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Development of temporal and spatial characteristics of anticipatory postural adjustments during gait initiation in children aged 3–10 years

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Abstract

This study aimed to analyze the development of direction specificities of temporal and spatial control and the coordination pattern of anticipatory postural adjustment (APA) along the anteroposterior (AP) and mediolateral (ML) directions during gait initiation (GI) in children aged 3–10 years. This study included 72 healthy children aged 3–10 years and 14 young adults. The child population was divided into four groups by age: 3–4, 5–6, 7–8, and 9–10 years. The GI task included GI using the dominant limb. The peak center of feet pressure (COP) shifts during APAs (APA_{peak}), initiation time of COP shifts (APA_{onset}), and the COP vectors in the horizontal plane were calculated to evaluate the *direction specificity* of spatial, temporal, and coordination control, respectively. A difference in direction specificity development was found for the APA_{peak}. The APA_{peak} in the mediolateral axis, but not in the anteroposterior axis, was significantly higher in the 7–8 years age group than in other groups. Although APA_{onset} was not found for direction specificity, a significant difference between the adult and children groups (5–6 years, 7–8 years, and 9–10 years) was observed in the direction of the COP vector. In conclusion, the developmental process of the spatial, temporal, and coordination control of APAs during GI varied with age. Furthermore, the spatial control and coordination pattern of APAs was found to be direction specific. All components of APAs, namely temporal and spatial control, coordination pattern, and direction specificities, should be analyzed to capture the developmental process of anticipatory postural control.

Keywords: Anticipatory postural adjustments; postural control; development; gait initiation; center of pressure; direction specificity

1. Introduction

Anticipatory postural control is a prerequisite for appropriate voluntary movement and many daily life activities, especially gait initiation (GI) and one-leg standing (Ledebt, Bril, & Brenière, 1998; Van der Fits et al., 1999). The ability to stand and walk independently is related to the development of anticipatory postural control (Van der Fits et al., 1999; Cignetti et al., 2013). Hence, gaining knowledge of the typical development process of anticipatory postural control is very important.

Anticipatory postural adjustments (APAs) are defined with respect to muscle activation and center of feet pressure (COP) displacements before focal movements and play a vital role in postural stabilization and propulsion during focal movement (Bouisset & Do, 2008). The development processes of APAs have been characterized by indicating various types of parameters, namely a “spatial” component (e.g., amplitude defined as the peak excursion of the COP or integrated muscle activities during the APA phase), “temporal” component (e.g., onset latency defined as the initiation time of the COP displacements before focal movements), and “coordination” pattern (e.g. COP trajectory in horizontal plane and muscle activity patterns), and demonstrated in various focal tasks, such as shoulder movement, releasing a load, lifting a leg, and GI (Assaiante et al., 2000; Barlaam et al., 2012; Girolami, Shiratori, & Aruin, 2010; Hay & Redon, 1999; Hay & Redon, 2001; Malouin & Richards, 2000; Mani et al., 2019; Palluel et al., 2008; Schmitz, Martin, & Assaiante, 1999; Schmitz, Martin, & Assaiante, 2002).

APAs exist in 3–4-year-old children; however, APA acquisition is yet fully achieved in stationary tasks during sitting and standing (Girolami et al., 2010; Hay & Redon, 1999; Hay & Redon, 2001;). The amplitude of backward COP shifts prior to focal movements (e.g., load release task or arm raising tasks) gradually increases until 8 years of age (Hay & Redon, 1999; Hay & Redon, 2001). In addition, by age 7, children have developed the ability to generate task-dependent APAs prior to shoulder movement during standing (Girolami et al., 2010). Thus, for stationary tasks, spatial postural control of APAs reaches an adult-like level by approximately 7 years of age (Girolami et al., 2010; Hay & Redon, 1999; Hay & Redon, 2001). On the contrary, a latency of APAs occurs earlier with growth (Barlaam et al., 2012). In a bimanual loading task, temporal postural control of APAs also become more effective with growth but are not yet fully mature in children aged 14–16 years (Barlaam et al., 2012; Schmitz et al., 1999; Schmitz et al., 2002). The temporal postural control of APAs is suggested to take longer to mature than spatial postural control (Barlaam et al., 2012). However, previous studies that focused on APAs during stationary tasks have mainly reported the development process of APAs along the anteroposterior (AP) direction. APAs along the mediolateral (ML) direction have not been extensively studied.

The development of spatial and temporal postural controls of APAs along the ML direction shown by previous studies focused on APAs during lifting the leg and showed similar behavior in stationary tasks (Mani, et al., 2019; Palluel et al., 2008). Mani et al.

(2019) indicated that the amplitude of APAs along the ML direction gradually increases until age 8 (Mani et al., 2019); however, children aged 7 and 8 years produce excessive APA patterns. At age 9–10, children achieve adult-like levels of the amplitude of APAs (Mani, et al., 2019). Contrarily, children aged 8–10 years have less temporal postural control of APAs on the ML axis than children aged 12 years and adults (Palluel et al., 2008). Thus, the temporal postural control of APAs along the ML direction prior to lifting the leg has also been suggested to take longer to mature than spatial postural control (Mani et al., 2019; Palluel et al., 2008). In addition, spatial postural control of APAs during dynamic tasks is suggested to take longer to mature than during stationary tasks, due to the task difficulty or direction specificities (Girolami et al., 2010; Hay & Redon, 2001; Mani et al., 2019).

In previous studies, development of the direction specificities of APAs along the AP and ML directions was focused on GI tasks and suggested to vary (Assaiante et al., 2000; Blanchet, Prince, & Messier, 2019; Ledebt et al., 1998; Malouin & Richards, 2000). Backward and lateral shifts of COP before initiating gait were suggested to play different roles: backward shifts help with "propulsion toward forward" to initiate forward stepping effectively and lateral shifts help with "postural stability" to promote movement of the center of body's mass (COM) toward the standing leg side (Bouisset & Do, 2008; Mille, Simoneau, & Rogers, 2014). Children aged 4–5 years and adults showed similar peak vertical force prior to GI (Assaiante et al., 2000). Furthermore, Malouin and Richards showed that for control of backward COP shifts, the anticipatory behavior of children aged 4–6 years is not yet fully achieved (Malouin & Richards, 2000). These studies claimed that the lateral spatial control of APAs during GI appeared to mature earlier than the backward control (Assaiante et al., 2000; Malouin & Richards, 2000). Another study demonstrated that systematic backward anticipatory control during GI was found for children aged 2.5 years, whereas the lateral anticipatory control was systematically observed later, at age 6 years (Ledebt et al., 1998). This study suggested that backward control of APAs during GI appeared to mature earlier than the lateral control (Ledebt et al., 1998). Recently, Blanchet et al. reported significant differences in the ML axis between 8 and 9-year-old children and adults, while these two groups performed similarly along the AP axis during a weight-shifting task (Blanchet et al., 2019). Therefore, the development of direction specificity of temporal and spatial postural control of APAs remains unknown.

The COP trajectory of APAs also provides us important knowledge on how the central nervous system controls APAs during GI in the horizontal plane (Malouin & Richards, 2000). The COP trajectories during APAs along the AP and ML axes are controlled by the "coordination" pattern between the ventrodorsal muscles (dominated by ankle muscles) and ML muscles (dominated by hip muscles) (Winter, 2009). Thus, the COP trajectory of APAs could detect the development of coordination patterns and direction specificities in APAs and may be an effective parameter (Corsi et al., 2019). To the best of our knowledge, only one study addresses the detailed COP trajectory during GI (Malouin & Richards, 2000). However, this study did not include participants aged 7–10 years (Malouin & Richards, 2000). Cognitive processing leads to a change in the timing and trajectory of APA shift in each direction (Sun, Guerra, & Shea, 2015). Therefore, how the ability of each component of APAs, namely "spatial" and "temporal" controls and "coordination" pattern, and direction specificities of APAs during GI develop remains unknown.

We aimed to analyze anticipatory postural control development during GI in children aged 3–10 years by examining the temporal (latency of the COP shifts) and spatial components (amplitude of the COP shifts), coordination patterns (COP trajectory in the horizontal plane), and direction specificities of COP displacements before initiating gait. We made the following hypotheses: 1) direction specificity development is present, and APAs in the AP axis mature earlier than those in the ML axis (Blanchet et al., 2019; Ledebt et al., 1998); 2) the development process of temporal and spatial control, and coordination pattern of APAs varies, that is, the temporal and coordination controls of APAs take longer to mature than spatial control, and these controls are not yet fully achieved until at least 10 years of age (Barlaam, et al., 2012; Mani, et al., 2019; Palluel et al., 2008; Schmitz, Martin, & Assaiante, 2002).

2. Methods

2.1. Participants

Seventy-two healthy children (42 boys and 30 girls) aged 3–10 years and 14 young healthy adults (22.8 ± 2.7 years) participated in the experiment (Table 1). Children who were born after 37 gestational weeks and had a birth weight > 2500 g were recruited. All participants had no significant history of medical, psychiatric, or neurological illness.

All participants, including the parents of each child, gave their informed consent prior to the start of the experiment. All study protocols were approved by the ethics committee at the institution where this study took place (17-11-2, 28-2-52), and the experiment was conducted according to the principles of the Declaration of Helsinki.

2.2. Equipment

Kinematic data were collected using a VICON Nexus 3D motion-capture system with 10 cameras running at 100 Hz (VICON, MX, USA). Twenty-seven reflective markers (9.5 mm in diameter) were placed on the skin at bony landmarks: one marker at the vertex, 7th cervical spine, and manubrium and two markers at the external acoustic foramen, acromioclavicular joint, lateral epicondyle of the upper arm, wrist, head of the third metacarpal, anterior superior iliac spine, posterior iliac spine, lateral epicondyle of the femur, lateral malleolus, second metatarsal head, and calcaneus (Mani et al., 2019). These markers were used for calculating the COM with a 14-segment model according to Jensen's anthropometric data (Jensen, 1986). Two force plates (Kistler, Winterthur, Switzerland) embedded in the ground were used in parallel for calculating the coordinates of COP. Force plate signals were collected at a sampling frequency of 1000 Hz and synchronized with the motion-capture system.

2.3. Procedures

The participants were asked to stand barefoot with their hands hanging relaxed along the body (Fig. 1). The feet were placed parallel and positioned to the right and left anterior superior iliac spine (ASIS), each on separate force plates. The placement of each foot was marked to standardize the starting position for each trial. The participants were first asked to stand relaxed with their eyes open and weight evenly distributed between both feet for at least 3 s (Fig. 1). Then, they were asked to start walking with the dominant limb (swing limb) at their natural speed after the verbal instructions of the experimenter, to take more than three steps, and to continue until they reached the end of a 5-m walkway. The experimenter checked the initial body weight distribution by checking the force plate data in the motion-capture system before starting each trial. Several practice trials were performed before data collection, and each participant was asked to perform three trials in which participants start walking with the same limb consecutively, with a 2-min rest after each trial.

2.4. Data and statistical analyses

The child population was clustered by age into the following groups: 3–4 years (*n* = 22), 5–6 years (*n* = 25), 7–8 years (*n* = 13), and 9–10 years (*n* = 12). As sex-related variations have not been observed in this study, boys and girls were combined. A priori power analysis was performed in G*power 3.1. The sample size was estimated from a pilot study carried out on 20 participants (five participants per group) for a calculated effect size of $f = 0.626$. We performed the power analysis using the F-test model of G*Power 3.1. Eight participants in each group were deemed sufficient to detect significant differences in the APA_{onset} between groups with a power (1-β) of 0.8.

All signals were processed offline using MATLAB R2018b software (MathWorks, Natick, MA, USA). Data from the VICON system and force plate data were filtered with a 20-Hz fourth-order, zero-lag Butterworth filter (Girolami et al., 2010; Winter, 2009). Coordinates of the COP in the backward shifts and lateral shifts were normalized by the percentage distance of foot length (% FL) and the percentage distance between the ASIS on both sides (% ASIS), respectively (Malouin & Richards, 2000).

The time when the vertical force of the swing leg reached zero value, signifying foot-off from the force plate, was identified (T_0) (Lin, Creath, & Rogers, 2016). The time of the first foot contact (FC) was defined as the time at which the heel marker of the swing leg in the vertical direction reached the lowest height after T_0.

The Shapiro–Wilk test was used to verify the normality of distribution in each parameter of each group. One-way analysis of variance was used to analyze parameters among the groups (3–4 years, 5–6 years, 7–8 years, 9–10 years, and adults). The Tukey *post-hoc* analysis was performed when appropriate. All statistical analyses were performed using IBM SPSS Statistics version 18 (IBM Corp., Armonk, NY, USA). Statistical significance was accepted at $p < 0.05$. Data are expressed as mean (standard deviation [SD]).

To evaluate the initial posture influencing GI task, initial positions of the COP (AP COP_{static} and ML COP_{static}) were defined as coordinates of the COP from the coordinates of the left heel marker at the APA_{onset}. APA_{onset} was defined as the time which was earlier between the time of APA initiation in the AP direction (AP APA_{onset}) and ML direction (ML APA_{onset}). AP APA_{onset} and ML APA_{onset} were defined as the times at which the displacement of COP in the backward direction and lateral direction toward the swing leg exceeded two standard deviations of the mean value of the COP displacement, respectively. The mean value was calculated during static standing from 3000 ms to 2000 ms before T_0. The time of APA termination was defined as the time at which the COP returned to its original baseline position toward the stance leg direction (Rajachandrakumar et al., 2017). The APA phase was defined as the duration from APA_{onset} to APA termination time. The COP time series was normalized such that, at the APA_{onset}, the AP and ML COP components were equal to zero by subtracting its first value from the corresponding AP and ML time series.

The maximum backward and lateral shifts toward the swing leg side of the COP during the APA phase were subsequently calculated (AP APA_{peak} and ML APA_{peak}). Furthermore, the coordination patterns of APAs in the horizontal plane were quantified using a modified vector coding technique for each participant during the APA phase to understand how the patterns of COP displacements in the horizontal plane during anticipatory control develop (Pataky, Robinson, & Vanrenterghem, 2013; Vieira et al., 2017). The COP vector was calculated by subtracting the coordinates at the APA_{onset} from the corresponding coordinates of the COP in the horizontal plane (Fig. 5A). The length (L) and direction (θ) of the COP vector were subsequently calculated. Each length and direction of the COP vector time series during the APA phase was interpolated with cubic splines to contain 101 points (0%–100%). The characteristics of the COP vector may indicate coordination patterns between the ventrodorsal muscles (dominated by ankle muscles) and ML muscles (dominated by hip muscles) (Malouin & Richards, 2000; Winter, 2009); thus, increasing the length of the COP vector meant that the CNS produced large muscle activation (Winter, 2009).

The peak velocity of the COM was also calculated by displacement derivation of the COM displacements in the sagittal plane, including both AP and vertical axes, from T_0 to FC to understand the quality of GI performance (Ledebt et al., 1998). The COM velocity was normalized by $\sqrt{gl}$ (Hof, 1996), where g is the acceleration of gravity and l is the height of the COM.

3. Results

All participants were included in the analyses. Figure 2 shows the COP displacements in the horizontal plane in each group. Patterns of COP displacements during anticipatory control were similar across all groups. All the children groups showed non-curvature and more variable patterns than the adult group, which suggests that the adult-like coordination patterns of APAs were not achieved until age 10 or more.

A significant difference was found in AP COP_{static} ($F_{4, 86} = 9.69$, $p < 0.01$; Table 2). AP COP_{static} was significantly more anterior in the adult group than in the 3–4, 5–6, and 7–8 years age groups ($p < 0.01$), and in the 9–10 years age groups than in the 3–4 years age groups ($p < 0.01$). No significant between-group differences were found in the ML COP_{static} ($F_{4, 86} = 0.34$, $p > 0.05$).

A significant difference in the AP APA_{onset} and ML APA_{onset} was found between the groups ($F_{4, 86} = 7.69$, $p < 0.01$ and $F_{4, 86} = 8.04$, $p < 0.01$, respectively; Fig. 3). A *post-hoc* analysis revealed that AP APA_{onset} and ML APA_{onset} occurred significantly earlier in the adult group than they did in all children groups ($p < 0.05$; Fig. 3).

A significant group difference was found in ML APA_{peak} ($F_{4, 86} = 6.45$, $p < 0.01$; Fig. 4B). ML APA_{peak} was significantly higher in the 7–8 years age group than in other groups ($p < 0.05$; Fig. 4B). In contrast, no significant between-group difference was found in AP

APA_{peak} ($F_{4, 86} = 2.42$, $p > 0.05$; Fig. 4A).

A significant difference was found in the direction of the COP vector from 49% to 100% ($p < 0.05$; Fig. 5B) and in its length from 47% to 96% during the APA phase ($p < 0.05$; Fig. 5C). A *post-hoc* analysis revealed that the direction was significantly higher in the adult group than in the 9–10 years age group from 61% to 100% ($p < 0.05$) and in the 5–6 years and 7–8 years age groups from 79% to 100% ($p < 0.05$). The length of the COP vector was significantly higher in the 7–8 years age group than in the 3–4 years age group from 47% to 91%, 5–6 years age group from 70% to 93%, and 9–10 years age group from 64% to 82% ($p < 0.05$). No significant difference in the length was found between the 7–8 years age group and adult group.

No significant between-group differences were found in the peak COM velocity (COM velocity: $F_{4, 86} = 0.89$, $p > 0.05$; Table 2).

4. Discussion

This study mainly found direction specificity in the development process of the spatial postural control of APAs. Contrarily, no direction specificity in the development process of the temporal postural control of APAs was found, and children aged 9–10 years did not attain adult-like levels of temporal postural control in both directions. Furthermore, the coordination patterns of APAs in the AP and ML axes was not achieved until at least 10 years of age. The development process of each *type of APA control during GI*, “temporal” (defined as the latency of the COP displacements), “spatial” (defined as the amplitude of the COP displacements), and “coordination” (defined as the COP trajectory) control of APAs during GI is different. This result suggests that each *type of APA control during GI* needs different control mechanisms. Thus, the temporal control, direction specificities in spatial control, and coordination pattern may be important characteristics of anticipatory control.

Although there was no direction specificity of APA_{onset}, COP shifts during APAs were found for the direction specificity. The spatial control of APAs, not but temporal control, may be more influenced by multiple body-function factors, including maturing antigravity muscles (Hadders-Algra, 2010), and task-dependent factors including the initial posture (Lu, Amundsen Huffmaster, Harvey, & MacKinnon, 2017), COM initial positions (Azuma, Ito, & Yamashita, 2007), movement speed (Bertucco & Cesari, 2010), postural demands, and motor experience (Looper, Wu, Angulo Barroso, Ulrich, & Ulrich, 2006). 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). The peak backward shift in the APAs depends on the velocity of the focal movement (Ledebt, Bril, & Brenière, 1998; Bertucco & Cesari, 2010). Most of the functional activities were executed along the AP axis, e.g., reaching for an object and opening doors. These experiences might improve the development of AP mechanisms (Looper, Wu, Angulo Barroso, Ulrich, & Ulrich, 2006). No significant between-group difference in the peak COM velocity and more anterior AP COP_{static} in adults than in children groups were found in this study (Table 2). Thus, children aged 3–4 years displayed very similar spatial control along the AP axis. In contrast, children aged 7–8 years produced larger APAs along the ML axis (Fig. 4B). The body weight transfer using both abductors and adductor hip 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 (Winter, Prince, Frank, Powell, & Zabjek, 1996). The result of this study may be influenced by the stance and distance between the feet during the initial posture. This is because the pelvic width-to-height ratio is larger in younger children. Studies suggested that the 5–8 year age range in children requires anticipatory behavior that is different from that in adults (Hay & Redon, 1999; Mani, Miyagishima, Kozuka, Kodama, Takeda, & Asaka, 2019; Schmitz, Martin, & Assaiante, 2002). The ability to propel COM toward the standing leg side during the APA phase may depend on excessive APAs at age 7–8 years to prioritize increasing postural stability. The results of our study suggest that therapists should check and set up the COM position and foot position prior to GI to assess or improve the spatial anticipatory control influenced by task condition.

The temporal and coordination controls of APAs take longer to mature than spatial postural control. In other words, the temporal and coordination controls of APAs were not yet achieved until at least 10 years of age (Fig. 3 and Fig. 5B). Contrarily, ML APA_{peak} becomes gradually effective at around age 7–8 years and reaches an adult-like level by age 10 (Fig. 4B and Fig. 5C). The results of the present study are supported by previous studies (Barlaam, Fortin, Vaugoyeau, Schmitz, & Assaiante, 2012; Girolami, Shiratori, & Aruin, 2010; Palluel, Ceyte, Oliver, & Nougier, 2008; Mani, Miyagishima, Kozuka, Kodama, Takeda, & Asaka, 2019; Schmitz, Martin, & Assaiante, 1999; Schmitz, Martin, & Assaiante, 2002). The basal ganglia, via their thalamic connections to the supplementary motor area, contribute to the time adjustment of APAs (Jacobs, Lou, Kraakevik, & Horak, 2009). Furthermore, Cignetti et al. (2018) demonstrated that APA control is related to the activities and connection of the cingulo-opercular, frontoparietal, and somatosensory-motor networks in both adults and children aged 8–12 years, however, this network is almost attained but not yet fully mature in children aged 8–12 years (Cignetti, Vaugoyeau, Decker, Grosbras, Girard, & Chaix, 2018). Important developments during adolescence occur in such subcortical regions (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999). Furthermore, studies suggested that the temporal organization of APAs and their amplitude scaling are separate constructs with distinct neural substrates, which may influence the development process of the coordination control of APAs (Jacobs, Lou, Kraakevik, & Horak, 2009; Smith & Fisher, 2018). Thus, the temporal control of APAs is suggested to take longer to mature than spatial control (Barlaam, Fortin, Vaugoyeau, Schmitz, & Assaiante, 2012; Girolami, Shiratori, & Aruin, 2010; Palluel, Ceyte, Oliver, & Nougier, 2008; Mani, Miyagishima, Kozuka, Kodama, Takeda, & Asaka, 2019; Schmitz, Martin, & Assaiante, 2002). A distinct approach for improving spatial and temporal control of APAs may be necessary to facilitate each neural organization.

To the best of our knowledge, only one study addresses the detailed COP trajectory during GI (Malouin & Richards, 2000). The study demonstrated the patterns of the COP trajectory in the AP and ML axes in children aged 3–10 years for the first time and that the coordination pattern of the COP in children aged 3–10 years did not show an adult-like pattern (Fig. 2; Fig. 5B). Increasing the direction of the COP vector up to 90° from 61% to 100% of the APA phase meant that the CNS could continue to activate the tibialis anterior muscles (Malouin & Richards, 2000). Malouin and Richards reported that children aged 4–6 years have not yet fully achieved preparatory adjustments involved in the control of forward progression (Malouin & Richards, 2000). The results of our study support their study and suggest that 10-year-old children cannot adjust the COP trajectory effectively; thus, the accuracy of coordination between ventral-dorsal muscles, dominated by ankle muscles, and ML muscles, dominated by hip muscles, similar to an adult-like pattern, do not show until age 10. The spatial coordination patterns of APAs are related to the topographic organization of the motor cortex, and these relationships change with aging (Smith & Fisher, 2018). The 7–16 years age group demonstrated the ability to generate a task-dependent coordination pattern of APAs (Girolami, Shiratori, Aruin, 2010). However, the coordination patterns in adolescence are almost attained but not fully mature (Schmitz, Martin, & Assaiante, 2002).

The COP trajectory of APAs (direction and length) may be effective in evaluating the coordination control of APAs that cannot be detected by the peak shifts and onsets. In future studies, EMG data should be collected to analyze relationships with COP trajectory and to understand how the CNS organizes the anticipatory control strategy during GI.

There are some limitations to this study. The anthropometric model used from Jensen's report (1986) was developed with a population of male children aged 4–15 years. The present study population included ~42% female and children as young as 3 years of age, which may influence the COM velocity results. In addition, the results of this study may be only applicable to the GI task, as other task-dependent factors influence the temporal and spatial control of APAs.

5. Conclusions

This study demonstrated the direction specificities of APA development and the different development processes of temporal and spatial control and coordination pattern of APAs during GI. APA shifts in the ML axis become gradually mature and reach an adult level by 9 years of age. Contrarily, the temporal and coordination controls of APAs take longer to mature than spatial control, and adult-like patterns are not achieved until age 10 or more. These results based on all components of APAs, namely temporal and spatial control, coordination pattern, and direction specificities, could be used as a reference for further studies dealing with pathologic motor development in children.

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Declarations of interest

The authors declare that there is no conflict of interest.

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Figure Captions

Figure 1. The participant stood on two force plates with the feet parallel and separate. Twenty-seven reflective markers were attached to bony landmarks. The two black boxes indicate the position of the force plates.

Figure 2. Grand mean center of feet pressure displacements in the anteroposterior and mediolateral axis with standard deviation in each group.

Figure 3. (A) Mean time of APA initiation in the backward direction (AP APA_{onset}) and (B) mean time of APA initiation in the lateral direction toward the swing leg (ML APA_{onset}) for each group (± SD). Significant differences in COP changes are indicated by an asterisk ($p < 0.05$). AP, anteroposterior; APA, anticipatory postural adjustment; COP, center of feet pressure; ML, mediolateral.

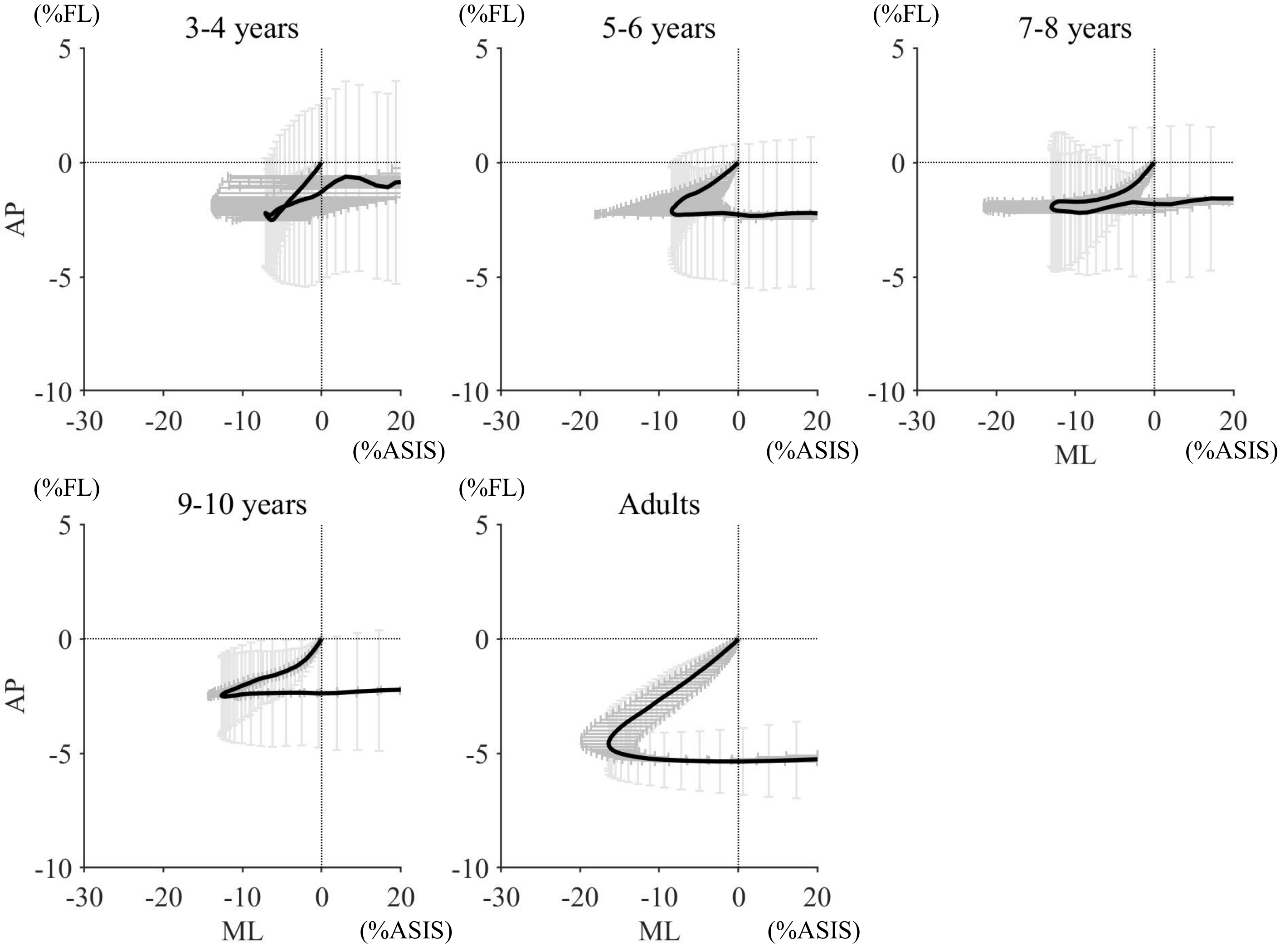
Figure 4. (A) Mean maximum backward and (B) lateral shifts toward the swing leg side of the COP during the APA phase (AP APA_{peak} and ML APA_{peak}, respectively) for each group (± SD). Significant differences in COP changes are indicated by an asterisk ($p < 0.05$). AP, anteroposterior; APA, anticipatory postural adjustment; COP, center of feet pressure; ML, mediolateral.

Figure 5. (A) Mean COP displacements in the AP and ML axes in the adult group. COP vector represents the length (L) and direction (θ). (B) Average resultant direction of the COP vector time series during the APA phase. Top and bottom error bars indicate the standard deviation in the adult group and 9–10 years age group, respectively. LETTERS are used to indicate WHERE A SIGNIFICANT DIFFERENCE WAS FOUND between the adult group and the 5–6 years (b), 7–8 years (c), and 9–10 years (d) groups. (C) Average resultant length of the COP vector time series during the APA phase. Top and bottom error bars indicate the standard deviation in the 7–8 years group and adult group, respectively. SYMBOLS are used to indicate WHERE A SIGNIFICANT DIFFERENCE WAS FOUND between the 7–8 years and 3–4 years (*), 5–6 years (†), and 9–10 years (‡) age groups.

AP, anteroposterior; APA, anticipatory postural adjustments; COP, center of feet pressure; ML, mediolateral.

Force plate

Fig. 1



3-4 years
5-6 years
7-8 years
9-10 years
Adults
(%FL)
AP
ML
(%ASIS)
5
0
-5
-10
-30
-20
-10
0
20

Fig. 2

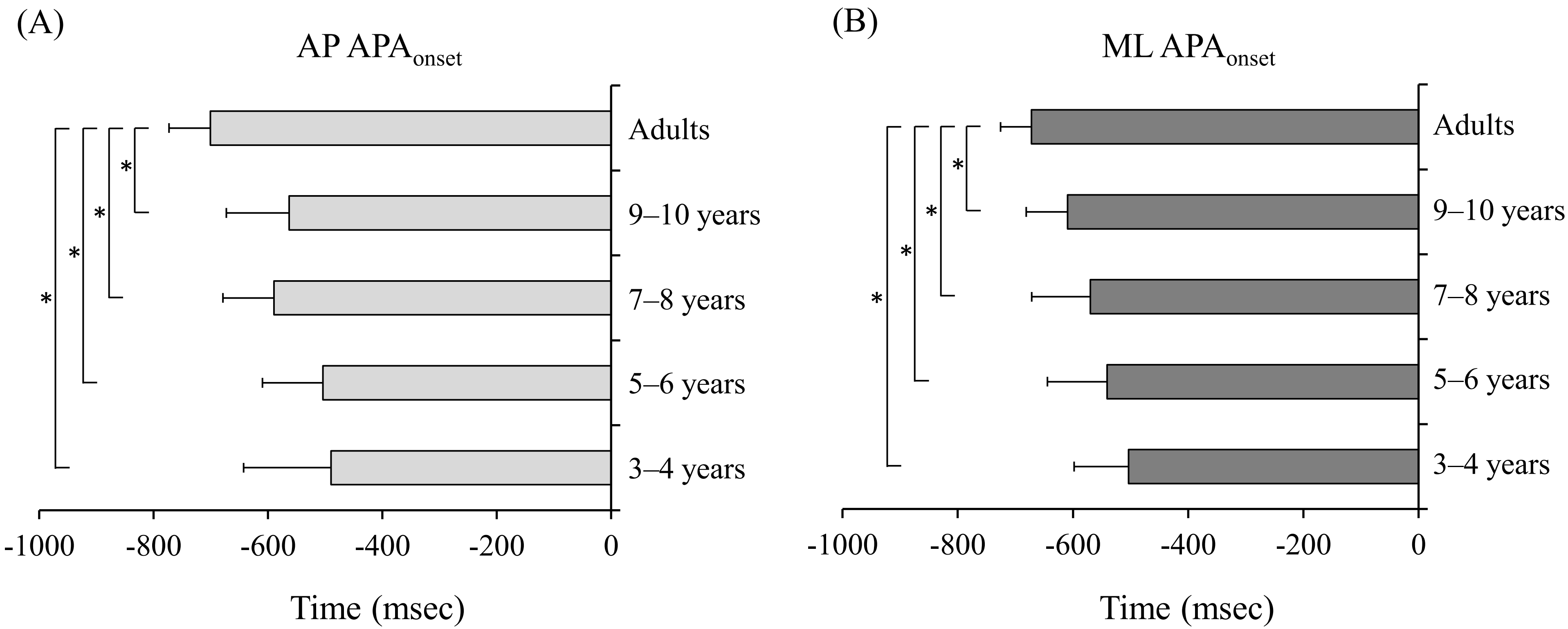

(A)
AP APA onset
Adults
9–10 years
7–8 years
5–6 years
3–4 years
-1000
-800
-600
-400
-200
0
Time (msec)
(B)
ML APA onset
Adults
9–10 years
7–8 years
5–6 years
3–4 years
-1000
-800
-600
-400
-200
0
Time (msec)

Fig. 3

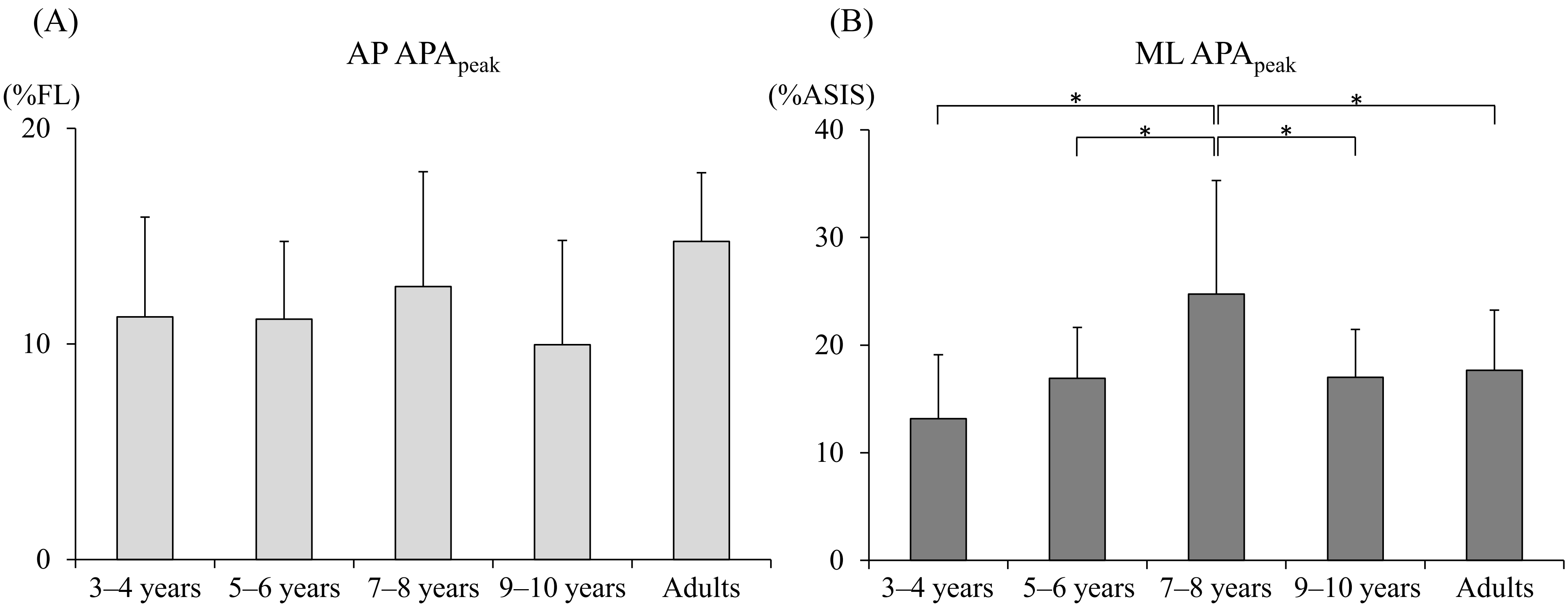
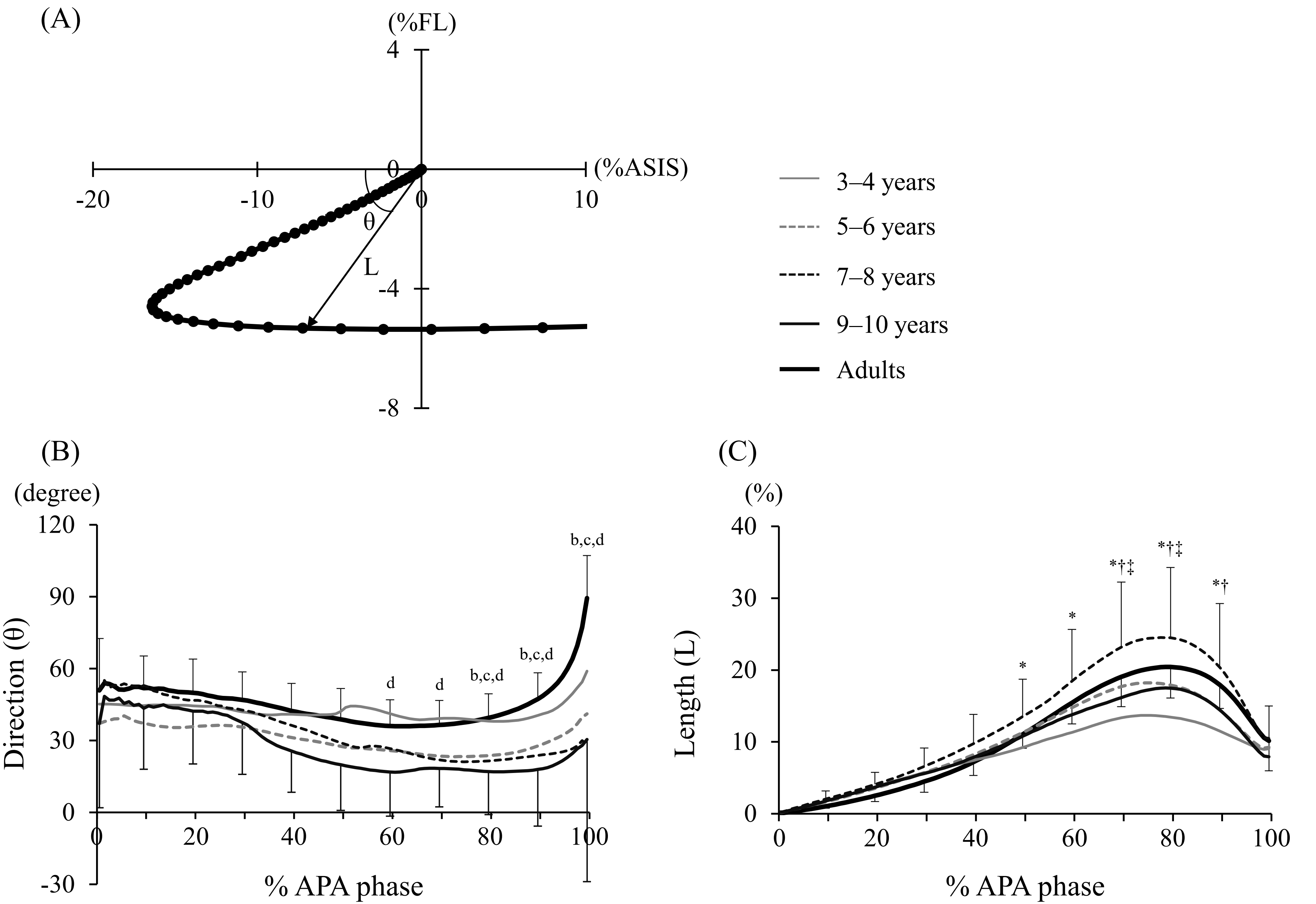

(A)
AP APApeak
(%FL)
20
10
0
3–4 years
5–6 years
7–8 years
9–10 years
Adults
(B)
ML APApeak
(%ASIS)
40
30
20
10
0
*
*
*
*
3–4 years
5–6 years
7–8 years
9–10 years
Adults

Fig. 4



(A)
(%FL)
4
0
-4
-8
(%ASIS)
-20
-10
0
10
θ
L
3–4 years
5–6 years
7–8 years
9–10 years
Adults
(B)
(degree)
Direction (θ)
120
90
60
30
0
-30
0
20
40
60
80
100
% APA phase
d
d
b,c,d
b,c,d
b,c,d
(C)
(%)
Length (L)
40
30
20
10
0
0
20
40
60
80
100
% APA phase
*
*
*†‡
*†‡
*†

Fig. 5

Table1: The characteristics of the children and adult participants

	3–4 years (n = 22)	5–6 years (n = 25)	7–8 years (n = 13)	9–10 years (n = 12)	Adults (n = 14)
Sex	Boy 13 Girl 9	Boy 14 Girl 11	Boy 8 Girl 5	Boy 7 Girl 5	Male 6 Female 8
Age (years)	4.1 ± 0.7	6.0 ± 0.6	7.8 ± 0.5	9.8 ± 0.7	22.8 ± 2.7
Height (cm)	101.5 ± 8.3	112.8 ± 6.0	124.9 ± 4.0	135.7 ± 6.7	167.1 ± 7.4
Weight (kg)	16.2 ± 2.7	20.2 ± 3.4	23.8 ± 1.1	30.2 ± 2.6	58.6 ± 7.6
Body Mass Index (kg/m^2)	15.7 ± 1.7	15.7 ± 1.3	15.3 ± 0.9	16.4 ± 1.2	20.9 ± 1.6
Distance between ASIS (cm)	17.4 ± 1.3	18.8 ± 1.6	19.0 ± 1.7	21.4 ± 1.1	26.9 ± 1.8
Foot length (cm)	15.8 ± 2.3	17.4 ± 0.9	18.3 ± 3.4	21.1 ± 1.0	24.8 ± 1.5

Table. 1

Table.2: Results of COP_{static} and COM velocity.

	3–4 years	5–6 years	7–8 years	9–10 years	Adults
AP COPstatic (%FL)	27.8 ± 9.0	30.8 ± 8.7	32.3 ± 6.4	36.8 ± 7.0[a]	44.2 ± 5.8[a,b,c]
ML COPstatic (%ASIS)	46.5 ± 11.4	49.4 ± 13.3	47.6 ± 12.1	48.3 ± 9.7	51.0 ± 8.0
COM velocity (%)	3.0 ± 0.7	3.2 ± 0.6	3.3 ± 0.7	3.1 ± 0.5	3.0 ± 0.4

Mean ± SD. Bold denotes significant data.

[a]: $p < 0.05$, compared to that of 3–4 years group

[b]: $p < 0.05$, compared to that of 5–6 years group

[c]: $p < 0.05$, compared to that of 7–8 years group

Table. 2