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The influence of gaze behaviour on postural control from early childhood into adulthood

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ABSTRACT

In the present study we aimed to track the influence of natural gaze behaviour on postural control from early childhood into adulthood. We measured time series of centre of pressure (COP) as well as head movement in three children groups aged around five ($n = 16$), eight ($n = 15$), and eleven ($n = 14$) and in one group of young adults ($n = 15$) during quiet stance with eyes closed, gaze fixed on a dot, and with gaze shifts between two dots. We adopted magnitude and irregularity of COP displacement as indexes of postural control and cross correlation between COP displacement and target oscillation as an index of the dynamical coupling between the postural and visual systems. Magnitude and irregularity of COP displacement decreased with age, which suggests a steady improvement of postural control from five to beyond eleven years of age. Cross correlations were weak and relative phases highly variable across age groups. Across conditions, and most prominently in the gaze shift conditions, 5-year-olds showed both more head movement and lower postural stability than other age groups. Finally, only in 5-year-olds did we find a marked deterioration of postural stability with gaze shifts. We thus conclude that excessive head movement, particularly during gaze shifts, may be a primary cause of lower postural stability in young children compared to older children and adults.

1. Introduction

Although often taken for granted, postural control is a skill that is basic to many complex motor tasks we perform daily. It is a basic yet complex skill that involves the subtle coordination of many muscles and the meaningful integration of multiple sensory systems. Accordingly, it takes a considerable time to acquire: controlling the standing posture is claimed to be ‘adult-like’ only around 12 years of age [1,2].

In the present study, we address the role of vision in the development of postural control, which has been the subject of great debate in the literature. Some researchers claimed that vision improves postural control more in children than in adults [2–6], while others found that vision improves postural control in adults but not in young children [7–9]. Riach and Hayes [8] even state that vision might hinder postural control in children.

The above studies used a rather crude occlusion paradigm (i.e., eyes open vs eyes closed) to investigate the role of vision in postural control development. To the best of our knowledge, the role of vision in postural control during natural gaze behaviour has not been studied in children. In adults, the role of vision in postural control has been studied in somewhat greater detail. Adult subjects were typically asked to track a moving dot or to shift their gaze between two dots while postural sway was measured as an index for postural stability. Results are highly contradictory: eye movement has been reported to cause increasing body sway [10–12], decreasing body sway [13–15] and unaltered body sway [13,16]. Not surprisingly then, there are also contradictory views on the relationship between vision and postural control. Rey et al. [13] suggest that a decrease of body sway during eye movement indicates a tighter control of posture through greater attentional investment. In line with this suggestion, Stoffregen et al. [14] propose that an important function of postural control is to stabilise the visual system in order to facilitate accurate small gaze movements. Yet Glasauer et al. [10] seem to have quite the opposite in mind when they state that because eye and head movement have a direct influence on posture (i.e., inducing more body sway), the eyes must be moving the body.

Studies on heading in locomotion seem to support this latter view: both in adults [17,18] and children [19], heading changes were found to be initiated by coordinated eye and head movements towards the new direction. However, in such studies, it is

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unclear whether the leading eye movements served navigation, postural control, or both. Hence they remain essentially mute on the issue of whether vision aids postural control or vice versa. Here we focus exclusively on vision's role in postural control (i.e., in quiet standing), and hence might be able to clarify their relationship and its development.

We combined occlusion and gaze shift paradigms – mimicking natural gaze behaviour in everyday life – in children of three equally spaced age groups and in young adults during quiet standing. We measured head movement and ground reaction forces/moments during quiet standing with eyes closed, gaze fixed on a dot, and gaze shifting back and forth between two dots. It was our primary aim to track the development of the influence of natural gaze behaviour on postural control from early childhood into adulthood.

2. Methods

2.1. Participants

Three groups of children (age in years: 5.7 ± 0.58 $n = 16$, 8.3 ± 0.49 $n = 15$ and 11.6 ± 0.58 $n = 14$, respectively) and one group of young adults between 18 and 35 years (28.6 ± 3.43 $n = 15$) took part in the study. All subjects were healthy and had no impairments relevant to the study. Prior to conducting the experiment, all participants as well as the children's parents gave their written informed consent. The local Ethics Committee approved the experiment.

2.2. Procedure

Weight, standing and sitting height and foot length of each participant were measured prior to the experimental protocol. Subsequently, participants were asked to stand barefoot on a force platform (Advanced Mechanical Technology, Inc., Watertown, MA, USA) with arms freely hanging and feet together (i.e., heels and forefoot touching). They were equipped with the following instrumentation: three active position markers attached to the head via a plastic frame (Zebris CMS20S, Medical GmbH), a mobile eye-tracking system (Applied Science Laboratories, Bedford, MA, USA), six wireless bipolar surface EMG electrodes (four on the left leg, one on the stomach and one on the back) (Noraxon, DTS, Scottsdale, AZ, USA) and two electro-goniometers (for left ankle and knee joint, respectively) (Biometrics Ltd., Cwmfelinfach, UK). EMG and goniometer data were not analysed in the present paper and eye tracker data were only used for monitoring participants' compliance with instructions. All equipment was lightweight and hence unlikely to interfere with the experimental tasks.

Then, participants absolved ten experimental conditions, four of which were analysed for the present study: an eyes closed condition (EC), a gaze fixed condition (GF) in which participants fixated a single coloured dot (diameter 5 cm) placed straight ahead and at eye level on a white wall at a distance of 110 cm from their eyes, and two gaze shift conditions in which they shifted their gaze between multiple such coloured dots to the rhythm of a metronome. A frequency of 0.8 Hz was chosen based on results of Stoffregen et al. [14], as well as pilot experiments indicating that this frequency could be comfortably performed by all age groups. The two gaze shift conditions were: shifting gaze horizontally between two dots over a visual angle of 22° (GSH) and shifting gaze vertically over a visual angle of 22° (GSV). The visual angle in conditions GSH and GSV was chosen because an angle of 11° from the centre is considered to be the range in which adults normally perform gaze shifts without head movement [20]. All participants absolved the conditions in the order presented above and performed one 30-second trial in each condition. In each trial, data recording started once the participant was stable in the required posture.

2.3. Data reduction

The ground reaction forces (i.e., F_x, F_y and F_z) and moments (i.e., M_x, M_y and M_z), recorded at 1500 Hz, were smoothed using a moving average with a 150 ms time window. From these smoothed time series, the centre of pressure (COP) pathway was calculated and centred on zero mean. The following outcome measures were determined: COP 95% ellipse area (EA) as an indicator for magnitude of COP movements, sample entropy (SE) as an indicator for the regularity of COP movements, and cross-correlation (CC) and relative phase (RP) between body sway and target oscillation as indicators for the coupling of the visual and postural systems. EA was normalised to each subject's approximate base of support area (calculated as foot length × 75% of foot length) because it is considered scale dependent. For the CC and RP analysis the medio-lateral (ML) and anterior–posterior (AP) direction of COP were analysed separately in order to assess the coupling of ML sway with horizontal and AP sway with vertical gaze shifts. After down-sampling force data to 100 Hz, SE was calculated using the software available at PhysioNet [21]. Optimal values for tolerance range ($r = 0.05$) and template length ($m = 3$) were estimated according to Lake et al. [22]. For each gaze shift condition, the cross correlation sequence was calculated over a range of ±0.625 s (i.e., one target period) and the maximal CC value and corresponding RP were determined. Finally, RP was normalised to range from 0° to 360° for subsequent statistical analysis.

In order to characterise gaze behaviour we determined head movement (HM) as a final outcome measure. HM was calculated from the range-of-motion (ROM) of head roll, yaw and pitch (measured at 60 Hz) as follows: $\mathrm{HM} = \sqrt{\mathrm{ROM}_{\mathrm{roll}}^2 + \mathrm{ROM}_{\mathrm{yaw}}^2 + \mathrm{ROM}_{\mathrm{pitch}}^2}$.

For HM, EA and SE, differences were calculated between the mean of GSH and GSV (further referred to as GS) and GF, as well as between EC and GF. This was done to assess the interaction between age and condition.

2.4. Statistical analyses

In accordance with our primary aim to track developmental changes, we confined our statistical analyses to comparisons between age groups. Given the non-normal distribution of most of our data, we adopted nonparametric tests. For all outcome measures (except RP) in each condition and for ΔHM, ΔEA, and ΔSE between GS and GF and between EC and GF, a Kruskal–Wallis ANOVA was performed, followed by a set of three planned Mann–Whitney *U*-tests: one between 5- and 8-year-olds, one between 8- and 11-year-olds, and one between 11-year-olds and adults. Because these sets were non-orthogonal, Benjamini–Hochberg (BH) corrections were applied to control for α-inflation. This strategy of producing – a priori – a selected set of planned comparisons is advocated by Ruxton and Beauchamp [23]. Differences in RP – a circular variable – between 5- and 8-year-olds, 8- and 11-year-olds, and 11-year-olds and adults were analysed using Watson's U^2 tests.

In all statistical tests, the critical α level was set to 0.05. For measures of effect size, r was calculated as $r = (z/\sqrt{N})$ (where Z is the approximation of the observed difference in terms of the standard normal distribution and N is the total number of samples) in the Mann–Whitney *U*-test, and η^2 was calculated as $\eta^2 = (\chi^2/N - 1)$ (where χ^2 is the test statistic and N is the total number of samples) in the Kruskal–Wallis ANOVA.

3. Results

3.1. Head movement (HM)

Kruskal–Wallis ANOVAs consistently revealed significant effects of age (EC: $\chi^2(3, N = 58) = 42.7$, $p < .001$, $\eta^2 = .75$, GF: $\chi^2(3, N = 58) = 39.7$, $p < .001$, $\eta^2 = .70$, GSH: $\chi^2(3, N = 58) = 34.2$, $p < .001$, $\eta^2 = .6$, GSV: $\chi^2(3, N = 56) = 37.6$, $p < .001$, $\eta^2 = .68$). Planned comparisons (i.e., Mann–Whitney *U*-tests) revealed significant differences between 5-year-olds and 8-year-olds and between 11-year-olds and adults in all conditions (see Table 1). Across conditions, 5-year-olds showed more head movement than 8-year-olds, and 11-year-olds showed more head movement than adults. The latter group hardly displayed any head movement at all during the four analysed experimental tasks (see Fig. 1A).

A Kruskal–Wallis ANOVA revealed a significant effect of age for ΔHM between GS and GF ($\chi^2(3, N = 53) = 23.5$, $p < .001$, $\eta^2 = .45$). Planned comparisons showed ΔHM between GS and GF to be significantly larger in 5-year-olds than in 8-year-olds and larger in 11-year-olds than in adults (see Table 2). The younger group in each comparison showed more head movement in the GS than in the GF condition (see Fig. 1A).

3.2. Normalised 95% ellipse area of centre of pressure displacement (EA)

Kruskal–Wallis ANOVAs consistently revealed significant effects of age (EC: $\chi^2(3, N = 58) = 37.1$, $p < .001$, $\eta^2 = .65$, GF: $\chi^2(3, N = 58) = 45.1$, $p < .001$, $\eta^2 = .79$, GSH: $\chi^2(3, N = 58) = 44.0$, $p < .001$, $\eta^2 = .77$, GSV: $\chi^2(3, N = 56) = 44.1$, $p < .001$, $\eta^2 = .80$). Planned comparisons showed significant differences between 5- and 8-year-olds, between 8- and 11-year-olds and between 11-year-olds and adults in all conditions (see Table 1). The younger group of each comparison showed higher values than the older group: their COP path covered a larger portion of their base of support (see Fig. 1B).

Furthermore, a Kruskal–Wallis ANOVA revealed a significant effect of age for ΔEA between GS and GF ($\chi^2(3, N = 53) = 10.2$,