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The cross-sectional relationships between age, standing static balance, and standing dynamic balance reactions in typically developing children

Benjamin C. Conner[a], Drew A. Petersen[b], Jamie Pigman[c], James B. Tracy[c], Curtis L. Johnson[d], Kurt Manal[c], Freeman Miller[e], Christopher M. Modlesky[f], Jeremy R. Crenshaw[c,*]

[a] College of Medicine – Phoenix, University of Arizona, Phoenix, AZ, United States
[b] Department of Physical Therapy, Drexel University, Philadelphia, PA, United States
[c] Department of Kinesiology and Applied Physiology, University of Delaware, Newark, DE, United States
[d] Department of Biomedical Engineering, University of Delaware, Newark, DE, United States
[e] Department of Orthopedics, Nemours A.I. duPont Hospital for Children, Wilmington, DE, United States
[f] Department of Kinesiology, University of Georgia, Athens, GA, United States

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ABSTRACT

Background: Static balance performance is a common metric for evaluating the development of postural control in children. Less is known about the potentially independent development of dynamic balance performance.
Research question: How does age relate to static (i.e. postural sway) and dynamic (i.e. stepping thresholds) standing balance performance, and what is the relationship between postural sway and stepping thresholds?
Methods: Twenty-six typically developing children (12 males, 14 females; 5–12 years of age) were recruited for this cross-sectional study. Static balance performance was quantified as the total path length during a postural sway assessment using a force platform with conditions of eyes open and eyes closed. Dynamic balance performance was quantified using a single-stepping threshold assessment, whereby participants attempted to prevent a step in response to treadmill-induced perturbations in the anterior and posterior directions. Relationships between age and body-size scaled measures of static and dynamic balance performance were assessed using Spearman rank correlations.
Results: There was a weak correlation between age and postural sway ($|r_s| < 0.10$, $p > 0.68$), but a moderate-to-strong correlation between age and single-stepping thresholds ($r_s > 0.68$, $p < 0.001$). A weak correlation was found between postural sway and single-stepping thresholds ($|r_s| < 0.20$, $p > 0.39$).
Significance: Dynamic, but not static standing balance performance, may improve with typical development between the ages of 5 and 12 years. Static and dynamic balance should be considered as unique constructs when assessed in children.

1. Introduction

Standing posture is controlled by the integration of sensorimotor processes to maintain one's center of mass within their base of support [1,2]. Such control, however, is dependent on the interaction of biomechanical constraints (e.g. size and strength), dynamics (e.g. the direction and magnitude of motion), movement strategies (e.g. ankle control, hip control, stepping, etc.), and previous experience [2]. As children age and develop, biomechanical constraints and previous experience change, potentially influencing movement strategies and dynamics. Given this complex interplay of age and control factors, a single assessment is unlikely to capture how postural control changes with development. Characterizing this typical development is an important first step that must occur before evaluating how early childhood neuromuscular impairment alters the trajectory of balance-skill acquisition.

Two distinct circumstances are associated with different postural control dynamics and strategies: 1) quiet standing and 2) responding to a perturbation. During quiet, quasi-static standing, volitional control of the ankle and hip muscles alter the slow center of mass movements [3]. Postural sway, often quantified from the trajectory of the center of pressure, is a common, reliable measure of postural steadiness during standing in children with and without neuromuscular impairment [4].

Abbreviations: SD, Standard deviation; COP, center of pressure; COM, center of mass; MoS, margin of stability; r_s, Spearman rank correlation coefficient

* Corresponding author at: Department of Kinesiology and Applied Physiology, 201u Health Sciences Complex, STAR Campus, 540 S. College Ave., Newark, DE, 19713, United States.

E-mail address: crenshaw@udel.edu (J.R. Crenshaw).

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Several studies have demonstrated age-related reductions in sway through childhood and adolescence [5–10]. The effect of limiting vision on sway, however, does not change with childhood development [5–7]. Therefore, static balance performance improves with age, but the reliance on vision to do so does not.

In contrast to standing, the dynamic reaction to an external perturbation necessitates rapid, whole-body reactions that include generating lower-extremity joint moments, stepping, counter-rotation of segments about the center of mass, and/or reaching for a stabilizing object [2,11]. With development, such as the onset of independent walking, children exhibit a more coordinated, directionally-specific neuromuscular response to a perturbation [12,13]. Compared to younger children, adolescents also have greater proactive balance, as evidenced by tasks with predicted self-initiated perturbations, such as the functional-reach test [8]. Additionally, children are more likely to rely on an "ankle strategy" to recover balance, while adults are more likely to incorporate a "hip strategy" [13]. After a perturbation, older children (mean age 12.0 years) were found to have less sway compared to young children (mean age 6.7 years) [14]. Although the coordination of balance reactions is altered with age, likely altering balance reaction capabilities, no studies to date have objectively assessed how dynamic balance performance changes over the course of development. An objective, reliable method for quantifying dynamic balance performance is through single-stepping thresholds, defined as the perturbation magnitudes that consistently elicit a protective step [15]. To our knowledge, such thresholds have not previously been correlated with age in children.

Although stepping thresholds quantify the *ability* or *willingness* to respond to an external postural disturbance with a feet-in-place response, the thresholds alone do not identify the underlying mechanisms that influence performance. One potential mechanism is the resulting dynamic instability from the perturbation. In this study, dynamic stability is evaluated as the margin of stability, a biomechanical measure that accounts for the position and velocity of the center of mass relative to the edge of the base of support [16–18]. The minimum margin of stability after a perturbation then, is a reflection of the size of the perturbation (i.e. larger perturbations cause greater instability) and the child's response to it (i.e. a more robust response limits instability). We do not know how age alters such dynamic stability maintenance in children.

This study represents an initial investigation of compensatory stepping thresholds assessed in typically developing children. We aimed to investigate the influence of age on postural sway (a measure of static balance control) and stepping thresholds (a measure of dynamic balance control), as well as evaluate how sway relates to stepping thresholds. We hypothesized that age would be inversely related to postural sway and positively related to stepping thresholds. In order to explore underlying mechanisms associated with the stepping threshold measure, we evaluated the relationship between age and the minimum margin of stability after a perturbation. In adults, standing balance performance and balance-reaction performance have not been strongly correlated [19–21]. Given this weak association between static and dynamic conditions, we did not expect sway and stepping thresholds to be strongly correlated in children.

2. Method

2.1. Participants

A convenience sample of 26 children with typical development (12 males, 14 females; mean age 9.4 (2.2) years; range 5.8 to 12.7 years) were recruited for this observational, cross-sectional study. Inclusion criteria included a guardian-reported ability to walk without assistance and follow instructions. Exclusion criteria included a guardian-reported diagnoses of neuromuscular impairment, as well as no history of musculoskeletal injury that affected balance or mobility. This report was secondary to an interdisciplinary pilot project to evaluate neural structure, balance, mobility, and physical activity in children with and without cerebral palsy (reports for other study components are in review and preparation). Therefore, the sample size was established to demonstrate feasibility and inform hypotheses for future, statistically powered studies in these areas. A sample size of 26 participants is large enough to detect a moderate correlation coefficient of 0.53 or greater as significant. Approval for this study was obtained from the Institutional Review Board at the University of Delaware. Written informed consent was provided by a legal guardian of each participant, and informed assent was provided by participants. All data collection procedures occurred in a motion-analysis laboratory in an academic setting.

2.2. Instrumentation

2.2.1. Kinematics

Participants were outfitted with 41 retro-reflective markers placed on their extremities, pelvis, trunk, and head. The trajectories of these markers were recorded by up to 13 cameras (Eagle system, Motion Analysis Corporation, Santa Rosa, CA, replaced mid-study by Oqus System, Qualisys, Gothenburg, Sweden; 120 Hz).

2.3. Measurements

2.3.1. Postural sway

Quasi-static postural control was assessed by measuring the trajectory of the center of pressure while participants stood, feet at shoulder width, on a force plate (Optima HPS, Advanced Mechanical Technology, Inc., Watertown, MA; 600–1200 Hz) under 2 conditions: eyes open and eyes closed. Participants were instructed to "stand as still as possible for 30 s", and completed one trial of each condition. Participants were also instructed to look straight ahead at an image approximately 10 feet away at approximately head height. Path length, a measure found to be reliable in children for a single trial [4], was calculated as the total center of pressure (COP) displacement during the 30-second trial. To account for differences in center of mass (COM) excursion with height, path length values were scaled to participant height [22]. A Romberg ratio was calculated by dividing the eyes closed by the eyes open path length [13].

2.3.2. Single-stepping threshold

Participants stood on a computer-controlled treadmill (ActiveStep, Simbex®, Lebanon, NH) while wearing a safety harness (DMM, Wales, UK). This harness was attached to an overhead rail and adjusted as to prevent contact of the knees or hands with the treadmill. Participants were instructed to "try not to step" in response to rapid treadmill belt accelerations applied with 400-millisecond surface translations. These disturbances were characterized by a triangular waveform velocity profile consisting of 200 ms acceleration and deceleration phases. After an initial treadmill belt acceleration of 0.5 m/s^2, a progressively challenging series of disturbances was applied. Posterior and anterior belt accelerations, inducing anterior and posterior sway, respectively, were delivered in a pseudo-randomized order. In other words, the direction of the disturbance was randomly determined for each trial, with the constraint that no more than four consecutive trials could be delivered in the same direction. In this paper, "posterior" and "anterior" disturbances refer to the direction of induced sway. For subsequent disturbances, the initial acceleration was increased or decreased in increments of 0.5 m/s^2 depending on success or failure. Failure was defined as either taking a step or using the harness to support greater than 20% of the participant's body weight, as recorded by a force transducer (Dillon, Fairmont, MN) in series with the harness system [23]. Failure was identified by a single investigator. When needed, observed steps were confirmed by a second investigator or by reviewing motion capture recordings. Anterior and posterior single-stepping thresholds were identified as the initial acceleration that resulted in

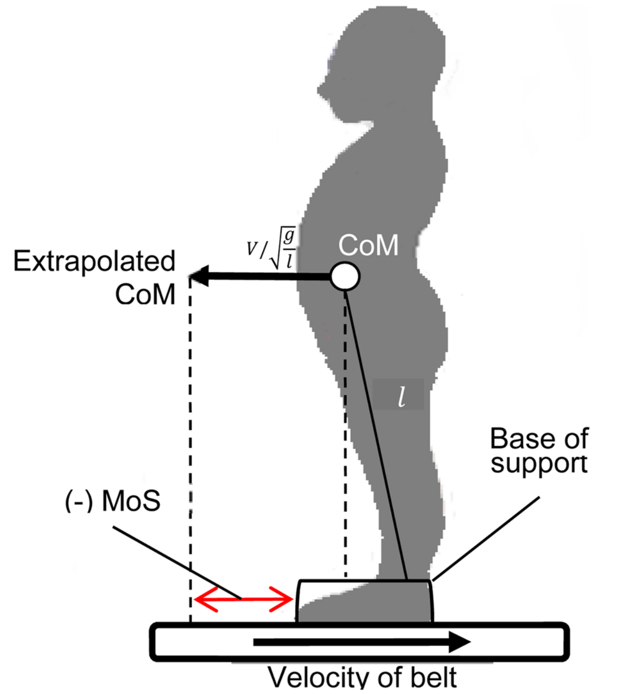

Fig. 1. Model representing the margin of stability (MoS) calculation, where the center of mass (CoM) position and scaled velocity ($\frac{v}{\sqrt{\frac{g}{l}}}$) are represented as the extrapolated CoM, the vertical projection of which falls outside of the base of support, resulting in a negative MoS.

four consecutive failed responses [15]. The series of disturbances was continued until both anterior and posterior single-stepping thresholds were determined. In order to consistently evaluate unitless values throughout the study, threshold accelerations were divided by gravity [22]. This approach effectively scales the disturbance to body size. In previous studies, we expressed non-scaled threshold values as the destabilizing moment associated with the treadmill belt acceleration, a calculation that includes body height and mass [15].

2.4. Analysis

Using kinematic data from motion analysis, dynamic stability was quantified as the margin of stability (MoS, Fig. 1) [17,18] as follows:

$$MoS = d + \frac{v}{\sqrt{g/l}} \tag{1}$$

where $d = x_{toe} - x_{CoM}$ (x is the anteroposterior position) and $v = v_{toe} - v_{CoM}$ (v is velocity) for anterior disturbances, and $d = x_{CoM} - x_{heel}$ and $v = v_{CoM} - v_{heel}$ for posterior disturbances. The COM position was calculated from kinematic data and anthropometric values [24]. The variable g represents gravity (9.81 m/s^2) and l is the sagittal-plane distance between the mean ankle joint center location and that of the whole-body COM, calculated on a frame-by-frame basis. For the trials representing the highest disturbance magnitude in which a step was prevented, the minimum (often most-negative) MoS after disturbance onset was determined. To keep all measures unitless, the MoS was scaled to participant height. LabVIEW programs (National Instruments, Austin, TX) were developed to calculate MoS measures.

2.4.1. Statistics

Spearman rank correlation coefficients were calculated to determine the relationships between and among scaled measures of balance (single-stepping threshold, postural sway, and MoS) and age. Due to the ordinal nature of our single-stepping threshold levels and our small sample size where assumptions of normality are difficult to test in a valid manner, a Spearman rank correlation coefficient was chosen as a conservative approach to correlation analysis. We used the following cutoffs for determining the strength of correlations: ≤0.3 was a negligible correlation, 0.3-0.5 was a low correlation, 0.5-0.7 was a moderate correlation, 0.7-0.9 was a high correlation, and > 0.9 was a very high correlation [25]. Statistics were evaluated using SPSS (v24, IBM, Armonk, NY; significance determined at $\alpha < 0.05$).

3. Results

Of the 26 participants recruited, 20 had complete data for analysis. Two of the participants did not have force plate data for postural sway analysis due to technical difficulties. Four of the participants were not able to complete thirty seconds of quiet stance for the postural sway protocol due to non-compliance (e.g. distraction or fidgeting). Anthropometric data and test results for each participant are reported in Appendix A.

Age was significantly correlated with dynamic balance measures, but not with postural sway (Table 1). With older age, scaled stepping-threshold values were larger ($r_s > 0.68$, $p < 0.001$; Fig. 2), and the minimum MoS were more negative (i.e. participants recovered from greater instability; $r_s < -0.56$, $p < 0.003$; Fig. 2). Age was not significantly correlated with scaled path lengths of postural sway

Table 1
Spearman rank correlation coefficients between age and experimental measures.

Measures		Age (years)	Postural Sway (Path Length)			Single-Stepping Thresholds (g)		Minimum Margin of Stability (% BH†)	
			Eyes Open (%BH†)	Eyes Closed (%BH†)	Romberg Ratio$^{\#}$	Anterior	Posterior	Anterior	Posterior
Postural Sway (Path Length)	Eyes Open (% BH†)	0.03	–	0.75**	−0.46*	0.15	−0.14	−0.20	0.22
	Eyes Closed (% BH†)	−0.07	0.75**	–	0.07	0.20	0.01	−0.32	−0.05
	Romberg Ratio	−0.10	−0.46*	0.07	–	0.05	0.16	−0.09	−0.28
Single-Stepping Thresholds (g)	Anterior	0.72***	0.15	0.20	0.05	–	0.62**	−0.93***	−0.70***
	Posterior	0.69***	−0.14	0.01	0.16	0.62**	–	−0.59**	−0.87***
Minimum Margin of Stability (%BH†)	Anterior	−0.57**	−0.20	−0.32	−0.09	−0.93***	−0.59**	–	0.72***
	Posterior	−0.62**	0.22	−0.05	−0.28	−0.70***	−0.70***	0.72***	–

* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.
† Percent Body Height (%BH) = [variable] (cm) / subject height (cm) x 100.
$^{\#}$ Romberg Ratio = (eyes closed path length) / (eyes open path length).

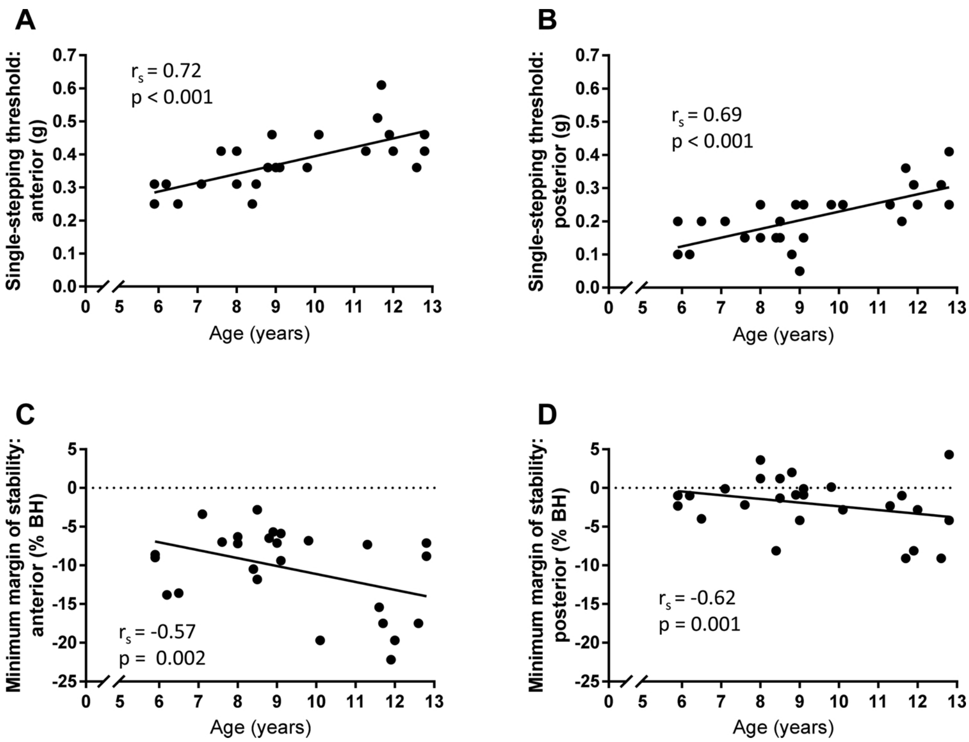

Fig. 2. Scaled single-stepping thresholds, expressed as units of gravity, versus participant age for the (A) anterior and (B) posterior direction. Scaled margin of stability (% body height) versus participant age for the (C) anterior and (D) posterior direction. The horizontal line denotes a margin of stability of 0 m, or the border between stability and instability.

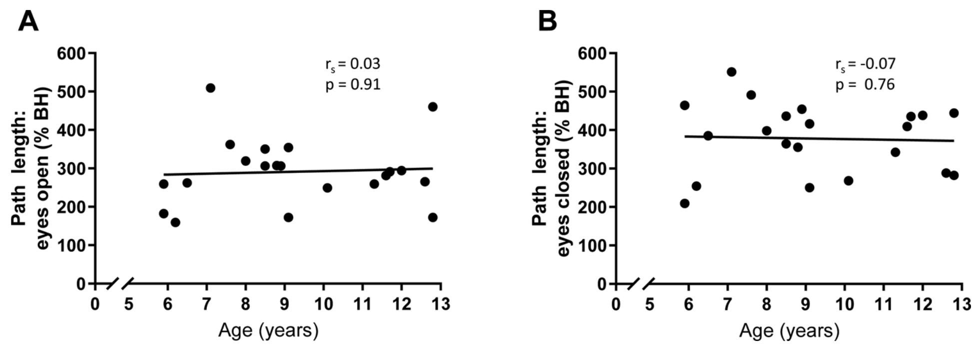

Fig. 3. Scaled path length [path length (cm)/height (cm) x 100] versus participant age for the (A) eyes open and (B) eyes closed conditions.

($|r_s| < 0.10$, $p > 0.68$; Fig. 3). Postural sway path lengths and sway ratios held negligible to low, non-significant correlations with stepping-thresholds ($|r_s| < 0.20$, $p > 0.39$) and the minimum MoS ($|r_s| < 0.32$, $p > 0.16$, Table 1).

4. Discussion

The purpose of this study was to investigate how age relates to static (i.e. postural sway) and dynamic (i.e. stepping thresholds) standing balance performance in children, as well as to evaluate how postural sway relates to stepping thresholds. We hypothesized that age would be inversely related to postural sway and positively related to stepping thresholds. This hypothesis was partially supported, as older age was associated with improved stepping thresholds but not with reduced sway. As anticipated, sway and stepping thresholds were only negligibly related. To our knowledge, this is the first study quantify how balance-reaction performance is related to age and measures of static balance in children.

Age was positively related to both anterior and posterior single-stepping thresholds in typically developing children. These results suggest that dynamic balance performance may continue to develop throughout the age span studied here. It is not clear, however, what factors influence this positive relationship between age and dynamic balance. Given moderate, negative correlations between age and dynamic stability measures (Table 1), older children were more able to, or more willing to, recover from dynamic instability with a feet-in-place response. We cannot determine if this result is due to an age-related improvement in the ability to prevent a step when unstable, or an age-related reduction in the preference to step when faced with dynamic instability. This result, that older children recovered from more instability, should be interpreted with regards to the size of the perturbation analysed. Older children had larger near-threshold perturbations that were of focus in our stability analysis. So, these larger near-threshold perturbations elicited more instability in older children. Had we observed no age-related influence on dynamic stability, the interpretation would be that smaller perturbations elicited the same degree of instability in younger children as larger perturbations did in older children. In other words, younger children would have had a less effective response in terms of resisting instability. This latter conclusion was made in a previous study of young, middle-aged, and older adults, inferring an age-related decline in the perturbation response [17].

Dynamic balance performance is a whole-body response dependent upon many underlying physiological factors, including proprioception, vision, vestibular function, reaction time, coordination, and strength. Although these underlying physiological factors were not directly measured in this study, we can postulate their importance to the findings of our study. The feet-in-place response studied here is likely dependent on the actively-generated ankle torque. Scaled peak ankle torque, as elicited by stimulation of the posterior tibial nerve, increases with age in children up to 11 years and likely beyond [26]. Similarly with age (up to 12 years), children exhibit higher rates of plantar flexor force development, shorter electromechanical delays, and stiffer Achilles tendons [27]. This evidence suggests that ankle muscle function may play a role in the age-related improvement of stepping thresholds observed in this study. Coordination of the neuromuscular response could also contribute to our observed results, as age is associated with less antagonist activity and an agonist response that is proportional to the perturbation amplitude [13]. Finally, in contrast to the functional efficiency of the visual and somatosensory inputs of balance, the integration of the vestibular system into balance maintenance does not seem to reach maturation before 10 years of age [28]. The improved stepping thresholds observed here may reflect this continual integration over the stages of development enrolled in this study. Our postural sway conditions did not specifically challenge the vestibular system by limiting both vision and proprioception (i.e. standing on a foam pad with eyes closed).

We did not observe age-related reductions in standing sway between the ages of 5 and 12 years. Previous studies that observed age-related reductions were likely influenced by the inclusion of very young children (2–4 years) with large sway, or older children and adults (13+ years) with reduced sway [5–7]. Our results, however, do agree with previous evidence that the Romberg Ratio does not change in this phase of development [5–7]. It may be that, compared to dynamic balance reactions, the task of maintaining a standing posture is not as challenging, with mastery occurring much earlier in childhood.

Our results support the assertion that postural control during quiet standing and after an external perturbation can be considered as two unique tasks. While both require similar, general sensorimotor processes, there are likely differences in the sensory weighting, latency, magnitude, and coordination of responses. This result agrees with that of previous studies of older adults [19,20,29]. In a study of adults over the age of 65, the maximum lean-release angle recovered with one step was negligibly correlated ($r \leq 0.16$) with multiple tests of static postural control [20]. Similarly, a study of older women found that postural steadiness during quiet standing was not predictive of balance recovery from a lean-release challenge [19]. In a study using the same stepping-threshold protocol as in this current work, a negligible relationship ($r = -0.23$) was evident between the Romberg ratio and single-stepping thresholds [29]. Further study is necessary to determine how stepping thresholds in children relate to other balance tasks, such as those that include walking and changing directions. A systematic review of how different balance tasks correlate across the lifespan suggest that each of these tasks represent a distinct skill set [30], with weaker between-measure correlations observed in children compared to those in older adults.

To our knowledge, this is the first study to evaluate how dynamic stability after a perturbation is altered with childhood age. A limitation of this initial study is a small sample size, which restricts the generalizability of our results to the entire pediatric population. In addition, the omission of children who could not complete the sway assessment may limit how our results apply to children with slight attentional deficits. The results of our initial study, however, demonstrate the general feasibility of our tests and can inform hypotheses for a larger, more rigorous, and mechanistic study of how rapid balance reactions develop in childhood and relate to other measures of postural control. With this sample size, we were also limited in our ability to assess these relationships separately in boys and girls, an aspect that should be considered given sex-related differences in development [31,32]. An additional limitation is that age may not best reflect physical development. However, in a large study looking at multiple regression equations for predicting the development of postural control in children, age was found to be the best predictor in both sexes compared to height, weight, and BMI [9]. Still, in future studies, aspects of development other than age should be considered [33], such as skeletal age or pubertal stage. This is an important consideration given the apparent differences in chronological and skeletal age in children with neuromuscular impairments, such as that associated with cerebral palsy, compared to their typically developing peers [34,35]. Furthermore, a limited number of measures were considered for dynamic and static conditions, with unconfirmed reliability for the dynamic measures in the pediatric population. Other measures of postural sway and dynamic balance could yield different conclusions than that made in this study.

In conclusion, balance reaction capabilities, but not necessarily standing postural steadiness is related to childhood age. It is apparent that older children are more able or willing to recover from instability imparted by the disturbance. The next step in this line of research is to evaluate how atypical development, such as that associated with early neuromuscular impairment, may alter such balance-reaction capabilities.

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Appendix A. Age, anthropometrics and experimental data for all participants

Age (years)	Anthropometrics			Postural Sway (Path Length)			Single-Stepping Thresholds (g)		Minimum Margin of Stability (% BH)	
	Sex	Height (cm)	Weight (kg)	Eyes Open (%BH)	Eyes Closed (%BH)	Romberg Ratio[#]	Anterior	Posterior	Anterior	Posterior
5.9	F	110	20.5	259	464	1.79	0.31	0.20	−8.6	−1.0
5.9	M	106	16.5	182	209	1.15	0.25	0.10	−9.0	−2.3
6.2	M	120	25.0	159	254	1.59	0.31	0.10	−13.8	−1.0
6.5	M	110	21.0	262	385	1.47	0.25	0.20	−13.6	−4.0
7.1	F	121	22.0	509	551	1.08	0.31	0.20	−3.4	−0.1
7.6	F	130	25.0	362	491	1.35	0.41	0.15	−7.0	−2.2
8.0	M	140	34.0	319	398	1.25	0.41	0.25	−6.3	1.2
8.0	F	127	37.5	–	–	–	0.31	0.15	−7.2	3.6
8.4	F	134	35.2	–	–	–	0.25	0.15	−10.5	−8.1
8.5	M	130	36.0	350	436	1.24	0.31	0.20	−11.8	−1.3
8.5	F	120	19.0	306	364	1.19	0.31	0.15	−2.8	1.2
8.8	F	140	35.5	307	355	1.16	0.36	0.10	−6.5	2.0
8.9	F	130	24.0	306	454	1.48	0.46	0.25	−5.7	−0.9
9.0	F	128	24.5	–	–	–	0.36	0.05	−7.1	−4.2

9.1	F	130	33.5	354	416	1.18	0.36	0.15	−9.4	−0.1
9.1	F	130	33.0	172	250	1.46	0.36	0.25	−5.9	−0.9
9.8	M	126	25.0	–	–	–	0.36	0.25	−6.8	0.1
10.1	M	140	28.5	249	268	1.08	0.46	0.25	−19.7	−2.8
11.3	F	160	49.5	259	342	1.32	0.41	0.25	−7.3	−2.3
11.6	F	140	32.0	281	409	1.45	0.51	0.20	−15.4	−1.0
11.7	M	150	35.5	291	435	1.49	0.61	0.36	−17.5	−9.1
11.9	M	150	38.0	–	–	–	0.46	0.31	−22.2	−8.1
12.0	F	149	40.0	294	438	1.49	0.41	0.25	−19.7	−2.8
12.6	M	147	35.5	265	288	1.09	0.36	0.31	−17.5	−9.1
12.8	M	167	49.0	172	282	1.64	0.41	0.41	−8.8	−4.2
12.8	M	175	55.0	460	444	0.96	0.46	0.25	−7.1	4.3

#Romberg Ratio = (eyes closed path length)/(eyes open path length).

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