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Development of postural control during single-leg standing in children aged 3–10 years

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ABSTRACT

Background: The ability to control the center of mass (COM) during single-leg standing (SLS) is imperative for individuals to walk independently. However, detailed biomechanical features of postural control during SLS performed by children remain to be comprehensively investigated. Research question: We aimed to investigate the development of postural control during SLS in children aged 3–10 years.

Methods: Forty-eight healthy children (26 boys and 22 girls) aged 3–10 years and 11 young adults participated in this experiment. The child population was divided into four groups by age: 3–4, 5–6, 7–8, and 9–10 years. The SLS task included standing on a single leg as long and as steady as possible for up to 30 s. A three-dimensional motion capture system and two force plates were used for calculating the COM and center of pressure (COP). The task was divided into three phases (accelerated, decelerated, and steady) on the basis of the relationship between COM and COP.

Results: COP–COM distances in the 5–6 years' and 7–8 years' groups were significantly increased during the acceleration phase when compared with those in the adult group. Furthermore, COP–COM distances during the decelerated phase were significantly higher in all children's groups compared with those in the adult group. Lastly, COP–COM distance during the steady phase was significantly higher in the 3–4 year age group than in the 9–10 year age and adults groups.

Significance: These results suggest that postural control during the acceleration and steady phases mature by 9 years. Conversely, children ~10 years did not attain adult-like levels of postural control during the decelerated phase. The developmental process for postural control at each phase possibly plays a significant role in the basic biomechanics of movement and does not display a monotonic pattern.

1. Introduction

Postural balance relies on the ability of the central nervous system (CNS) to control the body's center of mass (COM) within the base of support (BOS) [1]. The ability to control the COM during single-leg standing (SLS) is associated with stability in performing a gross motor task during upright standing [2] and walking independently [3]. Furthermore, SLS skill is an indicator of anticipatory control and needs anticipatory postural adjustments (APAs) [4,5].

The development process of postural control during SLS has been demonstrated [6–8]. A large developmental improvement in timing during SLS typically occurs until ~5 years of age and generally reaches the adult level by ~10 years [6,7]. Although the COP fluctuation during SLS decreases with age, there were no significant differences between the 4–7 years', 8–12 years', and 13–18 age groups [8].

We are only aware of one study addressing postural control development during the transition from double-leg standing (DLS) to SLS. Deschamps et al. [9] observed that COP fluctuation reduced with age during the transition phase. However, this study did not include participants aged between 3–5 years. Additionally, APAs have not been analyzed. APAs, which are defined with respect to muscle activation and COP displacements before focal movements [10], appear to play a vital role in postural stabilization and the creation of propulsive and braking forces during a transition task. To achieve effective APAs, the

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CNS is considered to use an efferent copy of the impending motor command (i.e., internal action representations) to predict the sensory consequences of an action considering the current and the desired end-state of the body equilibrium [11]. The acuity of proprioceptive or kinesthetic estimates and their integration with other sensory modalities have been shown to increase with age [12]. In addition, the capacity to generate and/or engage internal action representations has been reported to increase, as children become adolescents [13].

Mani et al. [4] reported a new division of the SLS task into three phases based on the relationship between COP and COM displacements. At the beginning of the SLS, COP shifted to the lifting leg to promote movement of the COM toward the standing leg [4,5]. This phase (accelerated phase: ACC phase) is accomplished via a feed-forward postural control mechanism immediately before the voluntary movement, called APAs, which already exist in 3–4-year-old children, but APA acquisition is yet to be fully achieved [14]. APAs become more efficient as children grow up. Hay and Redon [15] reported that APAs in 9–10-year-old children have reached the adult level. In contrast, Palluel et al. [5] reported that an adults' anticipatory behavior was reached by the age of 12 years. In the next SLS phase, the decelerated phase (DEC phase) is defined as the interval during which COP overtakes COM in the direction of the stance leg after lifting the swing leg to brake COM within BOS. Integration with a feed-forward postural control and feedback postural control is necessary for postural stability at the DEC phase [16,17]. Capacity to integrate predictive estimates with feedback-based processing was observed in 8–9-year-old children, but continues to undergo gradual refinement up to the age of 12 years [18]. During the final SLS phase (steady phase: ST phase), COM displacement is maintained within the base of support in the stance leg. Proprioceptive feedback of the lower extremity plays an essential role during SLS [19]. However, how the ability to control the COM and COP during SLS develops remains unknown.

Therefore, we aimed to analyze postural control development during SLS in children aged 3–10 years by examining the COP–COM distance. We hypothesized that 1) the COP–COM distance during the ACC phase gradually increases with age, and that children in the 9–10-year-old range reach the adult level [15]; 2) the COP–COM distance during DEC phase gradually decreases with age, and that the 9–10-year-old children do not reach the adult level as defined by Wilson's study [18]; and 3) the COP–COM distance during the ST phase gradually decreases with age, and that the 7–8-year-old group reach the adult level based on Zumbrunn's study [8].

2. Methods

2.1. Participants

Forty-eight healthy children (26 boys and 22 girls) aged from 3 to 10 years, and 11 young adults, participated in the experiment (Table. 1). The child population was divided into the following four groups by age: 3–4 years (n = 11), 5–6 years (n = 15), 7–8 years (n = 12), and 9–10 years (n = 10). All participants had no significant history of medical, psychiatric or neurological illness. All participants as well as the parents of each child gave their informed consent before the beginning of the experiment according to the Declaration of Helsinki. All study protocols were approved by the ethics committee at the institution where this study took place (17-11-1, 28-2-52).

Fig. 1. The subject stood on two force plates with the feet parallel and separate. Twenty-seven reflective markers were attached to bony landmarks. Small circles indicate the positions of reflective markers: vertex, 7th cervical spine, manubrium, bilateral of 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.

2.2. Equipment

Kinematic data in the frontal plane were collected using a VICON Nexus 3D motion-capture system with 10 cameras running at 100 Hz (VICON, Inter Reha Corporation, Tokyo, Japan). Twenty-seven reflective markers (9.5 mm in diameter) were placed on the skin at bony landmarks (Fig. 1). These markers were used for calculating the COM with a 14-segment model (2 feet, 2 shanks, 2 thighs, pelvis and trunk, head, 2 upper arms, 2 forearms, and 2 hands) according to Jensen's anthropometric data [20]. Two force plates (Kistler, Winterthur, Switzerland) were used in parallel for calculating the coordinates of COP in the frontal plane. Force plate signals were collected at a sampling frequency at 1000 Hz and synchronized with the motion-capture system.

2.3. Procedures

Participants were asked to stand barefoot with their hands hanging relaxed alongside the body. The feet were placed parallel and positioned to the right and left anterior superior iliac spine (ASIS), each on separate force plates. For SLS trials, the subjects were first asked to stand relaxed with their eyes open and weight evenly distributed between both feet for at least 3 s. Next, they were asked to lift the

Table 1
The charactersitcs of the children and adult participants.

	3–4 years (n = 11)	5–6 years (n = 15)	7–8 years (n = 12)	9–10 years (n = 10)	Adults (n = 11)
Sex	B6 G5	B8 G7	B7 G5	B5 G5	M5 F6
Age (years)	4.1 ± 0.6	5.9 ± 0.6	7.9 ± 0.4	9.9 ± 0.4	23.3 ± 2.7
Height (cm)	101.7 ± 10.1	113.8 ± 6.5	124.3 ± 4.4	133.8 ± 7.6	167.2 ± 8.0
Weight (kg)	15.4 ± 2.6	20.7 ± 3.5	23.5 ± 1.6	27.3 ± 3.7	58.8 ± 7.7
Distance between ASIS (cm)	16.7 ± 1.0	19.2 ± 1.5	18.8 ± 1.5	20.4 ± 1.2	26.9 ± 1.9
Leg length (cm)	46.7 ± 4.7	54.8 ± 3.7	62.4 ± 3.7	66.6 ± 4.6	83.6 ± 4.7

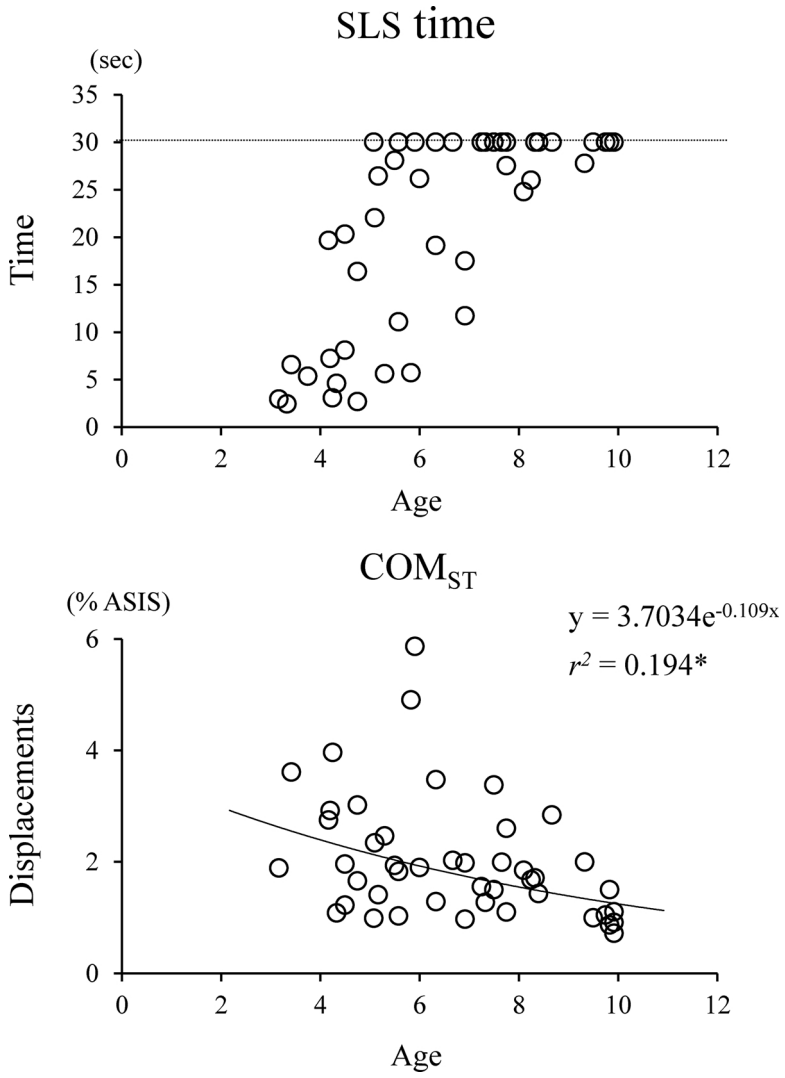

Fig. 2. Age-related changes in single-leg standing time and body sway. Bottom panel shows the results of regression analysis performed for COM_{ST} and age. * Significant correlation, $p < 0.05$.

preferred leg after verbal instructions from the experimenter. The task was to maintain the standing position for as long and as steady as possible, for up to 30 s. Several practice trials were allowed before data collection, and each subject was asked to perform three trials consecutively, with a 2-min rest after each trial.

2.4. Data and statistical analysis

All signals were processed offline using MATLAB R2015a software (MathWorks, Natick, MA, USA). Data from the VICON system and force plate data were filtered with a 20-Hz low-pass and a 10-Hz low-pass fourth-order, zero-lag Butterworth filter, respectively. Coordinates of the COM and COP in the frontal plane were normalized by the percentage distance between the ASIS on both sides (% ASIS).

The initiation time of SLS (T_0) was defined as the time when the vertical ground reaction force under the lifting-leg became zero. The termination time of SLS was defined as the time at which the ankle marker in the vertical direction reached the same coordinate as at T_0. The duration of SLS (SLS time) was measured from T_0 to termination time.

The time of APA initiation (T_{APA}) was defined as the time at which the displacement of COP in the lifting-leg direction exceeded two standard deviations of the mean value of the COP displacement. The mean value was calculated during the static standing from 3000 ms to 2000 ms before T_0. The time of APA termination (T_1) was defined as the time at which the returning displacement of COP in the standing-leg direction reached the same as the displacement of COM. Acceleration of COM was produced in the standing-leg direction during the first phase of SLS, defined as the time from T_{APA} to T_1 (ACC phase). The time at which the COM velocity first returned to zero after T_1 was also calculated (T_2). Deceleration of the COM was produced in the lifting-leg direction during the second phase of the SLS, defined as the time from T_1 to T_2 (DEC phase). The third phase was defined as the duration from T_2 to + 2000 ms after T_2 (ST phase). This time of 2000 ms was determined on the basis of the shortest SLS time recorded from all trials.

Next, the root means squares (RMSs) of COP–COM distances in each phase (D_{ACC}, D_{DEC}, and D_{ST}) and of COM displacements in the ST phase (COM_{ST}) were calculated. Finally, the velocity of the lifting leg was also calculated by the displacement derivation of the ankle marker in the vertical direction for understanding the quality of SLS performance [4].

A one-way ANOVA was used with the factors Group (3–4 years, 5–6 years, 7–8 years, 9–10 years, and adults) for analysis across group differences. The Tukey *post-hoc* analysis was performed when appropriate. Nonlinear regression analysis using exponential functions was applied to examine the relationships between the COM_{ST} and age. Additionally, Pearson's correlation coefficient was used to examine the relationships between D_{ACC} and D_{DEC} in each group to assess postural control strategies during the age frames. Statistical significance was accepted at

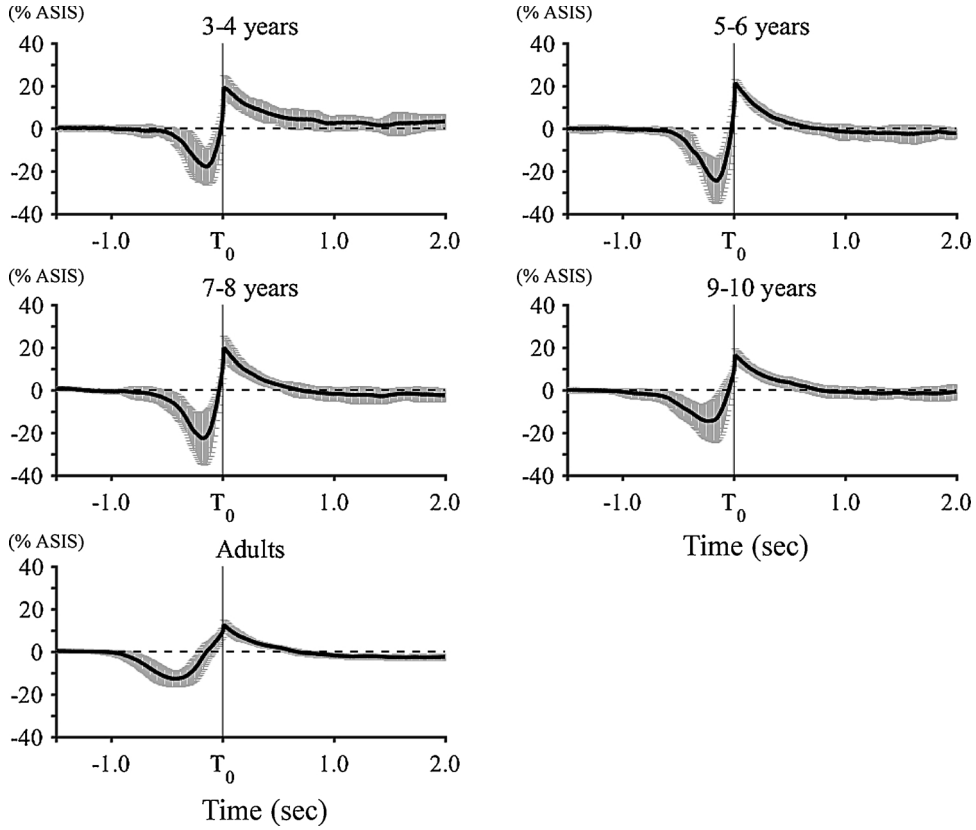

Fig. 3. Time profiles of the first few seconds for grand mean COP–COM distance in each group. The vertical line represents the initiation time of single-leg standing (T_0).

$p < 0.05$. Data are expressed as a mean ± the standard deviation (SD).

3. Results

All adult subjects were able to perform the task for > 30 s in all trials. Fig. 2 shows the SLS time for each child. The SLS time was 8.8 ± 6.7 s in 3–4 years group, 21.6 ± 9.2 s in 5–6 years group, 29.0 ± 1.9 s in 7–8 years group, and 29.8 ± 0.7 s in 9–10 years group. Furthermore, the COM_{ST} showed a significant correlation with age ($r^2 = 0.194$, $p < 0.01$; Fig. 2).

Fig. 3 shows the first 4.5 s of grand mean COP–COM distance (mean ± SD) in each group. Patterns of the COP–COM distance were similar across all groups.

Fig. 4 shows the results of the time of APA initiation (T_{APA}) and RMS of the COP–COM distance during each phase. A significant difference was found for the group in terms of T_{APA}, D_{ACC}, D_{DEC}, and D_{ST} (T_{APA}: $F_{4, 58} = 4.79$, $p < 0.01$, D_{ACC}: $F_{4, 58} = 5.16$, $p < 0.01$, D_{DEC}: $F_{4, 58} = 8.65$, $p < 0.01$, D_{ST}: $F_{4, 58} = 3.57$, $p < 0.05$). *Post-hoc* analysis revealed that T_{APA} occurred significantly earlier in adults than in all children's groups ($p < 0.05$). In addition, D_{ACC} was significantly higher in the 5–6 and 7–8 years groups than in the adult ($p < 0.05$). Specifically, D_{DEC} was significantly higher in all children's groups when compared with that in the adults group ($p < 0.05$). Furthermore, D_{ST} was significantly higher in the 3–4 years group than in the 9–10 and adults groups ($p < 0.05$). There were no significant between-group differences in peak velocity of the lifting leg ($F_{4, 58} = 1.75$, $p > 0.05$).

No significant correlations between D_{ACC} and D_{DEC} were found at 3–4 years, 5–6 years, and 9–10 years groups (Fig. 5). Conversely, significant correlations were found at 7–8 years ($r = 0.71$; $p = 0.01$) and at adulthood ($r = 0.85$; $p < 0.01$).

4. Discussion

The principal original finding of this investigation is that postural control during the ST phase is mature by 9 years of age. However, by 10 years, children did not attain adult-like levels of postural control during the DEC phase. Furthermore, although spatial postural control in APAs during the ACC phase is mature by 9 years of age, temporal postural control in APAs is not yet fully achieved until 10 years. That is, the development process of postural control at each phase during SLS is different and does not show a monotonic pattern.

4.1. Development of postural control during the acceleration phase

Although peak velocity of the lifting leg did not differ between groups, COP–COM distance at the ACC phase was increased in the 5–6 and 7–8 years groups when compared with adults (Fig. 4). This result suggests that the 5–8 year age range in children requires anticipatory behavior that is different from adult subjects [21]. Hay and Redon [15,22] demonstrated that APAs do not show a monotonic pattern of development, so children between the ages of 6 and 8 years produce excessive APA patterns when compared with those aged 9–10 years and adult subjects. The results of our study support these findings.

A feed-forward postural control seems to have been most actively involved in the 6–8 age range [22]. At ~8 years of age, children have been suggested to progress to an integrated feedforward and feedback postural control from feedback control for maintaining control [21]. The capacity to generate and/or engage internal action representations has been shown to increase from 6 to 18 years of age [13]. The 6-year-old children showed larger endpoint errors when they had to rely on kinesthetic feedback than the 10-year-old children, suggesting a less well-defined kinesthetic-motor internal representation in the younger children than in the older children and a higher dependence on

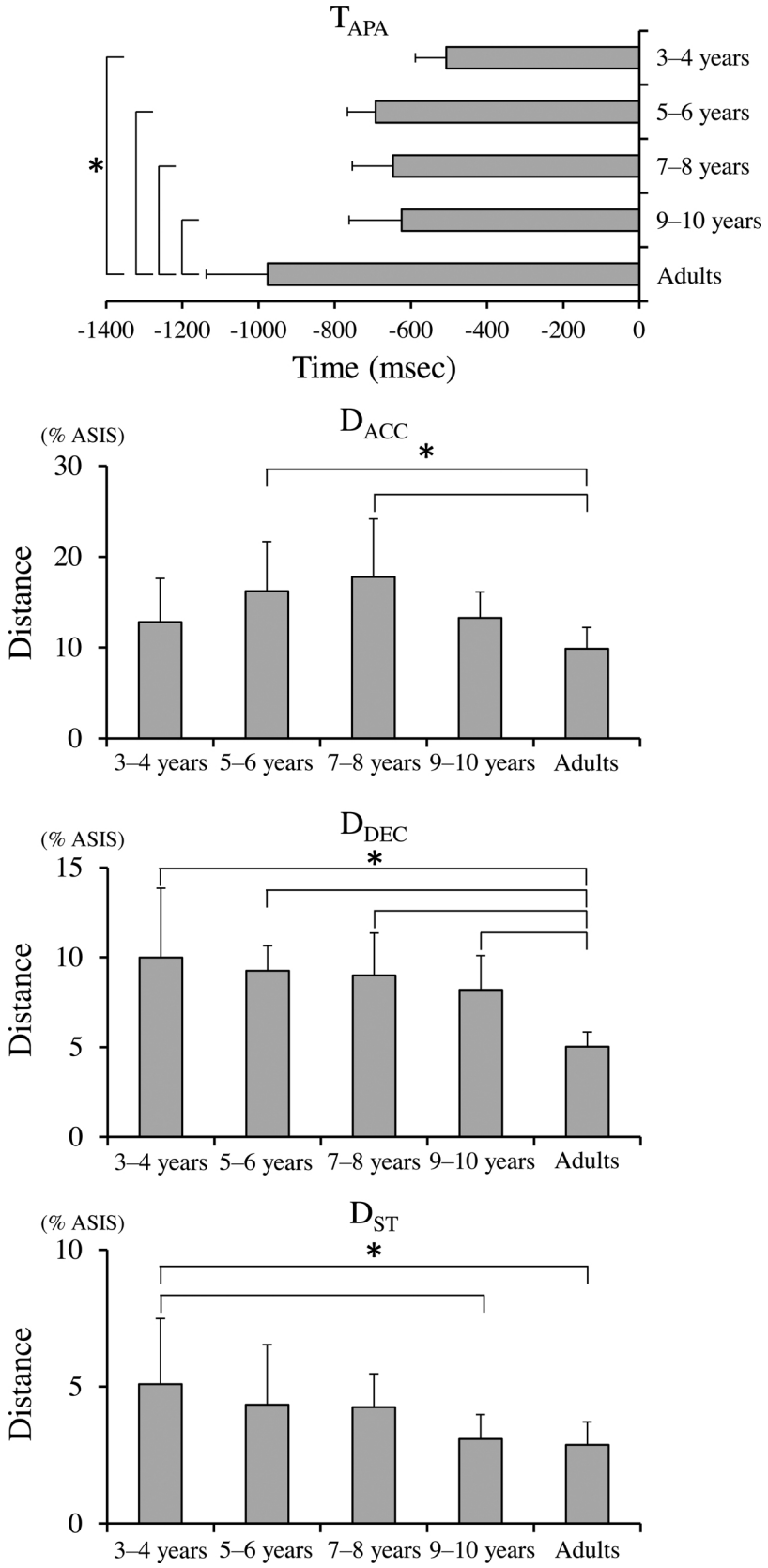

Fig. 4. Mean time of APAs initiation (T_{APA}) and RMS of COP–COM distance (± SD) in ACC, DEC, and ST phase for each group. Panels from top to bottom are T_{APA}, COP–COM distance at ACC phase, at DEC phase, and at ST phase.

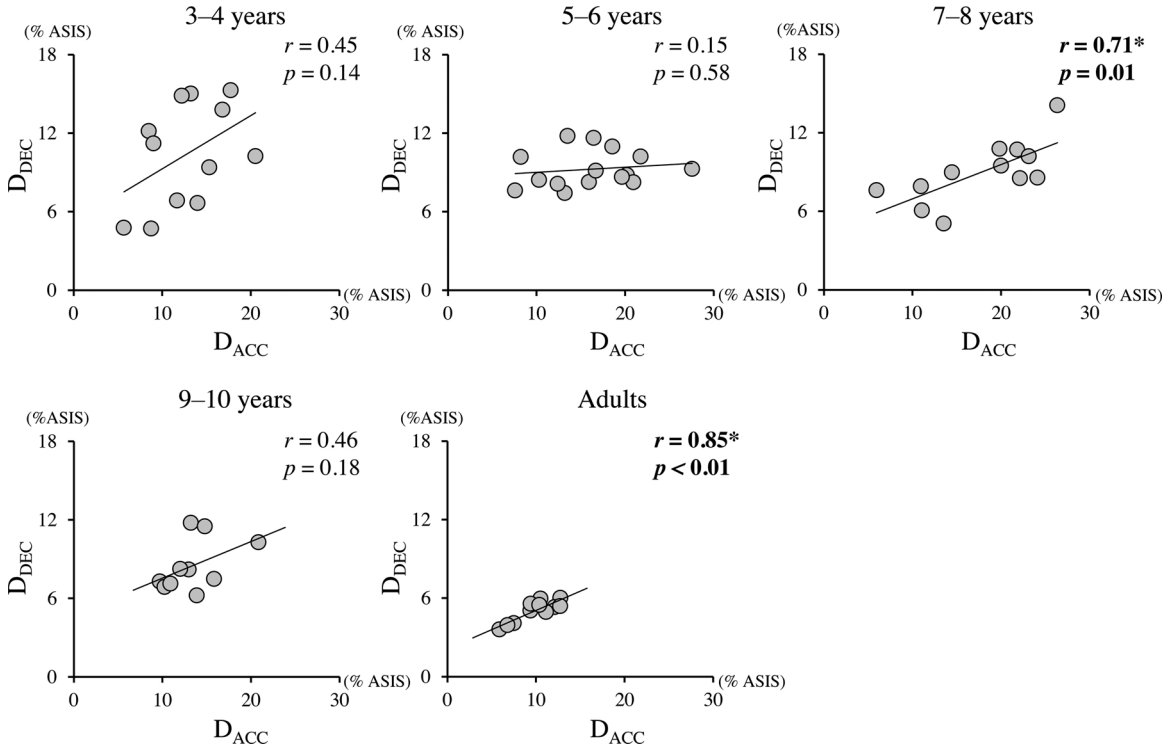

Fig. 5. Relationship between COP–COM distance in ACC phase and DEC phase for each group.

feedforward control [23]. Thus, the ability to propel COM during the ACC phase may depend on excessive APAs at ~7 years of age, which may switch from a feedback postural control to feedforward postural control. Indeed, anticipatory control becomes gradually effective at about 7–8 years of age during the transition phase (Fig. 5). In addition, the correlation coefficients with an amplitude of APAs and performance parameters in older children are higher than those in younger children [24]. Thus, children aged 5–8 years may have to produce larger APAs to propel the COM toward the stance leg. This suggests that development of spatial postural control in APAs does not show a monotonic pattern and that the anticipatory behavior observed in adults is not reached until 9 years of age.

In contrast to the spatial postural control of APAs, T_{APA} occurred significantly earlier in adults than in the children's groups (Fig. 4). This suggests that the temporal postural control in APAs is not yet fully achieved until at least 10 years of age. Timing adjustments of APAs show a monotonic pattern of development and are modulated according to age [5]. However, the immature pattern of temporal coordination of APAs was still present by 16 years of age [25]. The basal ganglia, via their thalamic connections to the supplementary motor area, actively participate in these timing adjustments [26]. Important developments occurring during adolescence occur in these subcortical regions [27]. The temporal control of APAs is suggested to take longer to mature compared with spatial control [5,25].

4.2. Development of postural control during the deceleration phase

All children's groups showed a larger COP–COM distance when compared with adult subjects (Fig. 4). These results suggest that 3–10-year-old children do not appropriately adjust COP displacements to the movement of the COM. In the DEC phase, it is necessary for COP displacements to be appropriately adjusted on the basis of continuous sensory feedback information from COM displacements. Therefore, integration with the feedforward postural control and feedback postural control should be an essential feature [16,17]. More efficient online control from feedback signals rapidly occurs after 8–9 years of age but continues to undergo gradual refinement up to 12 years of age [18]. There was no significant correlation between D_{ACC} and D_{DEC} at 9–10 years (Fig. 5). Development involves changes in the relative weightage of feedforward and feedback components and an increased capacity to move from one strategy to another, depending on the availability of information [28]. Thus, postural control strategy in individuals aged 9–10 years may switch to an integrated feedforward and feedback mechanism. This suggests that postural control during DEC phase may require higher balancing ability than that during the ACC and ST phase, and thus adult-like patterns are not achieved until 10 or more years of age.

4.3. Development of postural control during the steady phase

In the ST phase, COM displacements decreased with an increase in age (Fig. 2), and the COP–COM distance was higher in the 3–4-year-old group than in the 9–10-year-old group and adult group (Fig. 4). Furthermore, except for one subject, children aged 9–10 years were also able to perform the task for > 30 s (Fig. 2). Our findings, therefore, support other investigations that suggest that 10-year-old children can maintain single-leg standing as long as adult subjects [7]. Somatosensory systems start developing at 3–4 years of age, and the dominant sensory information for postural control moves from the visual to the somatosensory system at 4–6 years [29]. In addition, correlations between SLS time and lower-extremity muscle strength have been reported to be strong [19]. Thus, younger children may be unable to attain a SLS time up to 30 s because of immature muscle and cognitive function. Collectively, these results suggest that the maturation of muscle strength, somatosensory function, and accurate ankle control might contribute to the adjustment of COP displacement around the COM.

4.4. Limitations

The limited sample size, the two-year division of each group of children, and no analyzing characteristics associated with the sex could

be seen as a limitation. Intra-individual variability regarding body growth and capturing motor skills is very large in younger children up to 8 years of age [30]. Furthermore, girls tend to outperform boys in standing balance [6] and typically have better APAs [25]. Therefore, future investigations into the sex differences associated with SLS will likely yield valuable insight.

5. Conclusions

Postural control during the ACC and ST phase is mature at a minimum of 9 years of age. Conversely, children ~10 years of age did not attain adult-like levels of postural control during DEC phase and of the temporal postural control in APAs. The developmental process for postural control at each phase possibly plays a significant role in the basic biomechanics of movement and does not show a monotonic pattern. Thus, this investigation contributes crucial biomechanical knowledge concerning the development of SLS in early childhood and provides useful information for comparing children with developmental disorders.

Conflict of interest statement

The authors declare that there is no conflict of interest.

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References

[1] D.A. Winter, Biomechanics and Motor Control of Human Movements, fourth ed., John Wiley and Sons, New Jersey, 2009.
[2] R.W. Bohannon, K.M. Leary, Standing balance and function over the course of acute rehabilitation, Arch. Phys. Med. Rehabil. 76 (1995) 994–996.
[3] K. Guffey, M. Regier, C. Mancinelli, P. Pergami, Gait parameters associated with balance in healthy 2- to 4-year-old children, Gait Posture 43 (2016) 165–169.
[4] H. Mani, S.F. Hsiao, K. Takeda, N. Hasegawa, M. Tozuka, A. Tsuda, T. Ohashi, T. Suwahara, K. Ito, T. Asaka, Age-related changes in distance from center of mass to center of pressure during one-leg standing, J. Mot. Behav. 47 (2015) 282–290.
[5] E. Palluel, H. Ceyte, I. Olivier, V. Nougier, Anticipatory postural adjustments associated with a forward leg raising in children: effects of age, segmental acceleration and sensory context, Clin. Neurophysiol. 119 (2008) 2546–2554.
[6] T.H. Kakebeeke, I. Locatelli, V. Rousson, J. Caflisch, O.G. Jenni, Improvement in gross motor performance between 3 and 5 years of age, Percept. Mot. Skills 114 (2012) 795–806.
[7] C. Condon, K. Cremin, Static balance norms in children, Physiother. Res. Int. 19 (2014) 1–7.
[8] T. Zumbrunn, B.A. MacWilliams, B.A. Johnson, Evaluation of a single leg stance balance test in children, Gait Posture 34 (2011) 174–177.
[9] K. Deschamps, F. Staes, K. Peerlinck, K. Van Geet, C. Hermans, S. Lobet, Postural control of typical developing boys during the transition from double-leg stance to single-leg stance, Eur. J. Pediatr. 176 (2017) 273–278.
[10] S. Bouisset, M.C. Do, Posture, dynamic stability, and voluntary movement, Neurophysiol. Clin. 38 (2008) 345–362.
[11] D.M. Wolpert, M. Kawato, Multiple paired forward and inverse models for motor control, Neural Netw. 11 (1998) 1317–1329.
[12] B. Smits-Engelsman, J. Duysens, The line copy task for kinesthesia and internal movement representation: application in children, Hum. Mov. Sci. 27 (2008) 682–694.
[13] I. Fuelscher, J. Williams, K. Wilmut, P.G. Enticott, C. Hyde, Modeling the maturation of grip selection planning and action representation: insights from typical and atypical motor development, Front. Psychol. 9 (2016) 108.
[14] F. Malouin, C.L. Richards, Preparatory adjustments during gait initiation in 4-6-year-old children, Gait Posture 11 (2000) 239–253.
[15] L. Hay, C. Redon, Development of postural adaptation to arm raising, Exp. Brain Res. 139 (2001) 224–232.
[16] J.A. Leonard, V. Gritsenko, R. Ouckama, P.J. Stapley, Postural adjustments for online corrections of arm movements in standing humans, J. Neurophysiol. 105 (2011) 2375–2388.
[17] J.A. Leonard, V. Gritsenko, R. Ouckama, P.J. Stapley, Postural adjustments for online corrections of arm movements in standing humans, J. Neurophysiol. 105 (2011) 2375–2388.
[18] P.H. Wilson, C. Hyde, The development of rapid online control in children aged 6-12 years: reaching performance, Hum. Mov. Sci. 32 (2013) 1138–1150.
[19] L. Allet, H. Kim, J. Ashton-Miller, T. De Mott, J.K. Richardson, Frontal plane hip and ankle sensorimotor function, not age, predicts unipedal stance time, Muscle Nerve 45 (2012) 578–585.
[20] R.K. Jensen, Body segment mass, radius and radius of gyration proportions of children, J. Biomech. 19 (1986) 359–368.
[21] N. Kirshenbaum, C.L. Riach, J.L. Starkes, Non-linear development of postural control and strategy use in young children: a longitudinal study, Exp. Brain Res. 140 (2001) 420–431.
[22] L. Hay, C. Redon, Feedforward versus feedback control in children and adults subjected to a postural disturbance, Exp. Brain Res. 125 (1999) 153–162.
[23] J.L. Contreras-Vidal, Development of forward models for hand localization and movement control in 6- to 10-year-old children, Hum. Mov. Sci. 25 (2006) 634–645.
[24] A. Ledebt, B. Bril, Y. Brenière, The build-up of anticipatory behaviour. An analysis of the development of gait initiation in children, Exp. Brain. Res. 120 (1998) 9–17.
[25] F. Barlaam, C. Fortin, M. Vaugoyeau, C. Schmitz, C. Assaiante, Development of action representation during adolescence as assessed from anticipatory control in a bimanual load-lifting task, Neuroscience 221 (2012) 56–68.
[26] J.V. Jacobs, J.S. Lou, J.A. Kraakevik, F.B. Horak, The supplementary motor area contributes to the timing of the anticipatory postural adjustment during step initiation in participants with and without Parkinson's disease, Neuroscience 164 (2009) 877–885.
[27] E.R. Sowell, P.M. Thompson, C.J. Holmes, T.L. Jernigan, A.W. Toga, In vivo evidence for post-adolescent brain maturation in frontal and striatal regions, Nat. Neurosci. 2 (1999) 859–861.
[28] L. Hay, C. Bard, C. Ferrel, I. Olivier, M. Fleury, Role of proprioceptive information in movement programming and control in 5 to 11-year old children, Hum. Mov. Sci. 24 (2005) 139–154.
[29] S. Hirabayashi, Y. Iwasaki, Developmental perspective of sensory organization on postural control, Brain Dev. 17 (1995) 111–113.
[30] J. Müller, S. Müller, H. Baur, F. Mayer, Intra-individual gait speed variability in healthy children aged 1-15 years, Gait Posture 38 (2013) 631–636.