This item is the archived preprint of:

Age-related changes in postural sway in preschoolers

Reference:

Verbecque Evi, Lobo da Costa Paula Hentschel, Meyns Pieter, Desloovere Kaat, Vereeck Luc, Hallemans Ann.- Age-related changes in postural sway in preschoolers

Gait and posture - ISSN 0966-6362 - 44(2016), p. 116-122

Full text (Publishers DOI): <http://dx.doi.org/doi:10.1016/j.gaitpost.2015.11.016>

To cite this reference: <http://hdl.handle.net/10067/1328410151162165141>

Manuscript Number: GAIPOS-D-15-00249R2

Title: Age-related changes in postural sway in preschoolers

Article Type: Original Paper

Keywords: child, "postural balance"[mesh], "postural sway",
posturography, "child development"[mesh], "reference values"[mesh]

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Abstract: Objectives: The present study aimed to investigate age-related differences of postural sway in 3- to 6-year-old typically developing children in different sensory conditions and subsequently to provide reference values for global descriptive sway parameters in preschoolers.

Methods: Ninety-six typically developing children, between three and five years of age, participated in this cross-sectional study. Postural sway was measured for 40 seconds in four conditions (eyes open/eyes closed on stable ground/foam) by using a force plate. Global descriptive sway parameters were calculated and analysed using a 2x2x3 (surface x vision x age group) MANOVA ($p < 0.05$) in the children that were able to complete the task (40 seconds).

Results: When sensory information was altered, a significantly smaller number of 3- and 4-year-olds was able to complete the task. Significant main effects of vision ($p < 0.05$), surface ($p < 0.001$) and an interaction effect between vision and surface ($p < 0.05$) on all postural sway parameters were found. A significant main effect of age was found for antero-posterior amplitude ($p = 0.047$), medio-lateral root mean square ($p = 0.012$) and area ($p = 0.009$) between 3- and 5-year-olds and 4- and 5-year-olds. No interaction effects (surface x vision x age group) were found.

Conclusions: During natural stance, the amount of postural sway distinguishes five-year-olds from three- and four-year-olds, highlighting the need for age-specific reference values for specific balance-related sway parameters (e.g. RMS_ml). Regarding test conditions with altered sensory input, a larger number of 5-year-old children is able to perform more difficult tasks. Nevertheless, if 3- or 4-year-olds are able to perform the more difficult tasks, their performance can be compared to the older children.

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DATE
20 oktober 2015

Submission of the manuscript entitled: "Age-related changes in postural sway in preschoolers"

Dear Professor Bronstein,

Enclosed please find the revised manuscript entitled "Age-related changes in postural sway in preschoolers" that we would like to resubmit to **Gait & Posture**. The manuscript within has not been and will not be submitted for publication elsewhere. We are hopeful that the revised manuscript is suitable for publication in your journal.

Based on the reviewers' comments, we have added Romberg Quotients into the manuscript and rearranged the reference list. Because of the extra analyses, the manuscript now counts 3635 words, exceeding the limit. The reference list contains 33 references instead of the required 30. All changes in the manuscript are in red.

Each of the authors was involved in the conception of the study, and/or the analysis and interpretation of data (EV, PHLC, PM, KD, LV, AH); every author has assisted in drafting and revising the manuscript. Each of the authors has read the final version of the manuscript and concurs with the content in the manuscript.

Conflict of interest: none.

Sincerely,

Evi Verbecque

***2. Conflict of Interest Statement**

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*3. Response to Reviewers

Reviewers' comments:

Reviewer #3: I am now happy with the paper.

Reviewer #4: The authors appear to adequately address the points raised by this reviewer. The authors are encouraged to re-check the reference list and format.

Best wishes

Reply: The reference list has been corrected.

Reviewer #5: The authors responded to all of my concerns but did not follow my recommendation for further analyses. Particularly the Romberg Quotient would be easy to calculate and is well known in the clinical dizziness and vestibular ambulances. This is hard to understand.

Reply: As recommended, we calculated the Romberg Quotients on firm surface (EC/EO) and on foam (FEC/FEO). These results (mean and standard deviations) have been presented for each parameter for the whole group of preschoolers and for each age category. No age effects were found, but considerable variation in the RQ was. We have addressed this in the discussion.

Still I cannot follow the argumentation of the authors that older children tend to explore their limits of stability. This statement indicates that the older subjects intentionally tried to test their stability and moved their CoP intentionally while being examined. I would go along with the statement if the authors would provide questionnaires or interviews of the children what they felt and did during the testing. This is not the case; hence there is no evidence for this statement. I would leave the interpretation open and mention that further studies are needed to address this result. This would highlight the study as being important because it originates a new research question.

Reply: we have deleted the argumentation on the exploration of the limits of stability and replaced it with the need for further research on this topic, as recommended.

Age-related changes in postural sway in preschoolers

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Acknowledgements: Partial financial support by the CONSELHO FEDERAL DE DESENVOLVIMENTO CIENTÍFICO E TECNOLÓGICO (CNPq-Brazil) in form of a post-doc scholarship to PHLC is gratefully acknowledged. We thank Joke Van Dooren for data collection and the schools De KleineMuze, De KleineWereld and Polderstad school who made the assessment of the children possible.

Introduction

To achieve and maintain an upright standing position, sufficient postural control is required.^{1,2} Postural control can be defined as achieving a desired body position, such as upright standing and maintaining this position in any static (maintaining a posture) or dynamic (performing a motor skill) situation.¹⁻⁴ Therefore, postural *control* is a necessity to ensure stability of the body during widely differing motor tasks allowing skilled movement.² This requires perception of body and head position in space in relation to the environment, as well as perception of the position of body segments in relation to each other based on sensory information.¹⁻⁴ This information, obtained through the auditory, visual, vestibular and somatosensory systems, is processed in the brain, involving the selection of an appropriate balance strategy leading to an adequate motor output.¹ This output is provided by the motor system, which is responsible for the activation of the appropriate movement patterns in response to perturbations of balance.³⁻⁵

The assessment of postural control in children can be performed in different ways, varying from functional to technical approaches, and is of great importance because it provides information on functioning and motor development.^{2,3} Functional tests assess the ability to perform a task, but in contrast to technical tests, they do not quantify the movements of a child while it maintains his or her posture nor do they provide information on the influence of sensory input.⁶ The most common technical measure of postural control is the characterisation of postural sway by measuring centre of pressure (COP) displacements. This technique has two main advantages compared to the functional tests: 1) measuring postural sway ensures a very accurate quantitative measure (COP displacement) of maintaining a certain posture during a certain timeframe and 2) environmental factors, that challenge different sensory systems, can be easily implemented in the test battery (e.g. measuring postural sway with eyes open/closed on a firm/foam surface).⁷ To investigate the role of sensory information in postural control several approaches have been reported in literature. Furthermore, opinions differ on its development in children. Forssberg & Nashner (1982) stated that it is *probably* sensory integration that occurs during development of postural control, *rather* than the dominance

of a specific modality, as was reported by Shumway-Cook (1985).^{8,9} Sensory integration refers to reweighting multiple sensory inputs to maintain one's posture.^{8,10,11} To assess sensory integration, Foudriat (1993) applied the Sensory Organization Test in children, in which sway- and/or visual referencing can be used to alter sensory input. This test examines a child's ability to integrate multiple sensory inputs for postural control.¹² However, according to Bair and colleagues (2007), this technique would not be sufficient to quantify the sensory fusion process. They stated that the most adequate way to evaluate sensory integration during postural control, is by using a moving room.¹⁰ Several recent studies have shown **indeed**, that this type of assessment actually provides information on sensory reweighting during postural control.^{10,11} Nevertheless, moving room assessment requires specific and expensive equipment. From a clinical point of view, an easily applicable and fast way to determine whether a child's postural control is sufficient, would be enough. Therefore, static posturography, measuring spontaneous postural sway, in which global descriptive sway parameters (e.g. sway amplitude and sway velocity) are measured and this in different sensory conditions (e.g. standing with eyes open or closed on stable ground or foam) could provide enough information to determine whether a child's postural control deviates from what is normal.

In previous studies, different age categories have been investigated and all authors suggest that an important first *transitional* phase with regard to the amount of postural sway occurs in young children.¹³⁻¹⁶ The exact age of these *young children*, however, varies depending on the investigating authors. A literature review on reference values and developmental changes of postural sway during bipedal stance, revealed that preschoolers (children between the ages three and six) **are** usually addressed as one group, and that reference values for postural sway parameters in this group are scarce.^{13,17-21} Due to developmental changes in postural control during the preschool years, it could be expected that age-related differences of sway parameters can be identified, hence the relevance for age-specific reference values. Therefore the aim of this study is twofold: 1) to investigate age-related differences of postural sway in 3- to 6-year-old typically developing children in different sensory conditions and 2) to provide reference values for global descriptive sway parameters in

preschoolers. It is hypothesised that postural sway measures will differ between 3-, 4- and 5-year-olds, reflected by a decrease in the amount of sway with increasing age. Also, withdrawal or alteration of specific sensory information is expected to disturb younger children significantly more than older children, leading to increased sway.

Methods

Participants

A cross-sectional study was performed investigating postural sway in a sample of 96 children, consisting of three-year-olds (43.2 (3.9) months), four-year-olds (53.2 (3.8) months) and five-year-olds (64.8 (3.3) months). The children were recruited from three regular preschools in the city of Antwerp, Belgium. Data were collected between October 2013 and April 2014. This study was approved by the local ethical committee of the University of Antwerp (B300201316328). Prior to the assessment of postural sway, a questionnaire was completed by the parents, which was used to identify the presence of developmental problems and to map features of the child's birth, use of aids such as glasses, orthoses and cochlear implants. Children were excluded from the study if they had any known developmental or neuromotor disorder, severe visual or hearing impairment, used aids (except for glasses), had cochlear implantations, or when there was a lack of cooperation.

Test Procedure and protocol

To examine postural sway during upright bipedal stance, subjects stood barefoot on a force plate (0.4 x 0.5m, 1000 Hz, model OR 6-5-2000, Advanced Medical Technology Inc., Massachusetts, USA), with a standardised distance of 10 cm between the medial borders of the feet, for 40 seconds watching a film (iPad 2, 9.7 inch multi-touch screen) at eye level or with their eyes closed. Postural sway was measured in four non-randomised test conditions:

condition 1: EO; standing on firm surface with eyes open

condition 2: EC; standing on firm surface with eyes closed

condition 3: FEO; standing on a foam with eyes open

condition 4: FEC; standing on a foam with eyes closed

During each trial the subjects were asked to keep both arms along their body and stand as still as possible. A medium density foam pad (12 x 45 x 45 cm, NeuroCom International Inc., Clackamas, USA; 60 kg/cm³) was used in conditions 3 and 4. Each condition was explained in advance to each child and performed once as single trial measurements for postural sway have been shown to provide a representative sample of postural control in children.²² The trial was stopped if the child didn't understand or didn't follow the instructions, only then a second trial was performed. All subjects were permitted to rest between trials or conditions. Two therapists (EV, PHLC) tested all subjects. Throughout the entire test, one investigator stayed close to the subject to prevent falling, without interfering with his/her performance. The children were verbally encouraged by the investigator if needed.

Variables of interest

Demographic data (age, gender, height, use of aids) were used to describe the sample. The COP positions were calculated from the ground reaction forces (F_x , F_y , F_z) and appropriate moments of force around the x (M_x) and y (M_y) axes using formula 1 and 2 (table 1). The first ten seconds of each trial were discarded to avoid transients²³, leaving 30 seconds for analysis.

The COP amplitudes in antero-posterior (COP_{ap}) and medio-lateral directions (COP_{ml}), velocities (COP_v_{ap}, COP_v_{ml}), root mean squared error (RMS_{ap}, RMS_{ml}) and path (COP_{path}) were calculated using a custom made Matlab scripts (version 2013b for Windows, Mathworks) based on formula 3 - 9 according to Duarte & Freitas (table 1).²⁴ A second order low pass butterworth filter with a cut-off frequency of 12,5 Hz was used for filtering the COP.

The area was calculated by fitting an ellipse that corresponds with 85% of the surface COP points, according to the method described by Oliveira, using Principal Component Analysis (PCA).²⁵ With PCA the direction of the principal axis is defined as the axis of the first eigenvector of the covariance

matrix.²⁵ The direction of the minor axis (orthogonally positioned to the principal axis) is defined by the second eigenvector.²⁵ The Romberg Quotient (RQ) of each parameter was calculated on firm surface by dividing its value in the EC condition by its value in the EO condition. Similarly, a RQ was calculated for FEC over FEO conditions. A RQ value of 1 would indicate similar performance in EC and EO, a value >1 indicates relatively more sway in the EC.

Normalisation of global sway descriptors

In order to minimise inter-individual differences in the amount of postural sway due to growth, the formulas described by Hof (1996) to correct gait parameters for participants' stature were adapted, which is valid in walking but also applies to postural sway.^{26,27} In postural sway assessment, the movement of the centre of mass with the feet serving as a fixed pivot point, is being measured indirectly using the COP. COP amplitudes, path and RMS were divided by the subject's height. Velocities were divided by $\sqrt{9,81 \times \text{height}}$ and COP area was divided by squared height.²⁶ This way, non-dimensional values were obtained for all postural sway parameters.

Statistical analysis

Data were statistically analysed when the child was able to perform the task during 40 seconds, meaning they either passed or failed the condition and only the data of those who passed were analysed. Statistical analyses were conducted using SPSS (IBM SPSS statistics 22) for Windows. A Kolmogorov-Smirnov test was used to test the data for normality. Chi Square test was used to identify significant differences in the proportion of children that were able to complete the altered sensory conditions. A 2x2x3 (surface x vision x age group) multivariate general linear model was used to test the effects of age and perturbations of sensory information (vision, somatosensory information) on postural sway. A two-way analysis of variance was used to test for the effects of age and surface on the RQ. Post-hoc pairwise comparisons (independent Student t-tests) were performed with Tukey's test to determine differences between age groups. Statistical significance was set at $p < 0.05$.

Results

Participants

The study sample consisted of 96 children, of which 17 were excluded from data-analysis (3 due to technical issues and 14 because of software problems). Thus, data of 79 children are presented, classified into three age groups: 3-year-olds (n=24), 4-year-olds (n=27) and 5-year-olds (n=28). Table 2 presents the descriptive characteristics of the sample.

Variables of interest

Figure 1 shows the percentage of children that completed the different conditions. All children (100%) were able to perform the EO condition. With the 3-year-olds, 79.2% was able to perform EC, 83.3% FEO and 54.2% FEC. With the 4-year-olds, 85.2% was able to perform EC, 81.5% FEO and 74.1% FEC. With the 5-year-olds, 92.9% was able to complete EC, 89.3% FEO and 85.7% FEC. Chi Square showed significant differences between observed and expected values (if age had no effect) in 3 and 4-year-olds for EC ($p=0.021$) and FEC ($p<0.001$).

Figure 2 shows the effects of vision, surface and age on postural sway controlled for body height. Main effects of vision ($p<0.05$) and surface ($p<0.001$) on all postural sway parameters were found. Occlusion of vision and standing on foam increase postural sway values (figure 2). Furthermore, an interaction effect between surface and vision for all parameters ($p<0.05$) was found. When surface and vision were perturbed simultaneously, sway increased even more. A significant main effect of age was found for COP_{ap} ($p=0.047$), COP_{rms_ml} ($p=0.012$) and COP_{area} ($p=0.009$). Post-hoc pairwise comparison showed significant differences between 3- and 5-year-old children (COP_{rms_ml}: $p=0.004$; COP_{area}: $p=0.006$) and between 4- and 5-year-old children (COP_{ap}: $p=0.026$; COP_{rms_ml}: $p=0.012$; COP_{area}: $p=0.015$). No interactions were found between age-surface, age-vision or age-surface-vision.

Romberg quotient (RQ)

Figure 3 shows the variation of the RQ based on the age categories. No main effect of age ($p>0.05$) was found for both ratios (EC/EO; FEC/FEO). The RQ of all parameters on stable ground differ significantly from the RQ on foam ($p<0.05$). No interaction effect between age and surface was found. Mean values and standard deviations for the RQ, classified according to age and the whole group of preschoolers, are presented in table 3.

Reference values

Table 3 provides an overview of the unadjusted postural sway parameters, in each condition classified according to age and the whole group of preschoolers.

Discussion

The aim of this study was twofold: 1) to investigate age-related differences of postural sway in 3- to 6-year-old typically developing children in different sensory conditions and 2) to provide reference values for global descriptive sway parameters in preschoolers. These aims were achieved by recording the amount of sway during 40 seconds with eyes open/closed on firm/foam surface in different age-groups. Main findings are: 1) age-related differences were found during natural stance for specific spatial parameters (COP_rms_ml, COP_area and COP_ap), 2) sensory perturbations increase postural sway parameters in all preschoolers, 3) perturbing both vision and somatosensory information effects postural sway more than perturbing only 1 of the 2 sensory systems (interaction effect) and 4) three- and four-year-olds, who are able to perform FEO or FEC, show similar amounts of sway compared to five-year-olds.

In contrast to what we expected, based on what has been previously reported in literature, all sway parameters, even when normalised for body height, tend to increase with age. Nevertheless, only significant differences were found for the spatial parameters, that distinguish the 5- from the 3-year-

olds (COP_area) and the 5- from the 4-year-olds (COP_ap, RMS_ml and COP_area). Thus, sway velocity seems similar in all age groups, but the sway amplitude increases with age. Because all postural sway data were normalised for body height, the relative differences that were found between 3-, 4- and 5-year-olds cannot be due to the base of support and thus potential larger limits of stability. Based on our data, this increase of sway in 5-year-olds, cannot be explained. Further research is necessary to address this result. Regarding the limited number of sway parameters in which differences were found among preschoolers, in literature, COP_rms_ml has been reported as a general index for postural control (especially in different sensory conditions).²¹ Therefore, the differences in COP_rms_ml, that we found between 4- and 5-year-olds, seem to imply an actual difference in postural control.

All postural sway parameters increased significantly by restricting vision, challenging proprioceptive information and the combination of both. These findings are consistent with the literature, despite differences in protocol such as computerised dynamic posturography (EquiTest, Neurocom, Int).^{12,14,15} Here, the use of proprioceptive/visual information is challenged using a sway-referenced platform/surround and thus depend on the movements of the child.^{12,14,15} Hsu and colleagues, like us, used static posturography in 3 to 12-year-old children. At 12 years of age mature postural sway can be expected in altered sensory conditions, characterised by a decrease in both the amount of sway and in variability of sway patterns.¹³ Even though they were able to determine the transition from child-like to adult-like postural responses, they did not compare among children. Additionally, Romberg Quotients (RQ) were calculated to determine the influence of vision on firm surface (EC/EO) and on foam (FEC/FEO). Our mean RQ values on firm surface (EC/EO) were situated between 1 and 2. These values are different from those of Riach and Hayes (1987), who reported mean RQ values on firm surface (EC/EO) for cop_rms_ml and cop_rms_ap in children under age 5 below 1.²⁹ Their adult RQ values for cop_rms_ml (1.3 ± 0.4) and cop_rms_ap (1.45 ± 0.44) were lower than those found by Lê and Kapoula (2008), who stated that the RQ on firm surface amounts to about 2 for COP excursions, standard deviations of amplitudes and variance of velocity.^{29,30}

However, according to Lê and Kapoula (2008) the visual fixation at near (e.g. 40cm) or far distance (e.g. 200cm) has a significant influence on the RQ, respectively reaching about 2 with near visual fixation and 1 with far visual fixation.³⁰ In contrast to Riach and Hayes, who used a visual target at 5m, our children watched a video at near distance, which might explain the different results. Fujimoto and colleagues (2010) reported RQ values on foam (FEC/FEO) in adults for cop_v (median 2.2 – interquartile range 1.97-2.48) and cop_area (median 3.48 – interquartile range 2.36-4.23).³¹ Our mean RQ values (FEC/FEO) are situated between 1.3 and 2.4. However, a large variation in both RQ values (EC/EO; FEC/FEO) was found. Even though the RQ might serve as an easy measure for deviant postural control, e.g. RQ FEC/FEO is considered to reflect vestibular function (olithic function)³², further research on the diagnostic value of this parameter is necessary, because of the large variation in RQ values that we found in typically developing 3- to 6-year-old children.

In this study, age-related differences were investigated in order to determine whether age-specific reference values for postural sway parameters are necessary for diagnostic purposes, or whether reference values for preschoolers as one group suffice. Our results showed that a larger number of older children were able to cope with altered sensory information, but younger children, when able to perform the task, did similarly as older children. This can be explained by the number of children able to cope with sensory perturbations increased with age. Data were statistically analysed when the child was able to perform the task during 40 seconds, meaning they either passed or failed the condition and only the data of those who passed were analysed. The number of children able to complete the task increased with age. For example, quiet bipedal natural stance was possible for all children during 40 seconds, but when sensory information was challenged a significantly smaller number of 3- and 4-year-olds was able to complete the task (Chi Square test). These results suggest that younger children rely more on visual information than older children, because fewer younger children are able to cope with EC and FEC. The younger children, who were able to cope with these perturbations, show quite similar performances as the older children, because no significant interaction effect was found between age and vision or surface on postural sway. This lacking

1 interaction effect could be due to methodological characteristics of the measuring technique such as
2 handling missing data and the timeframe in which the sway was recorded. For example, when
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4 applying the Equitest, equilibrium scores are calculated varying from 0 (postural instability or failing
5 the task) to 100 (perfect postural stability or standing perfectly still).^{12,14,15} Using this protocol,
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7 children failing the test are not omitted from analysis, which might explain why age-related
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9 differences on Equitest scores have been shown in previous studies.^{12,14,15} In literature, different
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11 timeframes are reported when assessing postural sway in children, varying from 20 seconds up to 60
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13 seconds^{13,14}, or remaining undefined¹². Studies, using the Equitest, all report timeframes between 20
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15 and 30 seconds, and thereby might include more children in the analyses which results in increased
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17 power of the statistical test. On the other hand, choosing a longer timeframe for data recording has
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19 the advantage of being a more realistic estimation of the child's motor abilities even though this
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21 implies the possibility of more children failing FEO and FEC. However, we saw that our children were
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23 either able to perform the task during 40 seconds or failing immediately. Thus, in these tasks the
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25 timeframe does not seem to explain the percentages of children passing/failing in our sample as
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27 might be expected.
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35 The limited main age effect and the absence of interaction effects between condition and age,
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37 combined with the percentages of children passing/failing that are clearly age-related, provides
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39 valuable information for clinical practice. For example, adequate postural control could be
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41 determined by evaluating whether a preschooler can perform specific sensory conditions during a
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43 predefined timeframe, as has been established in adults by Vereeck and coworkers.³³ For example,
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45 Vereeck et al (2008) determined that adults in their 5th and 6th decade should be able to maintain
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47 tandem Romberg with the eyes closed during 10 seconds, whereas elderly people in their 7th and 8th
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49 decade only need to maintain standing on foam with the eyes open during 10 seconds to show
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51 sufficient postural control.³³ The conditions that were used to evaluate postural sway in our study,
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53 could also be translated to a functional test and therefore providing an easy and cheap assessment
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55 tool for postural control, e.g. maintaining EC and FEO during 10 seconds in 5-year-olds. However,
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1 further research needs to be performed to determine the exact timeframe and which task(s)
2 correspond with which age group.
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4 *Limitations of the study*

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7 In this study, during the assessment of each child, the four different sensory conditions were non-
8
9 **randomised**. Lack of **randomisation** of the test conditions could systematically induce fatigue in the
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11 more difficult (foam) conditions and thus influence their performance. Therefore, all children were
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13 allowed to rest between each condition. Also, according to the ecological approach to action and
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15 perception, the more experience a child has with a given task, the more its attention is focused to
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17 the proper environmental cues to regulate and accomplish the action.⁵ Therefore, it could be
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19 expected that the children show more adequate postural responses in the foam conditions. Also,
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21 each child performed **generally** only one trial in each condition, for 40 seconds, indicating that the
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23 influence of fatigue would be limited.
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27 *Conclusion*

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30 During natural stance, the amount of postural sway distinguishes 5-year-olds from 3- and 4-
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32 year-olds, highlighting the need for age-specific reference values for specific balance-related sway
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34 parameters (e.g. RMS_ml and COP_area). Standing postural control in conditions with altered
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36 sensory input improves with increasing age, as shown by a larger number of children that are able to
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38 perform more difficult tasks. However, children of all ages – when able to perform the task – show
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40 significantly more sway after sensory perturbation.
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Table 1: Overview of the formulas that were used to calculate postural sway parameters (amplitude, velocity, root mean square and path).

$COP_x = \frac{-c1 \cdot F_x - M_y}{F_z} + a1$	1
$COP_y = \frac{-c1 \cdot F_y + M_x}{F_z} + b1$	2
$COP_{ap} = \max(COP_y) - \min(COP_y)$	3
$COP_{ml} = \max(COP_x) - \min(COP_x)$	4
$COPv_{ap} = \frac{\sum_{i=1}^n COP_y(i+1) - COP_y(i) \cdot F}{n}$	5
$COPv_{ml} = \frac{\sum_{i=1}^n COP_x(i+1) - COP_x(i) \cdot F}{n}$	6
$COP_{rms_{ap}} = \frac{\sqrt{\sum_{i=1}^n (COP_y(i) - \overline{COP_y})^2}}{n}$	7
$COP_{rms_{ml}} = \frac{\sqrt{\sum_{i=1}^n (COP_x(i) - \overline{COP_x})^2}}{n}$	8
$COP_{path} = \sum_{i=1}^n \sqrt{(COP_x(i+1) - COP_x(i))^2 + (COP_y(i+1) - COP_y(i))^2}$	9
<p>Legend: The position of the true origin (a1,b1,c1). n = number of data points in a trial, F = measurement frequency</p>	

Table 2: Descriptive characteristics of the participants (number of children of whom the results were analysed, age, gender, body height and use of glasses).

Age Group	3 year-olds	4 year-olds	5 year-olds
Number of children (<i>n</i>)	24	27	28
Mean age (SD) (<i>months</i>)	43.2 (± 3.9)	53.2 ± 3.8	64.8 ± 3.3
M/F (<i>n</i>)	13/11	11/16	16/12
Mean body Height (SD) (<i>m</i>)	0.999 ± 0.042	1.069 ± 0.059	1.139 ± 0.041
Use of glasses (<i>n</i>)	1	0	3

Legend: n= number of children, M= male, F= female, m= meter, SD= standard deviation

Figure 1: Overview of the percentage of children that were able to complete each condition (*Eyes Open (EO)*: standing with eyes open on stable ground, *Eyes Closed (EC)*: standing with eyes closed on stable ground, *Foam Eyes Open (FEO)*: standing with eyes open on foam, and *Foam Eyes Closed (FEC)*: standing with eyes closed on foam) presented per age category (3, 4 and 5-year-olds). A condition was considered to be completed if the child was able to perform the task during 40 seconds without losing balance. Losing balance was defined as falling or the presence of protective reactions to prevent a fall.

Table 3: Overview of mean values and standard deviations for postural sway parameters unadjusted for body height (displacement, velocity, standard error, path and area) in each condition (Eyes Open (EO): standing with eyes open on stable ground, Eyes Closed (EC): standing with eyes closed on stable ground, Foam Eyes Open (FEO): standing with eyes open on foam, and Foam Eyes Closed (FEC): standing with eyes closed on foam), presented per age category (3, 4 and 5-year-olds).

	Task Age	Eyes Open	Eyes Closed	Foam, Eyes Open	Foam, Eyes Closed	Romberg Quotient	
Number of children able to complete the task (n,%)	3-year-olds	24 (100%)	19 (79%)	20 (83%)	13 (54%)	EC/EO	FEC/FEO
	4-year-olds	27 (100%)	23 (85%)	22 (81%)	20 (74%)		
	5-year-olds	28 (100%)	26 (93%)	25 (89%)	24 (86%)		
Mean Cop_ap (mm)	3- to 5-year-olds	<u>26.2 ± 17.1</u>	<u>26.7 ± 14.9</u>	<u>42.1 ± 54.8</u>	<u>54.8 ± 25.9</u>	<u>1.23 ± 0.64</u>	<u>1.49 ± 0.45</u>
	3-year-olds	24.0 ± 13.6	25.8 ± 11.1	36.6 ± 12.6	46.8 ± 16.7	1.33 ± 0.54	1.34 ± 0.38
	4-year-olds	22.4 ± 12.7^B	20.7 ± 11.0	39.3 ± 14.9	52.9 ± 20.0	<u>1.09 ± 0.37</u>	<u>1.42 ± 0.32</u>
	5-year-olds	31.8 ± 22.1^B	32.7 ± 18.1	49.0 ± 38.6	60.8 ± 32.8	<u>1.27 ± 0.86</u>	<u>1.65 ± 0.55</u>
Mean Cop_ml (mm)	3- to 5-year-olds	<u>24.5 ± 15.7</u>	<u>27.7 ± 17.9</u>	<u>41.0 ± 30.2</u>	<u>56.7 ± 22.3</u>	<u>1.27 ± 0.57</u>	<u>1.66 ± 0.59</u>
	3-year-olds	21.7 ± 11.1	23.9 ± 14.6	32.5 ± 10.2	49.2 ± 12.9	<u>1.26 ± 0.52</u>	<u>1.65 ± 0.56</u>
	4-year-olds	18.6 ± 9.3	25.7 ± 14.6	38.4 ± 18.7	58.5 ± 22.0	<u>1.37 ± 0.46</u>	<u>1.67 ± 0.61</u>
	5-year-olds	32.4 ± 20.4	32.3 ± 21.8	50.1 ± 44.4	59.2 ± 26.1	<u>1.19 ± 0.69</u>	<u>1.65 ± 0.61</u>
Mean Cop_path (mm)	3- to 5-year-olds	<u>380 ± 195</u>	<u>425 ± 206</u>	<u>689 ± 514</u>	<u>1036 ± 515</u>	<u>1.22 ± 0.39</u>	<u>1.70 ± 0.41</u>
	3-year-olds	345 ± 145	380 ± 150	597 ± 245	914 ± 449	<u>1.23 ± 0.36</u>	<u>1.47 ± 0.28</u>
	4-year-olds	328 ± 117	409 ± 179	658 ± 340	1146 ± 674	<u>1.29 ± 0.29</u>	<u>1.76 ± 0.46</u>
	5-year-olds	459 ± 261	474 ± 256	789 ± 750	1011 ± 382	<u>1.16 ± 0.49</u>	<u>1.77 ± 0.39</u>
Mean Cop_v_ap (mm/s)	3- to 5-year-olds	<u>11.1 ± 6.0</u>	<u>11.5 ± 5.6</u>	<u>20.3 ± 14.5</u>	<u>29.5 ± 16.6</u>	<u>1.14 ± 0.38</u>	<u>1.63 ± 0.48</u>
	3-year-olds	10.2 ± 4.6	10.7 ± 3.2	18.4 ± 7.8	26.9 ± 14.3	<u>1.21 ± 0.38</u>	<u>1.40 ± 0.28</u>
	4-year-olds	9.9 ± 3.7	10.4 ± 4.5	20.0 ± 11.0	32.6 ± 21.8	<u>1.13 ± 0.25</u>	<u>1.66 ± 0.45</u>
	5-year-olds	13.1 ± 8.1	13.0 ± 7.3	22.3 ± 20.4	28.3 ± 12.6	<u>1.10 ± 0.47</u>	<u>1.74 ± 0.56</u>
Mean Cop_v_ml (mm/s)	3- to 5-year-olds	<u>12.8 ± 7.3</u>	<u>15.2 ± 8.3</u>	<u>23.8 ± 20.0</u>	<u>36.6 ± 18.2</u>	<u>1.28 ± 0.42</u>	<u>1.77 ± 0.47</u>
	3-year-olds	11.5 ± 5.4	13.0 ± 7.3	19.9 ± 8.5	32.2 ± 16.4	<u>1.21 ± 0.31</u>	<u>1.56 ± 0.32</u>
	4-year-olds	10.7 ± 5.1	15.1 ± 7.5	22.3 ± 12.0	41.0 ± 23.6	<u>1.41 ± 0.35</u>	<u>1.85 ± 0.53</u>
	5-year-olds	15.8 ± 9.5	16.8 ± 9.6	28.1 ± 29.6	35.4 ± 13.3	<u>1.21 ± 0.53</u>	<u>1.83 ± 0.47</u>
Mean Cop_rms_ap (mm)	3- to 5-year-olds	<u>4.7 ± 2.8</u>	<u>5.1 ± 2.7</u>	<u>7.7 ± 3.9</u>	<u>10.0 ± 4.0</u>	<u>1.22 ± 0.57</u>	<u>1.44 ± 0.40</u>
	3-year-olds	4.5 ± 2.3	5.0 ± 2.4	6.7 ± 2.4	8.6 ± 2.5	<u>1.33 ± 0.61</u>	<u>1.30 ± 0.33</u>
	4-year-olds	4.0 ± 1.8	4.1 ± 2.2	7.3 ± 2.7	9.9 ± 3.9	<u>1.16 ± 0.87</u>	<u>1.41 ± 0.29</u>
	5-year-olds	5.8 ± 3.5	5.9 ± 3.0	8.8 ± 5.5	10.8 ± 4.5	<u>1.19 ± 0.64</u>	<u>1.54 ± 0.50</u>
Mean Cop_rms_ml (mm)	3- to 5-year-olds	<u>4.6 ± 3.0</u>	<u>5.2 ± 2.9</u>	<u>7.3 ± 4.3</u>	<u>10.1 ± 3.5</u>	<u>1.26 ± 0.45</u>	<u>1.59 ± 0.49</u>
	3-year-olds	4.1 ± 2.2	4.4 ± 2.4	5.9 ± 2.0	8.8 ± 2.0	<u>1.27 ± 0.42</u>	<u>1.62 ± 0.52</u>
	4-year-olds	3.4 ± 1.7^B	4.8 ± 2.4	6.7 ± 2.1	10.4 ± 4.1	<u>1.39 ± 0.39</u>	<u>1.60 ± 0.48</u>
	5-year-olds	6.2 ± 3.7^B	6.1 ± 3.4	8.9 ± 6.2	10.6 ± 3.6	<u>1.13 ± 0.50</u>	<u>1.55 ± 0.50</u>
Mean Cop_area (mm ²)	3- to 5-year-olds	<u>316 ± 422</u>	<u>362 ± 380</u>	<u>803 ± 1102</u>	<u>1301 ± 859</u>	<u>1.64 ± 1.18</u>	<u>2.31 ± 0.94</u>
	3-year-olds	241 ± 250^A	284 ± 260	491 ± 298	924 ± 493	<u>1.82 ± 0.99</u>	<u>2.20 ± 1.04</u>
	4-year-olds	167 ± 136^B	264 ± 226	613 ± 391	1323 ± 951	<u>1.66 ± 0.87</u>	<u>2.25 ± 0.75</u>
	5-year-olds	524 ± 609^{A,B}	507 ± 508	1219 ± 1685	1478 ± 897	<u>1.50 ± 1.52</u>	<u>2.42 ± 1.05</u>

Legend: Cop: centre of pressure, ap: displacement in antero-posterior direction, ml: displacement in medio-lateral direction, v: velocity of the Cop, rms: root mean square or standard error. ^A significant differences between 3- and 5-year-olds (p<0.05); ^B significant differences between 4- and 5-year-olds (p<0.05). Underlined values are significantly different from each other among the whole group of preschoolers.

Figure 2: Shows the effect of age, vision and foam on COP amplitudes in antero-posterior (ap) direction, **normalised** for body height. Figure 2A presents the effect of eyes open/eyes closed on stable ground and on foam in the total group of preschoolers. In figure 2B, the amount of COP amplitudes in ap direction is shown for each biological age with eyes open/eyes closed on stable ground and on foam.

2A. Effect of vision and foam on postural sway in 3 to 6-year-old children.

2B. Effect of age and vision/foam on postural sway.

Figure 3: shows the variation of the Romberg quotients based on the age categories for the Root Mean Square or standard error (COP_rms_ml) and the area (COP_area) of the mean position of the center of pressure. Romberg quotients are shown as the ratio EC/EO (stable ground) and FEC/FEO (foam).

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Research highlights

- Not all 3 and 4-year-olds are able to maintain bipedal stance with eyes closed
- Sensory perturbations provoke an increase of postural sway in all preschoolers
- 3-, 4- and 5-year-old children show similar amount of sway in different conditions