Age-Related Changes in Postural Control: Rambling and Trembling Trajectories

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This study identified and quantified rambling and trembling properties of the postural control system of children 4–12 years of age. Forty-five children of varying ages (4-, 8-, and 12-years) and 15 adults stood upright on a force plate and performed 5 trials with and 5 trials without vision with each trial lasting 30 s. Center of pressure, rambling, trembling, mean sway amplitude, and predominant frequency were obtained. Results revealed that the displacement of the center of pressure and overall rambling trajectories were age-related with younger children swaying more than older children and adults. Similarly, overall trembling trajectories for younger children were larger compared with older children and adults. These results suggested that a younger child’s larger body sway mostly results from difficulties using sensory information when estimating overall body position and velocity in an upright stance and is less a result from the noise in the postural control system.

Keywords: sensory information, development, control mechanisms, balance control, posture.

Maintaining an upright body orientation is one of the most critical tasks in the human motor repertoire. Moreover, the ability to balance all the forces acting on the body as one stands upright is a prerequisite to executing many activities of our daily life as well as allowing us mobility and independence (Maki & McIlroy, 1996). Furthermore, managing the stability of the body’s posture greatly influences the acquisition and performance of increasingly complex motor skills. Although postural control is unquestionable important, the mechanisms underlying age-related changes during postural control remains unresolved.

Developmental changes in the postural control have been observed throughout the first decade of life. More specifically, deviation of the body or center of pressure (COP) displacement diminishes with age (Figura, Cama, Capranica, Guidetti, & Pulejo, 1991; Riach & Hayes, 1987; Riach & Starkes, 1993; Taguchi & Tada, 1988; Usui, Maekawa, & Hirasawa, 1995), and infants and young children sway with increased frequencies when compared with adults (Ashmead & McCarty, 1991; Newell, Slobounov, Slobounova, & Molenaar, 1997). An interpretation of
these findings is that postural control performance increases with age and reaches adult-like functioning either around the seventh year of life (Odenrick & Sandstedt, 1984; Riach & Hayes, 1987; Riach & Starkes, 1993) or only after the first decade of life bipedal (Figura, Cama, Capranica, Guidetti, & Pulejo, 1991). This is particularly the case in more demanding tasks (Godoi & Barela, 2008; Zernicke, Gregor, & Cratty, 1982).

Children before 7 years of age also show difficulties using sensory information. These children maintain an upright stance with greater difficulty when compared with older children. Sometimes when conflicting sensory cues from two different sensory channels are manipulated their upright stance becomes compromised (Forssberg & Nashner, 1982; Shumway-Cook & Woollacott, 1985). Such observations have been used to suggest that young children depend more on visual information, incapable of performing sensory integration, that is, young children have greater difficulty fusing sensory information from different modalities when compared with adults (Woollacott, Debû, & Mowatt, 1987).

These studies provided important knowledge about postural control in children, yet the mechanisms underlying these age-related changes remains unknown. During the last decade, studies have focused on how infants (Barela, Jeka, & Clark, 1999; Bertenthal, Rose, & Bai, 1997; Metcalfe, 2005a; Metcalfe, 2005b) and children (Barela, Jeka, & Clark, 2003; Godoi & Barela, 2008; Schmuckler, 1997) use sensory information and how this information is coupled with body sway. For instance, Barela et al. (2003) suggested that increased variability in the postural sway of children could be due to increased noise levels inherent in their postural control system when compared with adults. Moreover, the noise observed in children’s sway is due to two sources of noise. One noise source could be the estimation of the position and velocity of their body orientation, which would reflect a measurement noise in the internal state estimation. The second source of noise is related to a “process noise”, that is, the difference between the signal sent to the muscular system and the movement produced by the muscles. Such suggestions about these two possible noise components in children’s postural control system need to be resolved. Examining sway properties in children may be useful for understanding developmental changes in postural control.

Characterization of sway properties in an unperturbed stance is commonly used as a tool for understanding the nature of postural control in adults (e.g., Amblard, Crémieux, Marchand, & Carblanc, 1985; Collins & De Luca, 1993; Lestienne & Gurfinikel, 1988; Zatsiorsky & Duarte, 1999). In brief, postural control involves at least two mechanisms: one mechanism determines body dynamics and defines a reference point and the other mechanism maintains the body’s equilibrium around this defined reference point. These two mechanisms were denominated as conservative and operative, respectively, (Lestienne & Gurfinkel, 1988) and seem to function at two different time scales (Amblard, Crémieux, Marchand, & Carblanc, 1985; Gatev, Thomas, Keppele, & Hallett, 1999). Using a stabilogram diffusion function, Collins and De Luca (1993) suggested the existence of two regimes in postural control: a short-term open-loop control mechanism and a longer-term closed-loop control mechanism. Although this model receives criticism (Dijkstra, 2000; Peterka, 2000), it has been used to characterize both the temporal organization of unperturbed sway and the nature of sensory motor control in young children (Metcalfe, 2005a) and elderly adults (Collins, De Luca, Burrows, & Lipsitz, 1995).
Based on a biomechanical approach, Zatsiorsky and Duarte (1999) developed a different method of stabilogram diffusion with the goal of distinguishing the motion of a moving reference point and the oscillation of the COP around the reference point trajectory. Such a decomposition procedure was intended to provide useful ways to explore and examine postural control mechanisms, with the decomposition of the moving reference point denominated rambling and the oscillation around the reference point denominated trembling. In a following paper, Zatsiorsky and Duarte (2000) examined such procedures in adults’ quiet stance and suggested that these data would support the hypothesis that adults in a quiet stance would display oscillation due to the migration of the reference point (rambling) and the deviation away from that point (trembling).

This COP decomposition procedure seems to be useful in analyzing body sway components in children, especially when uncovering potential mechanisms associated with age-related changes. For instance, if children’s larger sway is due to difficulties in estimating the internal state, that is, in determining COP position and velocity, as suggested for adults (Zatsiorsky & Duarte, 2000), then the sway due to the migration of the reference point, that is the rambling, would be larger. Similarly, if children’s larger sway is due to the discrepancy between the planned action and what was performed (i.e., a noisier process system) then the deviation from the reference point would also be larger. Thus the suggestion forwarded by Barela et al. (2003) regarding the properties of children’s postural control could be examined.

The goal of this study was to identify and quantify the rambling and trembling properties in the postural control system of children 4–12 years of age. It was hypothesized that both rambling and trembling trajectories would decrease, but with different profile changes. More specifically, children could reduce first the noise components in the COP sway (trembling) and, afterward, and more consistently throughout the ages, could improve the estimation of body dynamics leading reduced rambling trajectories.

**Methods**

**Participants**

Sixty participants were distributed equally into four age-groups: 4- (\(M = 4.23\) and \(SD = 0.33\)), 8- (\(M = 8.23\) and \(SD = 0.35\)), and 12-year-old children (\(M = 12.02\) and \(SD = 0.30\)), and young adults (\(M = 24.02\) and \(SD = 2.12\)). The children were recruited through personal contact with friends and relatives, and the young adults were undergraduate or graduate student volunteers. All subjects were healthy with no prior adverse physical or mental conditions, and each subject’s parents reported normal motor development during infancy. Each child’s parent and each adult participant provided written informed consent before participation, according to procedures approved by the Institutional Review Board.

**Procedures**

Participants were asked to maintain a stationary upright stance on a force plate (Kistler model 9289A) with feet parallel and slightly apart in the medial-lateral direction while looking at a picture fixed to a wall at eye level. Each participant performed 10
trials lasting 30 s each with and without vision. During the condition with vision, participants were asked to look at a picture (cartoon character—approximately 10 cm × 10 cm) on the frontal wall of the room placed 1 m away from the participant. During the condition without vision, participants wore opaque goggles preventing any visual cues from the surrounding environment. Five trials with the two vision conditions randomized within each trial were collected. To confirm participant compliance with the experimental task, all trials performed by the children were videotaped. When a child did not accomplish his or her task, the trial was repeated.

Trials began with the participants assuming the required upright stance on the force plate when the experimenter said “ready”, “go”. Immediately following this, the experimenter initiated data acquisition. Force plate data were collected using the analogical OPTOTRAK data acquisition unit (Northern Digital, Inc) at a sampling rate of 100 Hz.

**Data Analysis**

Force plate data were filtered using a Butterworth filter, fourth order and 5 Hz cut-off frequency, defined after residual analysis (Winter, 1990), and used to estimate COP trajectories for both medial-lateral and anterior-posterior directions. Next, the procedures described by Zatsiorsky and Duarte (1999) to obtain the rambling and trembling trajectories for medial-lateral and anterior-posterior directions were employed. Initially the experimenter identified and recorded each moment when the horizontal forces in each direction applied in the plate equaled zero (F_{hor.AP} = 0, F_{hor.ML} = 0). These moments corresponded to equilibrium points. Next, these moments were identified in the COP trajectories and interpolated using a cubic spline function. The trajectory obtained after this interpolation corresponded to the estimated rambling trajectory, representing a change from one equilibrium point to another (Zatsiorsky & Duarte, 1999, 2000). The trembling trajectory was determined by subtracting the estimated rambling trajectory from the corresponding COP trajectory which corresponded to the sway around the rambling trajectory (the equilibrium point).

To quantify the magnitude of all three trajectories, mean sway amplitude was calculated, first, by subtracting both the average position and any low frequency components from the original signal and, then, by calculating the standard deviation. In addition, the predominant frequency (peak frequency) in all three trajectories was computed using Welch’s method (50% overlap, segment lengths of 2048 points, 0.04 Hz resolution) to estimate the power spectral density. Both the mean sway amplitude and the predominant frequency were obtained for each trajectory (COP, rambling, and trembling) in both directions (medial-lateral and anterior-posterior) for each trial. Since five trials were collected in each condition, a mean for each variable was calculated. Therefore, only one value for each participant during each condition was used for future analysis. All the data were processed using customized Matlab (Math Works—version 5.3) programs.

**Statistical Analysis**

Six multivariate analyses of variance (MANOVAs) with the four age-groups and the two vision conditions as factors (last factor treated as a repeated measure)
were employed. The dependent measures for each MANOVA were the mean sway amplitude and predominant frequency for the COP, trembling, and rambling trajectories in each direction, medial-lateral and anterior-posterior. When necessary, univariate analyses and post hoc HSD Tukey’s tests, with Bonferroni adjustments, were employed. All statistical analyses were performed using the SPSS program (SPSS for Windows—version 6.1) and the alpha value was kept at 0.05.

## Results

### Center of Pressure Trajectories

COP displacement for all participants was decreased with vision compared with without vision. In addition, young children displayed larger COP trajectories than old children and adults. Figure 1 depicts the COP trajectory mean sway amplitude in the anterior-posterior and medial-lateral directions, for the four age-groups with and without vision. MANOVA revealed a group, Wilks’s Lambda = 0.36, F(6,110)=11.85, p < .001, and a vision effect, Wilks’s Lambda = 0.22, F(2,55)=94.75, p < .001, but no group and vision interaction. Univariate tests exposed group differences for both anterior-posterior, F(3,56)=16.78, p < .001, and medial-lateral, F(3,56)=26.46, p < .001, directions. Post hoc tests revealed that 4-, 8-, and 12-year-old children displayed larger COP trajectories when compared with adults in both the medial-lateral and anterior-posterior directions. In addition, the COP trajectories for 4-year-olds were larger than that of the COP trajectories for 12-year-olds in both the medial-lateral and anterior-posterior directions and larger than that of the COP trajectories for 8-year-olds in the anterior-posterior direction. Furthermore, children and adults displayed a larger COP trajectory without vision compared with participants with vision in both the anterior-posterior, F(1,56)=153.96, p < .001, and medial-lateral, F(1,56)=37.62, p < .001, directions.

![Figure 1](image-url) — Means and standard deviation of the center of pressure mean sway amplitude for all age-groups with and without vision in the anterior-posterior (a) and medial-lateral (b) directions.
The predominant frequency of the COP trajectory was approximately 0.2 Hz for all groups with and without vision. Figure 2 depicts the predominant COP trajectory frequencies in the anterior-posterior and medial-lateral directions for the four age-groups with and without vision. The MANOVA revealed a group effect, Wilks’s Lambda = 0.65, F(6,110)=4.26, p > .05, but no vision effect, Wilks’s Lambda = 0.99, F(2,55)=0.18, p > .05, and also revealed a group and vision interaction, Wilks’s Lambda = 0.91, F(6,110)=0.81, p > .05. Univariate analyses indicated a group effect only for the medial-lateral direction, F(3,56)=9.10, p < .001. Post hoc tests revealed that adults oscillated at higher frequencies than 4- and 8-year-old children.

Figure 2 — Means and standard deviation of the center of pressure predominant frequency for all age-groups with and without vision in the anterior-posterior (a) and medial-lateral (b) directions.

Rambling and Trembling Trajectories

Age-related and vision differences were observed for the rambling trajectory magnitude. Figure 3 depicts the rambling and trembling trajectory mean sway amplitudes, in both the anterior-posterior and medial-lateral directions, for the four age-groups with and without vision. For the rambling, a MANOVA revealed a group, Wilks’s Lambda = 0.31, F(6,110)=14.10, p < .001, and a vision effect, Wilks’s Lambda = 0.38, F(2,55)=43.53, p < .001, but no group and vision interaction, Wilks’s Lambda = 0.93, F(6,110)=0.66, p > .05. Univariate analyses revealed group differences in both the anterior-posterior, F(3,56)= 8.42, p < .001, and medial-lateral, F(3,56)=35.91, p < .001, directions. Post hoc tests showed that all children displayed increased rambling trajectories when compared with adults, and that 4-year-old children displayed increased rambling trajectories compared with 12-year-old children in both the anterior-posterior and medial-lateral directions. Finally, 4-year-old children displayed increased rambling trajectories when compared with 8-year-old children in the medial-lateral direction. Univariate analyses also revealed increased rambling trajectories without vision when compared with trials with vision in both the anterior-posterior, F(1,56)=77.27, p < .001, and medial-lateral, F(1,56)=7.33, p < .01, directions.
For the trembling trajectory, a MANOVA also revealed group, Wilks’s Lambda = 0.62, F(6,110)=4.85, p < .001, and vision effects, Wilks’s Lambda = 0.72, F(2,55)=10.25, p < .001, but no group and vision interaction, Wilks’s Lambda = 0.89, F(6,110)=1.01, p > .05. Univariate analyses revealed group differences in both the anterior-posterior, F(3,56)=9.04, p < .001, and medial-lateral, F(3,56)=5.83, p < .01, directions. Post hoc tests indicated that 4-year-old children had increased trembling trajectories when compared with 12-year-old children and adults in both the anterior-posterior and medial-lateral directions. In addition, 8-year-old children displayed increased trembling trajectories when compared with adults in the anterior-posterior direction. Univariate analyses indicated increased trembling trajectories without vision when compared with trials with vision condition in both the anterior-posterior, F(1,56)=8.56, p < .01, and medial-lateral, F(1,56)=13.68, p < .001, directions.

**Figure 3** — Means and standard deviation of the mean sway amplitude for the rambling trajectories for all age-groups with and without vision in the anterior-posterior (a) and medial-lateral (b) directions and for the trembling trajectories for all age-groups with and without vision in the anterior-posterior (c) and medial-lateral (d) directions. (The scale in figures c and d are different for better visualization).
The rambling trajectory predominant frequency was approximately 0.2 Hz whereas the trembling trajectory predominant frequency was approximately 0.4 Hz. Figure 4 depicts the predominant frequencies for the rambling and trembling trajectories in both the anterior-posterior and medial-lateral directions for the four age-groups with and without vision. For the rambling trajectory, a MANOVA revealed only a group effect, Wilks’s Lambda = 0.75, $F(6,110)=2.75$, $p < .05$. Univariate analyses, however, did not reveal any differences among the groups in both the anterior-posterior, $F(3,56)=0.84$, $p > .05$, and medial-lateral, $F(3,56)=0.49$, $p > .05$, directions for the predominant frequencies for both rambling and trembling. Finally the trembling trajectory, a MANOVA did not reveal any group, vision, and group and vision interactions.

Figure 4 — Means and standard deviation of the predominant frequency for the rambling trajectories for all age-groups with and without vision in the anterior-posterior (a) and medial-lateral (b) directions and for the trembling trajectories for all age-groups with and without vision in the anterior-posterior (c) and medial-lateral (d) directions.
Discussion

The purpose of this study was to identify, quantify, and compare the rambling and trembling properties of the postural control system of 4-, 8-, and 12-year-old children and adults. Overall, our results replicate previous findings that indicated both age and vision reduced COP trajectories. In addition, our results also showed age-related reduction in rambling and trembling trajectories. However, COP dynamics and the deviation from the reference point followed different developmental courses. While the magnitude of the rambling trajectory decreased along most of the studied ages, the magnitude of the trembling trajectory underwent a dramatic change around the age of 4 in this study. These results indicate that while younger children’s postural control is still affected by a noisier system, older children have already reached system noise levels similar to adults, and that age-related changes in postural control performance seem related to how children determine their deviation from a reference point when maintaining an upright stance.

Age-related changes in postural control performance while maintaining an upright stance have been observed in several studies (Figura, Cama, Capranica, Guidetti, & Pulejo, 1991; Riach & Hayes, 1987; Usui, Maekawa, & Hirasawa, 1995) and our results corroborate these previous findings. In addition, our results also clearly show that the performance of postural control, even in a simple task such as an upright stance, remains different between 12-year-old children and adults. A few studies have also found that postural control performance in many cases is not adult-like even after the first decade of life (Figura, Cama, Capranica, Guidetti, & Pulejo, 1991; Godoi & Barela, 2008; Taguchi & Tada, 1988). In summary, this study, along with other independent studies, has demonstrated that postural control continues to develop beyond the first decade of life.

Our results have not revealed higher COP frequencies in children while maintaining an upright stance; children and adults swayed with frequencies around 0.2 Hz, as Soames and Atha (1982) have suggested to be the natural frequency for the human upright stance. Unexpectedly, however, we did observe that adults swayed with higher frequencies in the medial-lateral direction when compared with children. Although such a finding was unexpected, one possible explanation could be that adults significantly reduced their displacement of their COP but while doing so, increase their COP frequency. Similar reductions in the displacement of the COP were recently observed during body sway in adults when they lightly touched a stationary surface (Bonfim, Grossi, Pacolla, & Barela, 2008).

Finally, while visual information reduces adult’s and children’s displacement of COP in both medial-lateral and anterior-posterior directions, as others have observed (Dijkstra, Gielen, & Melis, 1992; Odenrick & Sandstedt, 1984; Riach & Starkes, 1989; Taguchi & Tada, 1988), vision does not influence body sway frequency. Moreover, it seems that the vision effects in reducing COP displacement is similar throughout all ages observed in this study with no dramatic change in the contribution of postural control performance. This result questions any dramatic shift in the integration of sensory information during early ages, as previously suggested by Woollacott et al. (1987). Alternatively, it seems that children as well adults take advantage of additional information to improve their stable postural control.

As expected, the decomposition procedure, which obtained the rambling and trembling trajectories, was useful in analyzing body sway in children, especially
when uncovering potential mechanisms associated with age-related changes. Developmental changes in postural control related mostly to how children use sensory information to determine a reference position with respect to which the overall body dynamics are maintained. As age increased, there was a consistent reduction in the amount of overall sway related to the rambling trajectory. Differently, trembling trajectories were only significantly larger in 4-year-old children when compared with 12-year-old children and adults, in both the medial-lateral and anterior-posterior directions, and in 8-year-old children when compared with adults in the anterior-posterior direction. Changes in these processes underlie the development of postural control that occurs in a nonmonotonic manner. The postural control system needs to have less unpredictable influences (noise) to refine the relationship between sensory information and motor activity related to maintaining stable positions.

Our results clearly indicated that children are less accurate than adults when estimating body dynamics, overall position, and velocity. Consequently children displayed larger body sway when compared with adults. Such difficulties of children in selecting the most useful information, among all the many stimuli available, has been observed even when sensory cues were manipulated (Barela, Jeka, & Clark, 2003; Godoi & Barela, 2008) which may compromise an upright stance in young (Lee & Aronson, 1974) and old children (Forssberg & Nashner, 1982).

Similar to the reduction in the displacement of the COP with age, the overall rambling trajectories also decrease with age. These results indicate that the central nervous system receives more accurate and, consequently, reliable information regarding body dynamics, thereby, improving its estimation of the overall body position and velocity implementing better sway control. Curiously, all children (even 12-year-olds) displayed increased overall rambling trajectories than adults and among the children, 4-year-olds displayed larger overall rambling trajectories than 12- and 8-year-olds (only in the medial-lateral direction in this last comparison). Therefore, age-related changes in the control of migration from one position to another during an upright stance occurs throughout the first decade of life, and children do not reach adult-like values even at 12 years of age.

When vision was available, there was a significant reduction in the overall amount of rambling trajectory oscillation. Additional information improves the estimation of body dynamics, and consequently, body oscillation is reduced mostly due to the reduction in migration from one equilibrium position to another. Vision also significantly decreased the overall amount of trembling trajectory oscillation, but to a lesser amount compared with the rambling trajectory. Therefore, if the rambling trajectory reflects the difficulty of the central nervous system in acquiring useful information, to determine the reference equilibrium point (Zatsiorsky & Duarte, 2000) when an additional source of information is available, then the effect of such a difficulty in controlling postural sway is diminished or the search of useful information is reduced (Riccio, 1993). If this is the case, it seems unlikely that there is an abrupt change in the sensory integration process throughout the first decade as previously suggested by Woollacott et al. (1987).

Finally, younger children show more difficulty in maintaining body position around their reference points, particularly for the 4-year-olds, compared with the older children (12-year-old) and adults. This difficulty could have less to do with acquiring and using sensory information more to do with a noisier system. Conse-
sequently the postural control system would have difficulties in implementing what was planned. In this case, the contribution of such a source error in the system is only manifested in the first years of life, and its contribution to overall body sway is quite small. Actually, as observed for adults (Zatsiorsky & Duarte, 2000), the contribution of sway around the reference points in children is roughly one third of the migration from one reference point to another.

After 8 years of age, the trembling trajectory magnitudes were similar among the ages tested in this study. This indicates similar magnitudes of error between children and adults, due to noise in the postural control system, yet overall body sway is still larger in children. Therefore, even though age-related changes are observed during early ages, the noise in the postural control system due to error regarding planning and implementation seems not to be the main source of difference between postural control in children and adults. The postural control system requires a reliable system regarding what is planned and implemented. Afterward, the development of a stable relationship between sensory information and body control could follow.

Conclusion

Age-related changes in upright postural control were observed throughout the first decade of life with younger children swaying more than older children. In addition, all children tested swayed more than the adults tested. Our results indicated that a larger displacement of the COP is mostly due to the use of sensory information to maintain a stable upright stance without moving as much from one position to another, as inferred by the rambling magnitude COP trajectories. Noise in the postural control system also contributed to the overall displacement of the COP as revealed by the trembling COP trajectories, but age-related differences were no longer observed after 8 years of life even though overall displacement of the COP is still larger than adults. These results suggested that both the use of sensory information and a reduction of noise in the postural control system contribute to developmental changes in postural control, but these processes change in a non-monotonic manner.

References


