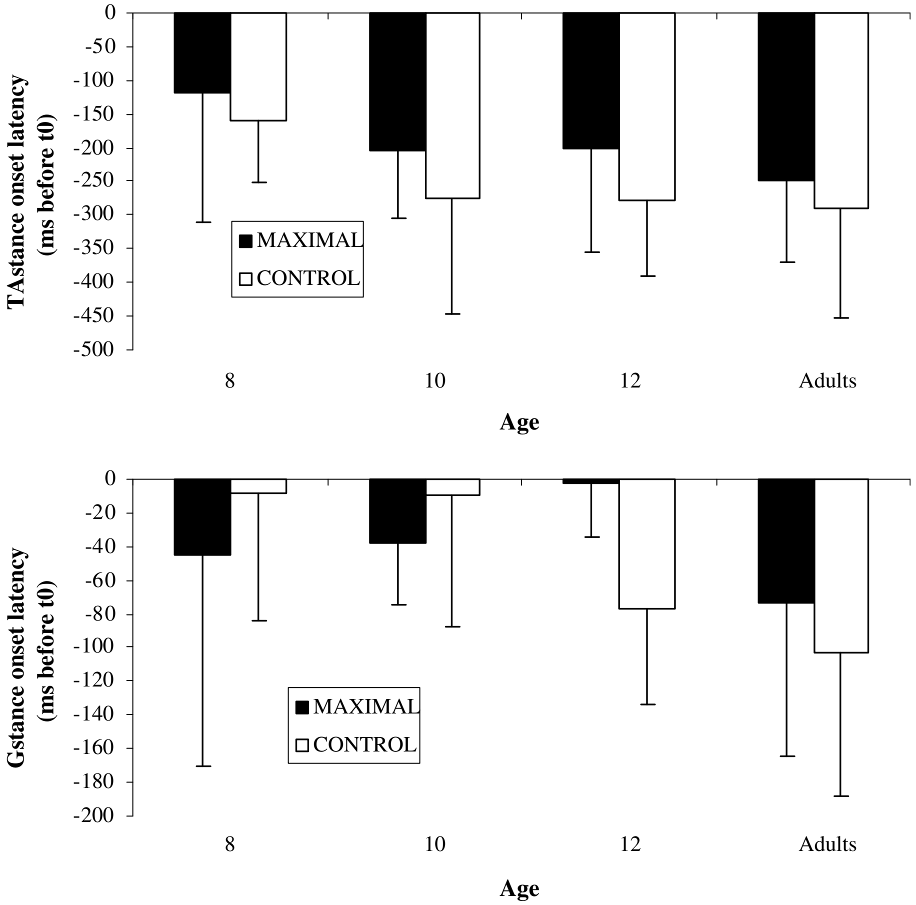

Fig. 5. EMG activity of the $\text{TA}_{\text{stance}}$ and G_{stance} (ms before t_0) in the *CONTROL* and *MAXIMAL* conditions according to age. The main effect of segmental acceleration was significant ($p < 0.05$).

would involve changes in APAs. We also wanted to check whether this parameter involved the same behaviour in children and adults. No interaction of age × segmental acceleration was found for all variables: The development of the APAs was therefore not related to the segmental acceleration of the forthcoming movement. However, the segmental acceleration similarly affected the generation and calibration of APAs in children and adults. No effect was established on the AP axis but a greater amplitude of the thrust and unloading phases on the ML axis was observed at maximal acceleration in all groups: It confirmed the previous results (Bouisset et al., 2000; Lee et al., 1987). Moreover, the unloading duration was greater in the *CONTROL* than in the *MAXIMAL* condition. The aim of the anticipatory CoP shift is to unload the leg and to maintain balance during the movement. Biomechanically, performing a ballistic movement requires more propulsive forces than a slower one (i.e., a higher amplitude and lower duration of the thrust exerted on the ground). In other words, a greater quantity of energy has to be stored in order to displace the CoP towards the supporting leg. This energy was then released faster in a ballistic movement, inducing a shorter duration of the unloading phase at maximal acceleration. Mouchnino et al. (1992a,b) reported that the thrust phase started before movement onset. This CoP shift partly resulted from the activity of distal muscles (GM, TA): The later onset of ML APAs observed in the *MAXIMAL* condition was associated with a later TA burst. The present results are in accordance with Mouchnino et al.'s findings (1992a,b). For example, the ML APAs started 392 and 549 ms before movement onset in the *MAXIMAL* and *CONTROL* conditions. To sum up, the segmental acceleration influenced both the generation and calibration of APAs in children and adults but had no effect on the development of APAs.

This study showed that a change in sensory information led to a similar behaviour in children and adults. For the four groups, no change in APAs was observed when the vision was suppressed. As indicated by Shumway-Cook and Woollacott (1985), children aged 8 to 12 were able to integrate and coordinate the different sensory inputs available. Nevertheless, the alteration of proprioceptive inputs led to (1) an overall earlier onset of APAs on the ML axis, and (2) an overall increase of the thrust and unloading durations for each population. Therefore, proprioceptive information is essential for the generation and calibration of APAs in children as well as in adults. In an unloading task, Forget and Lamarre (1990) observed a decreased amplitude in the absence of proprioceptive feedback and concluded that the proprioceptive cues were essential for the calibration of APAs. As no interaction of age × sensory context was found for all variables, it can be concluded that the development of APAs was not related to the sensory inputs available.

Bremner (1993) suggested that "in the realm of purposefully controlled action we need to invoke the notion of cognitive structures and representations that allow infants to solve the numerous new problems that they face as they gain control over action". The movement performed in the present study was an unusual leg movement: Unlike walking or stepping, it is not performed in daily life. Therefore, it is very likely that some participants built up an internal representation of this movement after a few trials. In fact, some children were unable to begin the experimentation without online visual or proprioceptive feedbacks (i.e., in the *NV* or *VIB* con-

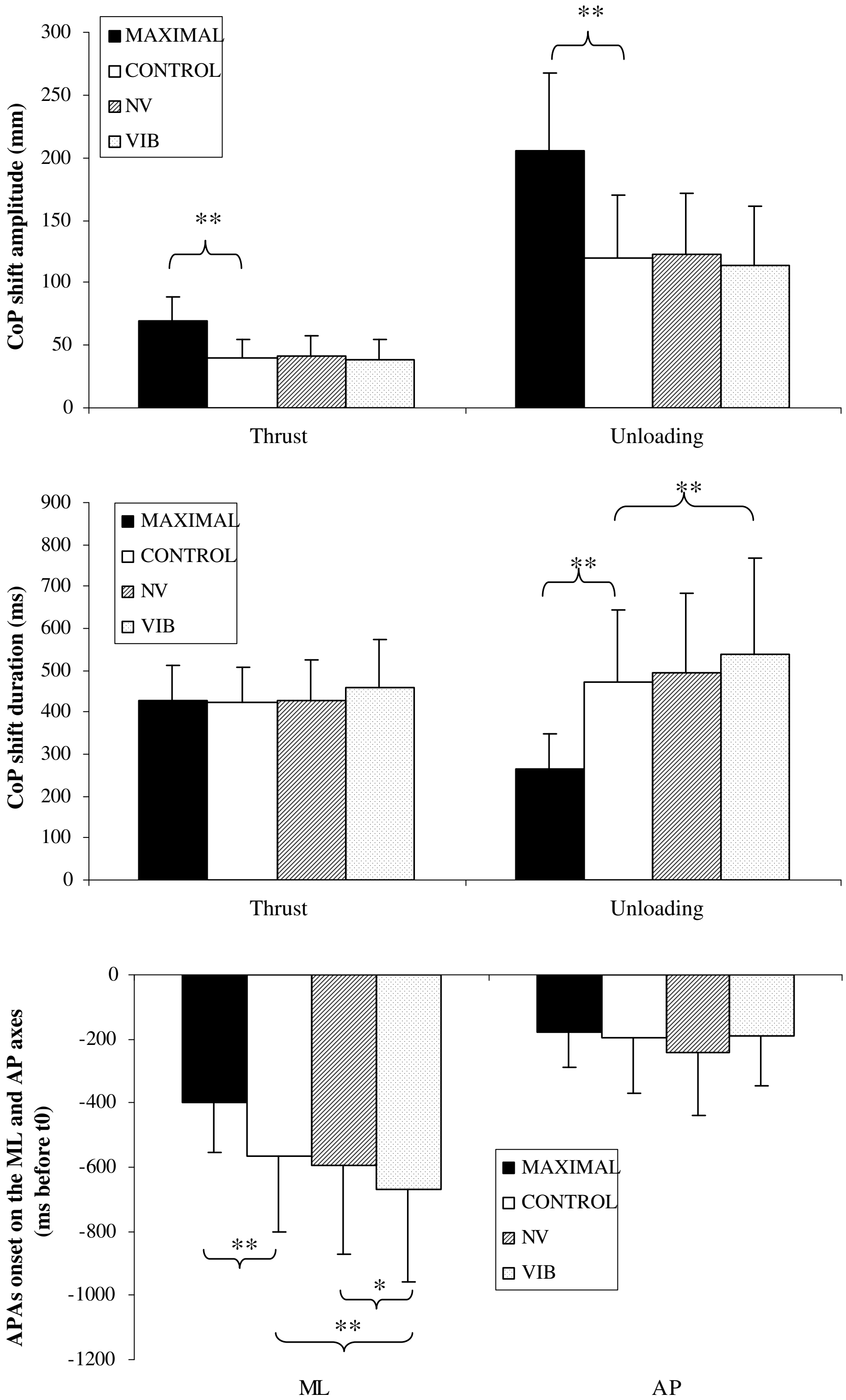

Fig. 6. CoP shift amplitude (mm), duration of the thrust (ms) and unloading phases and APAs onset on the ML and AP axes (ms before t_0) in the *CONTROL*, *MAXIMAL*, *NV* and *VIB* conditions. The significant values are reported ($^{*}P < 0.05$, $^{**}P < 0.01$).

ditions). They missed the target, could not keep the same acceleration when the latter was imposed at 16 ms^{-2}, or lost balance. The interpretation of this observation is that children needed, first of all, all sensory cues to get a better representation of the new movement to perform. Sensory inputs may really contribute to the development of APAs in children.

In conclusion, the present findings indicate that the generation and calibration of APAs are modulated according to age, temporal, and sensory parameters of the forthcoming movement. All children exhibited an anticipatory behaviour but the adult-like behaviour was reached at 12 only. The absence of interaction of age × segmental acceleration or age × sensory context suggested that the development of APAs did not depend on the segmental acceleration and sensory inputs available. No clear developmental stage was determined between the younger group and the adults. But the need for some children to build up an internal representation of the forthcoming movement, and the differences observed between the younger children (aged 8–10) and the older groups (12 and adults) suggested that the anticipatory behaviour improved during mid-childhood. As APAs were already present in younger children, further research should be led to see whether systematic and functional APAs are involved for such leg raising movements in children younger than 8.

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