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Postural sway in children: a literature review

Evi Verbecque, Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Science, University of Antwerp, Belgium

Corresponding author: Universiteitsplein 1, 2610 Wilrijk, Belgium. evi.verbecque@uantwerpen.be

Luc Vereeck, PhD, Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Science, University of Antwerp, Belgium

Ann Hallemans, PhD, Department of Translational Neurosciences, Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Science, Department of Functional Morphology, Faculty of Sciences, University of Antwerp, Belgium.

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Abstract

Background and aim

Static posturography can serve as an easy and fast way to determine whether a child possesses sufficient balance control in different sensory conditions. Therefore, the aim of this review is to map age-related differences in postural sway during childhood in typically developing children, using static posturography and to provide an overview of the available (age-specific) reference values in scientific literature.

Methods

The search strategy was performed in five databases (Pubmed, Web of Science, ScienceDirect, Cochrane Clinical Trials, Medline (Ovid)) November 2nd 2014 and updated twice: March 16th 2015 and July 20th 2015. The following keywords were used: (children OR child) AND ("postural control" OR "postural stability" OR equilibrium OR posture OR "postural balance"[mesh]) AND ("quiet stance" OR standing OR stance OR "quiet stance" OR static) AND ("postural sway" OR posturography OR "body sway" OR stabilography OR "trunk sway" OR "medio-lateral sway" OR "antero-posterior sway"). Relevant studies were identified using predefined selection criteria, applied on title and abstract (phase 1) and on full text (phase 2), supplemented with reference screening after the second phase.

Results

A total of 14 studies met the criteria. This review showed three main findings: 1) during natural bipedal stance with the eyes open, all studies reported a decrease in postural sway with increasing age, with conflicting results on the (non-)linearity of its development, 2) with eyes closed, all children show more sway than with eyes open and 3) only four studies reported numeric sway values that could serve as reference values, mainly focusing on children aged five and older.

Conclusion

Considerable disagreement exists on the (non-)linearity of the development of postural sway in children. By choosing arbitrary age categories, it remains unclear between which age groups differences are situated. Future research is necessary to determine for which age groups age-specific reference values are relevant.

Introduction

Postural control can be defined as achieving a desired body position (e.g. upright standing) and maintaining this position in any static (maintaining a posture) or dynamic (performing a motor skill) situation.¹ Postural control develops early in life following a specific pattern. In infants, as postural reflex activity emerges, righting and orientation of the head and body in space is possible. These postural reflexes provide the infant in the first year of life with the ability to achieve and maintain several postures, such as sitting and standing independently.² A typically developing child is able to stand independently at the age of 12 months.^{2,3} However, after the motor milestone of independent stance is reached, further refinement of postural control in this specific posture continues to develop during childhood.⁴⁻⁷ Postural control plays an important role in child development, as it is a necessity to achieve both new postures in early life and more complex motor skills.^{2,4-7} When postural control does not develop adequately, subsequently, overall motor development will be influenced.^{2,7} Therefore, to prevent the burden of motor delay, it is of great importance that postural deficits are identified early-on.²

In scientific literature, many authors report use of posturography to quantify postural control in children.⁴⁻⁷ Using posturography, the amount of body sway is measured in a certain posture, usually standing independently, during a predefined timeframe via registration of displacements of the centre of pressure (COP), often in different sensory conditions. This assessment tool provides information about the exact motor behavior (postural sway) of the child to preserve his or her balance.⁴ It allows us not only to quantify the movements of a child while it maintains his or her posture, but also, by introducing different sensory conditions, the importance of sensory input to maintain a specific posture can be investigated. Therefore, this technique has been used to provide insights into developmental changes of postural control in standing.⁴⁻⁷

Two types of posturography should be distinguished: dynamic (e.g. EquiTest, Neurocom, Int., moving room) versus static (fixed force plate) posturography.⁵ In both techniques, the amount of sway is measured, but the implementation of sensory perturbations differs.⁵ For example, using the Equitest,

visual/proprioceptive perturbations are performed using a sway-referenced surround/platform and thus depend on the movements of the child.^{4,5} Another example of dynamic posturography, is the moving room, in which sway is measured as a result of moving surround often combined with light touch to examine influence of visual/proprioceptive information on postural control.^{5,6} In static posturography sensory perturbations are implemented by closing the eyes and/or standing on foam, resulting in the two conditions: eyes open/eyes closed and stable ground/foam. When this type of posturography is applied, the visual surround and/or platform remain stable, thereby providing information on the motor output in the form of postural sway as a result of visual, proprioceptive and/or vestibular perturbations.⁷ Thus, both types of posturography use different protocols, resulting in postural sway measures that cannot be compared with each other. Also, even though dynamic posturographic techniques have been used to determine developmental changes regarding sensory integration of postural control, they require very specific and expensive laboratory-based equipment, whereas static posturography can serve as an easy and fast way to determine whether a child possesses sufficient postural control in different sensory conditions.

Static posturography is often used as an outcome measure for the comparison of postural control in typically developing children (TDC) and children with underlying pathologies, such as developmental coordination disorder.⁸ Also, several authors have investigated developmental changes of postural control during standing in TDC by comparing postural sway parameters among different age groups. Taking early identification of postural deficits into account, reference values are imperative to determine whether a child shows deviating postural control, hence the relevance for mapping reference values for postural sway parameters. Therefore, the aim of this review is to map age-related differences in postural sway during childhood in TDC, using static posturography and to provide an overview of (age-specific) reference values that are available in scientific literature.

Children younger than two years of age show difficulty in standing quietly on demand because infancy is an early developmental stage of postural control function, characterized by underdeveloped nervous and sensory systems and muscle strength in the lower limbs.^{7,9} Therefore, this review aims to include children from the age of two until the age of 18.

Method

Sources and search strategy

A search strategy was defined: (*children OR child*) AND ("*postural control*" OR "*postural stability*" OR "*equilibrium*" OR "*posture*" OR "*postural balance*"[mesh]) AND ("*quiet stance*" OR "*standing*" OR "*stance*" OR "*static*") AND ("*postural sway*" OR "*posturography*" OR "*body sway*" OR "*stabilography*" OR "*trunk sway*" OR "*medio-lateral sway*" OR "*antero-posterior sway*"). The search query was ran in 5 databases (Pubmed, Web of Science, ScienceDirect, Cochrane Clinical Trials, Medline (Ovid)) November 2nd 2014 and updated twice: March 16th 2015 and July 20th 2015. No limits were used, except in ScienceDirect: a journal search was performed including scientific articles. Mesh terminology was only used in Pubmed.

Study selection

Eligibility of the search results was determined by applying the following inclusion criteria:

1. Participants were TDC from age two until age 18 and adults that served as a control group.
Thus, the data-analysis of the children had to be presented separately from that of the adults.
2. Minimum two groups of participants (e.g. two groups of TDC or one group of children and one group of adults) participated and their results were compared, thereby development of postural sway could be investigated.
3. Postural sway was evaluated using *static posturography* during *bipedal stance* on a force plate, as a single task. Bipedal stance was chosen because this posture can be assessed in all children from age 2 to age 18.
4. At least differences between age-groups or main effects of age on postural sway, using global descriptive sway parameters such as COP displacements, had to be reported.
5. Original articles written in English, Dutch, French or German.

Screening for relevant studies was done in two phases: application of the predefined inclusion criteria on title and abstract (phase 1) and on full text (phase 2). After the second selection phase, the references of all included studies were screened and, if eligible for this study, included, to ensure that no relevant literature was missed.

Data-extraction

Data-extraction consisted of the different age-categories and the corresponding number of participants, characteristics of the measurement, conditions in which the parameters for postural sway were measured, parameters for postural sway that were measured, and results concerning reference values and the influence of age-, condition- and their combined effect on postural sway. The most often reported length unit was mm, therefore numeric reference values were extracted and, if necessary, units were converted to mm and mm² for spatial parameters and mm/s for velocity measures, to allow comparison between different studies. No statistical analysis could be performed on the extracted data. Mean values and standard deviations of reported sway parameters were plotted according to age. Amplitudes, path and area were clustered and referred to as “magnitude of sway” as these parameters provide information on the sway magnitude in any direction. Root mean square and velocity were categorized as “responsiveness of sway” as these parameters provide information on corrective movements.

Results

Information sources and search strategy

The search strategy resulted in 832 hits in all databases. After deduplication, 595 unique hits remained, which were screened on title and abstract. After the first screening phase, 50 studies met the criteria and were taken to screening phase 2, for a more in-depth screening on full text. A total of 11 studies was found eligible for data-extraction. Reference screening of these 11 studies, revealed an additional three studies, that met the criteria, resulting in a net result of 14 studies. The selection procedure is presented in figure 1.

Data-extraction

Participants

All participants of the included literature were children between age 2^{14,15} and 18^{19,21}. Four studies examined postural sway in groups with different biological ages¹⁰⁻¹³ (age 3 to 13) and ten studies in groups with different age ranges¹⁴⁻²³ (table 1). Seven of the 14 studies explicitly reported the children to be healthy, using specific predefined selection criteria to exclude children with pathological conditions in which postural control could be compromised. Selection criteria of the individual studies are presented in table 2.

Ten studies used adults as a control group.^{10-12,14,16-19,21,23} Most adult groups that were used, consisted of adults in their twenties.^{12,14,16-19,23} Schärli and Hsu also used adults in their thirties.^{10,21} Riach and Starkes (1994) did not report the age range nor mean age of the adult group.¹¹

Characteristics of the measurement

Table 1 gives an overview of the characteristics of the measurements of each individual study regarding foot and arm position, use of visual fixation, the number of trials that were recorded and trial duration, whether a try-out trial was allowed and at which sequence different sensory conditions (eyes open/eyes closed/stable ground/ foam) were applied.

Parameters for postural sway

A large variety of parameters for postural sway was used to examine postural control. Eight studies reported magnitude of sway: 1) the maximal excursion of the COP in any direction (COP_range¹⁹), in antero-posterior direction (COP_ap^{17,20}) or in medio-lateral direction (COP_ml^{17,20}), 2) the total path of the COP excursion (COP_path^{18,20}) or 3) the total area of the COP excursion (COP-area^{10,14,15,18,20-22}). Ten studies investigated responsiveness of sway as 1) the root mean square of the deviations from the mean position of the center of pressure in any direction (COP_rms^{12,13,20,21}), in antero-posterior direction (COP_rms_ap²³), or in medio-lateral direction (COP_rms_ml^{16,23}), 2) a composite velocity measure (COP_v^{10,11,19}) or in a specific direction (COP_v_ap²² of COP_v_ml^{16,22}) or 3) root mean square of the deviations of the mean velocity of the COP in any direction (COP_v_rms¹²).

Conditions in which postural control was assessed

The included studies investigated postural sway in four different conditions: 1) EO: standing on stable ground eyes open (with or without visual target)¹⁰⁻²³, 2) EC: standing on stable ground eyes closed^{10,11,13-17,18,20-22}, 3) FEO: standing on foam eyes open¹⁰ and 4) FEC: standing on foam with the eyes closed¹⁰. Eleven studies investigated differences between the conditions EO and EC to determine the influence of visual information on postural stability.^{10,11,13-17,18,20-22} For the influence of proprioception on postural stability, foam was used.¹⁰

The effect of condition: EO versus EC

Vision-related differences are shown in table 3. Overall, all postural sway parameters tend to increase when visual information is removed.^{10,11,12-22} Though investigated in 12 studies, only eight studies reported the main effect of vision, showing that all postural sway parameters increase significantly when the eyes were closed.^{11,13-16,17,20,22}

The effect of condition: stable ground versus foam

Regarding foam, no main effect of foam was reported by Hsu and coworkers.¹⁰

Age effects in EO and reference values

Three of the 14 studies reported numeric sway values in the EO condition.^{10,20,23} An overview of these sway values for the different ages or age groups, with corresponding age-related differences, is shown in table 3. The other 11 studies investigated main effects of age and subsequently reported post-hoc comparison between the age groups to determine age-related changes in postural sway, without providing numeric sway values.^{11,12-19,21,22}

Overall, all postural sway parameters tend to decrease with increasing age.¹⁰⁻²³ Results showed that sway parameters in young children tend to be larger than in older children ($p < 0.05$), both in magnitude^{10,17,21,22} and in responsiveness^{10,11,16,21-23}, which is consistent with plotted results in figure

2.

Magnitude of sway

When compared between children, COP amplitudes are significantly larger in 4-year-olds compared to 8-year-olds (COP_ap) and 12-year-olds (COP_ap, COP_ml) ($p<0.05$).¹⁷ With reference to adults, significantly larger values were found for COP amplitudes in 4-, 8-, 12-year-olds ($p<0.05$)¹⁷ and for the total COP displacement for children under age 12 ($p<0.01$)¹⁸ Area of the mean COP position was larger in children under age 8 ($p<0.01$)^{21,22} and larger in 8-year-olds compared to 11-year-olds ($p=0.003$)²¹. Compared to adults, the area of displacement of the COP was significantly larger under age 5 ($p<0.05$)¹⁰ and under age 12 ($p<0.05$)^{18,21}.

Even though, 6 studies compared children until age 12 to 13 with adults, only Sakaguchi compared postural sway in adolescents older than 13 years old with that of young adults.¹⁸ They stated that sway path and area in their group of 13- to 15-year-olds was no longer significantly different from that of adults, but provided no evidence for this statement.

When standing on foam, Hsu and coworkers (2009), reported that children under age 8 show significantly larger sway area ($p<0.001$) compared to adults (area not reported).

Responsiveness of sway

Two studies reported deviations from the mean position of the COP to be significantly larger under age 8 compared to all older age groups ($p<0.05$)^{12,23}, whereas Stambolieva and coworkers reported 8-year-olds to show more deviation than both younger and older children ($p<0.05$)¹³. Significantly larger values were found for deviations from the mean position of the COP in children younger than age 8 when compared to adults ($p<0.05$)^{12,16,22} Again, velocity measures in children under 8 years of age are larger than those of older children.^{11,16} With reference to adults, velocity measures in all directions, are significantly larger in children under age 7 ($p<0.05$)¹⁰ and under age 11 ($p<0.05$)^{12,16}.

When standing on foam, velocity of the mean COP position in children under age 8 was significantly higher ($p<0.001$) compared to adults (velocity: 16.4 (0.6) mm/s).

Age effects in EC and reference values

Three of the 12 studies reported numeric sway values in EC condition.^{10,19,20} Reported sway values for the different ages or age groups, with corresponding vision-related differences, are shown in table 3. With the eyes closed, postural sway decreases with age ($p<0.05$).^{10,14,15,18-21} Eight studies reported that all sway parameters in young children are significantly larger than in older children when the eyes are closed, both in magnitude^{10,14,15,18,19,20,21} and in responsiveness^{10,19,21,22} ($p<0.05$), which is consistent with plotted results in figure 2.^{14,18,19}

Magnitude of sway

Rival and coworkers found that with the eyes closed COP amplitudes increase between age 6 and age 8 and decrease again after age 8 ($p<0.05$), whereas Monteiro Ferronato and coworkers reported no interaction effect between age and vision for COP_ap and COP_ml.^{17,19} Area of the mean COP position was larger in 2- to 3-year-olds compared to 4- to 5-year-olds ($p<0.01$) and in 2- to 5-year-olds when compared to adults ($p<0.05$).^{10,14} Standing on foam with the eyes closed induced significantly larger sway area ($p<0.05$) in children under age 7 compared to adults (area: not reported).¹⁰

Responsiveness of sway

Regarding deviations from the mean position of the COP and total COP displacement, no interaction effect was reported between age and vision.^{13,18,20,21} Bair and coworkers found no interaction effect between age and vision for COP_rms.¹⁶ Riach and Starkes reported no interaction effect between age and vision for velocity measures were found, whereas Rival and coworkers found a significant linear decrease with increasing age in the condition EC ($p<0.01$).^{11,19} Standing on foam with the eyes closed induced significantly higher velocity measures ($p<0.05$) under age 12 compared to adults (velocity: 23.5 (1.1) mm/s).¹⁰

Discussion

The aim of this review was to map age-related differences in postural sway during childhood in TDC, using static posturography and to provide an overview of (age-specific) reference values that are available in scientific literature. Main findings of this literature review are: 1) during natural bipedal

stance with the eyes open, all studies reported a decrease in postural sway with increasing age, 2) with eyes closed, all children show more sway than with eyes open and 3) only four studies reported numeric sway values that could serve as reference values, mainly focusing on children aged five and older.

Natural bipedal stance and age

Clearly age-related differences were found in the amount of postural sway during natural stance. In addition to the reported differences, some authors emphasized the non-linearity in development of postural control and identified turning points. A turning point can be defined as a certain age (range) where different motor behavior is observed before and after this age (range).

For example, Stambolieva and coworkers described 8-year-olds to show less sway (COP_rms) than younger children and more sway than older children aged 9 and 10¹³. On the other hand, six studies^{11,12,16,21-23} reported children under the age of 8 to show significantly larger sway than children aged 8 and older. In the group of children under age 8, no consensus exists regarding the presence (for COP_rms, COP_v)^{11,12,16,17} or absence (for COP_rms, COP_v, COP_area)^{13,21-23} of age-related differences in postural sway. These findings seem to suggest the emergence of a first turning point regarding postural sway at the age of 8. A second turning point seems to occur at age 13. Several ages have been reported regarding when adult-like postural responses are observed, from as young as the age of 6 (for sway area) to over the age of 12 (for sway velocity).¹⁰ But most studies found age differences in postural sway up until the age of 12.^{12,16-18,21} So, from the age of 13, children seem to reach adult-like responses during natural bipedal stance, suggesting a second turning point. Nevertheless, only one study did compare adult performances with performances of adolescents, but reported no numeric sway values or p-values to provide evidence of differences between adolescents and adults.¹⁸

Despite these suggestions in literature, based on the sway values that were plotted in figure 2, the existence of turning points cannot be confirmed, as sway values appear to decrease gradually with increasing age. Thus, even though the ages of 8 and 13 might seem a turning point, further

research on their existence and the exact age of their occurrence should be performed, preferably in a sufficiently large sample of children, adolescents and adults.

Sensory perturbation and age

As could be expected, standing with the eyes closed, induced significantly more sway in all children.^{11,13-15,17,20-22} With the eyes closed, sway velocity, area and amplitude range decreased significantly with increasing age.^{14,19}

However, different studies that investigated age-related changes in the eyes closed condition^{10,18,19,21} used different statistical procedures. Five studies investigated interaction effects between age and vision and only Newell¹⁴ found a significant interaction effect for COP_area. In the other four studies no interaction effect was found^{11,16,17,22}, thereby suggesting that the effect of eye closure was the same across all age groups. On the other hand, four studies compared the amount of sway between age groups in the EC condition and found significant differences between the age groups.^{10,18,19,21} Thus, based on these results, postural sway seems to show a gradual decrease with increasing age in the EC. However, results seem to depend on the applied statistical analysis (comparison of conditions rather than main and interaction effects of age and vision)^{10,18,21} or protocol (measures of sway exclusively in EC)¹⁹. Therefore at this time no conclusions can be drawn regarding the combined influence of age and vision on postural sway. Further research on this topic is necessary to determine the actual effect of both age and removal of visual information on sway in children.

Few data are available regarding the effects of somatosensory perturbation in children. Only one study applied foam in their protocol. Even though it is clear from their results that children younger than 12 have significantly larger sway on foam than adults, they did not investigate the main effect of foam and its interaction effects with vision and age.¹⁰

Reference values

Only four studies reported reference values in TDC, of which 1 study provided reference values per biological age¹⁰, whereas 3 studies reported values for age-groups^{19,20,23}. Furthermore, different studies used different sway parameters. This resulted in numeric reference values for amplitude,

deviations of the mean position and total displacement based on data of only one study. Two studies reported numeric values on area and velocity. Moreover, numeric sway values for children under age five have been reported by only one study, which were limited to area and velocity.¹⁰ Thus, reference values are available but for a mix of biological ages and age-groups.

None of the studies used cluster classification to justify the age groups they created, which implies that these age groups were a result of convenience and thereby developmental changes might be missed. Due to developmental progressions regarding motor development, it could be expected that differences among biological ages could exist, but might remain unrevealed as a result of choosing arbitrary age categories. Therefore, the reference values as currently available in literature are insufficient. Further research on this topic is necessary to determine whether reference values based on biological age are necessary in children and if not, which biological ages can be considered one group. Especially in children under age five numeric sway values for other parameters than velocity and area should be determined.

Measurement characteristics

An inventory of the measurement characteristics showed considerable differences in the applied protocols. These differences could partially explain the inconclusive results regarding age-related changes in postural sway during natural stance in younger children.

For example, the foot position varied from feet together (n=4), feet parallel with either 2 cm apart or “slightly apart” (n=2), feet parallel (n=3), comfortable foot position (n=1), feet at shoulder width (n=1) or at pelvis width (n=1) or undefined (n=2). The position of the feet however might have a large impact on the amount of sway, as it directly influences the limits of stability. Theoretically, also the arm position might influence the results, but 11 out of 14 studies reported the arms to be freely next to the body whereas the 3 remaining studies did not define the arm position. Therefore, arm position is probably not a confounding factor in this literature review.

Twelve out of fourteen studies reported use of a visual target with varying distances of 1 to 8 meters at eye level or 60° visual angle. Riach and Starkes (1989) showed that using a visual target

1 results in a significant decrease of postural sway and therefore plays an important role when
2 comparing sway results. This might be related to the enhanced motivation and concentration that is
3 introduced in younger children.²⁴
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6 Regarding trial duration, most studies recorded sway during 30 seconds, but data recording
7 was also reported to last 10, 15, 20, 25 and 60 seconds. Longer timeframes for data recording are
8 more challenging for younger children to maintain their position, but might provide a more realistic
9 estimation of the child's motor abilities. Shorter timeframes on the other hand, might overestimate a
10 child's motor ability. Thus, recording time might be a confounding factor in this review, especially in
11 younger children. Thereby it might partially explain the inconclusive results in children under age 8.
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21 Finally, the sequence in which several tasks are presented to a child, could influence their
22 performance (e.g. due to fatigue), especially when more than one trial in more than one condition is
23 being recorded. Therefore, randomization of the conditions seems the most appropriate measuring
24 technique to investigate the condition-related changes on postural sway. However, only 6 studies
25 reported randomization of conditions.
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33 **Implications for future research and clinical practice**

34 This review provides valuable information highlighting the lacunas and conflicting results in
35 literature on development of postural sway in children. Furthermore, the limited availability of
36 reference values for postural sway in age-specific categories is pointed out.
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43 Although several studies have investigated development of postural sway in children,
44 considerable disagreement exists on its (non-)linearity. Clearly, postural sway decreases with
45 increasing age, but whether this decrease emerges as turning points or as a gradual decrease
46 remains unclear. This could be due to the choice of the age categories under investigation, which was
47 done arbitrary. Accurate documentation of these developmental changes however, is of paramount
48 importance for the determination of reference values. Up until now, only four studies reported
49 numeric sway values that could be used as reference values, mainly in children aged five and older,
50 suggesting 1) far more research is necessary in children younger than age 5 and 2) future research is
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necessary to determine whether reference values are relevant for each biological age or whether age groups can be constructed. Future studies should consider performing cluster classification to objectively determine age groups differing in postural sway. To enhance application of previous research into clinical practice the authors recommend to report actual numeric sway data.

The influence of sensory perturbations has been investigated mainly for eyes closed. Although one study applied foam conditions with eyes open and closed and compared the amount of sway between age groups, no interaction effects were investigated. To address use of sensory information and the development of sensorimotor integration in children, several conditions need to be compared, e.g. EO, EC, FEO, FEC. Use of these different conditions allows to determine main effects of vision and surface and their interaction effects. Apart from providing insights into sensorimotor development in children, this information is important when investigating balance in children with underlying pathologies since poor performance might be either related to immaturity of postural control or to the underlying pathology.

As measurement characteristics can influence the amount of body sway, some considerations can be taken into account. Preferably, these conditions should be applied in a randomized sequence to prevent distortion of results due to fatigue in the more difficult conditions. In the EO a visual target should be used to enhance attention and motivation (especially in young children). As the first 10 seconds of each trial should be discarded to avoid transients, time recordings should at least comprise 30 seconds.

Conclusion

Postural sway decreases with increasing age, both with eyes open and eyes closed. However, Although considerable disagreement exists on whether this development occurs linearly or whether turning points can be identified. As static posturography is an often applied technique to determine whether a child shows deviating postural control, accurate reference values are indispensable. Current information in literature is disperse using different measures and different age-categories, making it difficult to establish clear cut-off values for normal postural sway at a certain age. Future

research is necessary to gather reference data and determine relevant age categories, using
adequate and transparent methodology.

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Figure 1: Flowchart

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Table 1: methodological characteristics of the individual studies																
Author	Age (range) per group (years) with corresponding number of children in each group (N)															
	ADULTS															
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Bair 2011 ¹⁶	3-4 y/o N=8	5-6 y/o N=9	7-8 y/o N=9													
Figura 1991 ¹²																
García 2011 ²²																
Hsu 2009 ¹⁰																
Monteiro Ferronato 2011 ¹⁷																
Newell 1997 ¹⁴	2-3 y/o N=12	3-4 y/o N=15	4-5 y/o N=12													
Riach & Starkes 1989 ²³																
Riach & Starkes 1994 ¹¹																
Rival 2005 ¹⁹																
Sakaguchi 1994 ¹⁸																
Schärli 2012 ²¹																
Slobounov & Newell 1994 ¹⁵																
Stambolieva 2012 ¹³																
Wolff 1998 ²⁰																
When several conditions are shown, the number of trials described correspond with each condition.																
Abbreviations: N= number of participants; s= seconds; m= meter; (F)EO= (foam) eyes open; (F)EC= (foam) eyes closed; y/o: years old;																
Sway Parameters: COP amplitude: maximal excursion of the COP in any direction (COP_range), in the antero-posterior direction (COP_ap) or mediolateral direction (COP_ml); COP root mean square: the root mean square of the deviations from the mean position of the center of pressure in any direction (COP_rms), in the antero-posterior direction (COP_rms_ap) and in the mediolateral direction (COP_rms_ml); COP path: the total COP displacement (COP_path); COP area: the area of the mean COP position (COP_area); COP velocity: velocity of the COP displacement																

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Table 2: Selection criteria as defined by each author

	Hsu 2009	Bair 2011	Monteiro Ferronato 2011	Sakaguchi 1994	Wolff 1998	Schärli 2012	Garcia 2011
Balance(-related) deficits							
- No current or past medical diagnosis or injury affecting balance	x	x			x	x	
- Absence of neurological disorders	x			x	x		x
- Absence of vestibular disorders	x				x		
- Absence of musculoskeletal disorders			x	x	x		x
- No symptoms of dizziness or light-headedness	x						
- no history of two or more unexplained falls within the past 6 months	x						
Psychological or mental conditions (including depression)	x		x				
Normal vision with or without glasses	x						
Normal motor development during infancy as reported by the parents			x				

Table 3: overview of reference values for postural sway and age-related differences																				
Sway Parameter	Author	C	Age (range) per group (years) with corresponding mean (SD) sway values																	AGE DIFFERENCES
			3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Adults	
COP_range (mm)	Rival 2005 ¹⁹	EO			N/A			N/A		N/A									N/A	Post-hoc: age 5-6 < age 7-8, age 5-6 > age 9-10 and adults, age 7-8 > age 9-10 and adults, age 9-10 > adults (p<0.05)
		EC			13.43 (0.7)		16.62 (1.6)		11.65 (0.9)										4.02 (0.3)	
COP_ap (mm)	Wolff 1998 ²⁰	EO			17.8 (8.8)		20.0 (4.7)		20.0 (3.2)		15.6 (4.2)		17.6 (3.8)		16.9 (3.1)				Post-hoc: /	
		EC			25.0 (11.1)		23.3 (5.9)		23.3 (5.4)		18.8 (5.5)		19.8 (4.7)		21.3 (5.5)				Post-hoc: /	
COP_ml (mm)	Wolff 1998 ²⁰	EO			15.3 (9.1)		15.9 (4.7)		15.8 (3.3)		12.9 (5.6)		12.7 (5.7)		11.5 (5.1)				Post-hoc: /	
		EC			20.0 (10.8)		18.4 (6.3)		17.5 (4.6)		14.2 (5.5)		12.8 (4.4)		13.7 (5.3)				Post-hoc: /	
COP_rms (mm)	Wolff 1998 ²⁰	EO			5.9 (2.1)		5.1 (1.4)		5.0 (0.8)		4.3 (1.2)		4.4 (1.4)		4.3 (1.0)				Post-hoc: /	
		EC			7.2 (2.4)		5.6 (1.6)		5.4 (1.3)		4.5 (1.7)		4.4 (1.2)		4.8 (1.3)				Post-hoc: /	
COP_rms_ap (mm)	Riach & Starkes 1989 ²³	EO			6.4 (/) ^A		5.2 (/) ^A		4.6 (/) ^A										Post-hoc: age 5-7 > 8-9 and 10-12 (p<0.05)	
		EC			N/A		N/A		N/A		N/A								N/A	
COP_rms_ml (mm)	Riach & Starkes 1989 ²³	EO			6.9 (/) ^A		6.6 (/) ^A		6.0 (/) ^A										Post-hoc: children aged 5-7 >> all other participants	
		EC			N/A		N/A		N/A		N/A								N/A	
COP_path (mm)	Wolff 1998 ²⁰	EO			390 (93)		342 (75)		339 (90)		297 (108)		285 (99)		261 (75)				Post-hoc: /	
		EC			555 (156)		435 (114)		435 (117)		357 (99)		360 (111)		339 (99)				Post-hoc: /	
COP_area (mm ²)	Hsu 2009 ¹⁰	EO	1350 (290) ^A	990 (110) ^A	/	/	/	/	/	/	/	/	/	/	/	/	/	/	3- and 4-year-olds > adults (p<0.05)	
		EC	1500 (310) ^A	1080 (120) ^A	990 (100) ^A	/	/	/	/	/	/	/	/	/	/	/	/	/	3-, 4- and 5-year-olds > adults (p<0.05)	
COP_v (mm/s)	Wolff 1998 ²⁰	EO			813 (525) ^B		576 (246) ^B		561 (210) ^B		444 (300) ^B		423 (264) ^B		375 (210) ^B				Post-hoc: /	
		EC			1428 (1038) ^B		822 (423) ^B		777 (342) ^B		552 (366) ^B		540 (318) ^B		540 (315) ^B				Post-hoc: /	
COP_v (mm/s)	Hsu 2009 ¹⁰	EO	25.5 (3.0) ^A	21.3 (0.9) ^A	18.3 (0.8) ^A	18.2 (0.9) ^A	/	/	/	/	/	/	/	/	/	/	/	/	3-, 4-, 5- and 6-year-olds > adults (p<0.05)	
		EC	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	7- to 12-year-olds > adults (p>0.05)	
COP_v (mm/s)	Rival 2005 ¹⁹	EO			N/A		N/A		N/A										Post-hoc: /	
		EC			49.21 (2.5)		45.72 (2.0)		36.81 (0.9)										N/A	
Legend: sway values for each postural sway parameter are presented in the eyes open (EO) and eyes closed(EC) condition categorized according to the investigated age category. When differences between age-groups were reported in the individual studies, boxes were colored, with different colors representing significant differences.																				
Abbreviations: C: sensory condition; N/A: not applicable as this condition was not assessed; /: not reported; ^A mm/s and mm ² /s converted to mm and mm ² ; ^B mm/s and mm ² /s converted to mm and mm ² by multiplying by the duration of the acquisition;																				
Sway Parameters: COP amplitude: maximal excursion of the COP in any direction (COP_range), in the antero-posterior direction (COP_ap) or mediolateral direction (COP_ml); COP root mean square: the root mean square of the deviations from the mean position of the center of pressure in any direction (COP_rms), in the antero-posterior direction (COP_rms_ap) and in the mediolateral direction (COP_rms_ml); COP path: the total COP displacement (COP_path); COP area: the area of the mean COP position (COP_area); COP velocity: velocity of the COP displacement																				

Figure 2: reported sway values, shown as magnitude and responsiveness, plotted according to age.

Legend: Dots represent mean sway (mm; left vertical axis) and mean age (year; horizontal axis) per age group. Horizontal bars show the standard deviation for age whereas vertical bars show the standard deviation for sway. Right vertical axis corresponds with area (magnitude of sway) and with velocity (responsiveness of sway). Path was converted to cm for visual purposes.

Research highlights

- Postural sway during natural bipedal stance decreases with increasing age
- All children sway more with their eyes closed than with their eyes open
- Only four studies reported numeric sway values in children, mainly from the age of five