Published in final edited form as:

Exp Brain Res. 2010 February ; 201(1): 13. doi:10.1007/s00221-009-2001-4.

Head stability during quiet sitting in children with cerebral palsy: effect of vision and trunk support

Sandra Saavedra, Marjorie Woollacott, and Paul van Donkelaar

Department of Human Physiology and Institute of Neuroscience, University of Oregon, Eugene, Oregon, USA

Abstract

Deficits in postural control are one of the hallmarks of disability in children with cerebral palsy. Yet, much remains unknown regarding the etiology of postural deficits in these children. Here we evaluated postural control at a simplified task level by measuring head stability during quiet sitting while systematically manipulating the level of trunk support and vision in 15 children with CP (6–16 years), 26 typically developing (TD) children (4–14 years), and 11 adults. While TD children did not differ significantly from adults, children with CP had greater head movement than adults in both the sagittal and frontal planes under all conditions except frontal plane movement with Torso Support. Vision did not affect head stability in the sagittal plane for any group while it had differential effects on head stability in the frontal plane. Lack of vision improved head stability in adults and older TD children while destabilizing the head in young children (TD and CP) during the most unstable sitting position. Moreover, vision affected children with CP differently depending on their movement disorder. Children with spastic CP performed worse with eyes closed while those with dyskinetic CP had improved head stability with eyes closed. Our results demonstrate that children with mild to moderate CP have deficits in head stability even during quiet sitting.

Keywords

posture control; development

Deficits in postural control are one of the hallmarks of disability in children with cerebral palsy (CP) (Bax, 2005, Rosenbaum et al 2002). One of the primary goals of postural control is to stabilize the head in space (Pozzo et al 1990, Prince et al. 1994, Assaiante & Amblard 1995). The sensory organs for visual and vestibular systems are embedded in the head, making refined head control of critical importance for both orientation and balance. Studies of head control in children with CP have shown increased head movement during transitions between postures (Dan et al 2000), during reaching (Saavedra et al 2009) and even when making visual saccades (Jacobson & Dutton 2000; Good et al 2001; Saavedra et al 2009). Studies of sitting postural control have demonstrated increased sway in the frontal plane in children with spastic CP compared to TD peers during both static and dynamic conditions (Liao et al. 2003b). Studies examining sitting control during surface perturbations have shown that children with spastic CP have increased frequency of antagonist activation, increased number of muscles recruited and a tendency for rostral to caudal muscle recruitment (Brogren et al 1996, 2001). These researchers have suggested that “top down” recruitment of postural muscles may be a strategy used by children with CP to ensure stabilization of the head in space. Taken together these studies indicate that children with CP are unable to adequately stabilize their head in space

during dynamic tasks and this may be related to immature or abnormal patterns of trunk muscle activation.

It is unknown whether head instability in children with CP is related to coordination for dynamic tasks such as reaching or if there is an underlying deficit of postural control that constrains head stability even during quiet sitting. To our knowledge no studies have examined postural constraints in regards to head stability in children with CP. Therefore we have undertaken an evaluation of the contributions of trunk control and vision to head stability during quiet sitting in children with CP. Examination of the mechanisms of postural control at this basic foundational level may yield critical information regarding constraints on postural control in children with CP.

Adults vary the movement patterns of distal joints (Buchanan & Horak 1999, Pozzo et al. 1990, Hsu et al 2007; Nadeau et al. 2003), grade timing and amplitude of trunk muscles (Prince et al. 1994, Winter 1995, de Seze et al 2008), and alter the head/neck control strategy (Nashner 1985, Assaiante & Amblard 1995, Keshner et al. 1999) in order to attenuate head movement during dynamic tasks. Upright control of the head emerges in typically developing (TD) infants at 3–4 months of age. Thelen & Spencer (1998) suggested that head stability is a skill that needs to be relearned or reorganized each time a new balance problem is confronted; yet development of head stability has received relatively little attention from posture control researchers. Little is known about the developmental process in regard to task specific attenuation of head movement until children begin to ambulate.

Ledebt et al (1995) demonstrated that toddlers are able to attenuate the peak-to-peak amplitude of head movement by adjusting the movement patterns of distal joints within 10–15 weeks of the onset of independent ambulation. Assaiante & Amblard (1995) examined head stabilization strategies in TD children and adults and presented evidence of four successive developmental periods. TD children do not approach the full adult like repertoire of head stabilization strategies until after 8 years of age (Assaiante 1998). While these studies have investigated head control in typical children and adults during dynamic activities, and many studies have evaluated steady state postural control using global measures of postural control (center of mass or center of pressure), we are not aware of any studies examining the development of head stability during quiet sitting.

In a previous study of eye-hand coordination we used three postural conditions while sitting on a bench: 1) No Support, 2) Pelvic Support (hip/pelvic strapping system provides stabilization to the legs and aligns the trunk vertically with minimal reduction in degrees of freedom) and 3) Torso Support (vertical alignment with reduced degrees of freedom in the trunk). The results of the previous study suggested that children with CP may have deficits in trunk control (Saavedra et al 2009). The same support conditions were used in this study to examine the contribution of trunk control to head stability. We hypothesized that children with CP as well as young TD children (4–6 yrs) would have immature or deficient trunk control and we predicted that this would result in greater instability of the head in No Support or Pelvic Support conditions and no difference from typically developing older children or adults in head stability when rigid support was provided at the torso.

Ferdjallah et al. (2002) showed that ML and transverse plane motion were significantly increased in young TD children and children with CP during eyes closed testing when standing quietly. Other studies using posturography have shown a significant increase in sway measures with eyes closed while standing on unstable surfaces, with lesser, frequently non-significant changes when standing on stable surfaces with eyes closed (Cherng et al 1999; Liao et al 1997, 2003; Nashner et al 1983). All of these studies used global measures of postural control (COM, COP) and thus did not explicitly examine the effect of vision on head stability. We examined

the contribution of vision to head stability by asking subjects to open or close their eyes during quiet sitting at each level of support. We predicted that the head would be more stable for all subjects with eyes open and that subjects who depended strongly on visual input (younger TD children and children with CP) would have significantly greater instability of the head with eyes closed.

Thus, the primary goal of the current study was to examine the contributions of trunk control and vision to head stability during quiet sitting in children with CP. For this purpose kinematic data was recorded from children aged 4–16 years with and without CP as they sat quietly with eyes open or eyes closed with different levels of external postural support. Results were compared with those from a group of healthy young adults.

Methods

Subjects

Fifteen children with CP (ages 6–16) who were participating in another study were recruited for this study. Data from 11 young healthy adults (ages 22–30) and 26 typically developing children (ages 4–14) was used for comparison. All children who completed the study had parental report of normal or corrected to normal visual acuity. Eligibility criteria for children with CP included: a diagnosis of CP (Gross Motor Function Classification System (GMFCS) I, II or III), ability to sit independently on a bench, and ability to follow simple directions. The Gross Motor Function Classification System classifies the gross motor function of children and youth with cerebral palsy on the basis of their self-initiated movement with particular emphasis on sitting, walking, and wheeled mobility (Palisano et al 2008). Children with more severe motor disability (GMFCS IV and V) were excluded from the current study because they were unable to sit independently on a bench. All children with CP selected for the study were assessed using a complete neurologic and musculoskeletal exam by a board certified neuro-developmental pediatrician. Table 1 shows demographics for the children with CP. History and etiological details were limited in some cases due to children not residing with their birth parents and/or not having MRI reports available. The study was conducted in accord with the declaration of Helsinki guidelines and had ethical approval from the Human Subjects Committee at University of Oregon. Written consent was obtained from participants and/or their legal guardians prior to beginning the data collection.

Experimental Tasks—Magnetic tracking (Ascension Minibird system) was used to collect head sway while the children performed alternating eyes open/eyes closed trials. Sampling frequency was 60 Hz. The magnetic tracking system had a recording volume of 1 m³ with a spatial accuracy of 1.8mm. One sensor was attached to the center of the forehead just above the eyes using a headband. Participants sat on a bench facing a computer screen with feet on the floor or on a stool. They were instructed to “sit still like a statue” with arms folded across their torso. The participant began with fixation on a visual cue and subsequently closed or opened their eyes in response to auditory beeps and disappearance or reappearance of a fixation cue. Each trial consisted of 60 seconds of quiet sitting with alternating eyes open/eyes closed conditions (15 seconds each). An attendant remained in the room with the children to observe and reinforce correct responses. Trials were completed under 3 different levels of external trunk support (Fig. 1). In the No Support condition, participants sat on the bench with no additional support; this allowed evaluation of the child’s most natural, well-practiced responses. In the “Pelvic Support” condition, straps were used to stabilize the thighs and pelvis, and to ensure vertical alignment of the pelvis. In the Torso Support condition, a rigid external support was placed around the trunk at the level of the xiphoid process in addition to the pelvic support straps. The three support conditions were completed in a counterbalanced order across subjects.

This data collection was included during the course of a broader study. The full data collection time was ~ 90 minutes per child. The data collection for this set of experimental tasks was 15 minutes. Due to the length of the total data session we chose to keep this segment minimal. T-tests for each group verified that there were no significant group differences between trial 1 and trial 2 of eyes open or eyes closed. We averaged across the two trials to reduce the effect of intra-subject variability.

Data Reduction

Head movement was digitized for off-line analysis using custom Matlab programs. Data was parsed and segmented (10 sec per condition), by discarding 4.5 sec from the beginning of each condition and .5 sec from the end of each condition to eliminate any transitional instability between eyes open and closed tasks. This resulted in 2 trials for eyes open and 2 trials of eyes closed for each level of support. Trials were discarded if the attendant noted that the child failed to open or close their eyes, failed to keep eyes closed on no vision trials, or turned their head during the trial. During data analysis further trials were discarded if obvious artifacts were present. Data were filtered with a zero lag 4th order low-pass Butterworth filter (cut off frequency 5 Hz) prior to calculating dependent variables. Variables were averaged across trials for eyes open and eyes closed conditions, resulting in 6 trials for each individual. We calculated dependent variables from three types of measurement; 1) a displacement-related measure, root mean square (RMS)), 2) rate-related measures (mean velocity (MV), variability of speed (RMSV), and 3) a frequency-related measure (frequency below which 95% of the power is found (P95)) in sagittal and frontal planes of movement. These variables were used by Maurer and Peterka (2005) when creating their model for interpretation of sway data. Maurer and Peterka's simple model of postural sway can be used to formulate hypotheses regarding the physiological processes that contribute to changes in sway dynamics. They analyzed the relationships between sway measures (which provide only a parametric description of sway) and underlying model parameters (which describe physiologically meaningful features of postural control) and showed that displacement related variables (RMS and others) were positively correlated with time delay and noise level but negatively correlated with stiffness, while rate-related measures (specifically RMSV and MV) were positively correlated with stiffness, time delay and noise. Thus, an increase in active stiffness is associated with decreased amplitude (RMS), paired with increased mean velocity (MV). Similar findings have been demonstrated during instructed trunk muscle co-activation in healthy adults (Reeves et al, 2006). Therefore, if active stiffness is used as a postural control strategy we would expect to see decreased RMS concurrent with increased MV.

Statistical Analysis

Mixed within/between repeated measures ANOVA (SPSS version 17.0) was used to evaluate the effect of vision and support on subjects grouped by age, and diagnosis. CP groups (6–9 years, 10–16 years) were compared with TD children (4–6 years, 7–9 years, 10–14 years) and adults. These age groups were chosen because 4 to 6 and 7 to 9 have been shown to be transitional periods in posture (Woollacott & Shumway Cook 1985) and feedback control (Hay 1981, Kirschenbaum 2001). Typical children age 10 and older have more adult like posture. These age groups allowed us to compare children with CP with same age peer groups, as well as with younger groups to assess the possibility of developmental delay. A priori polynomial contrasts were used to determine the effects of support and UCLA Stats technique for analysis of 3 way interactions was used as needed. Post hoc Tukey tests were used to examine differences between groups and paired t-tests were used to examine differences within groups. Eta square (η^2) was calculated as a measure of effect size. When the data sets lacked sphericity (between group factors had significantly different variances) Greenhouse-Geiser corrections were used to assure validity of effects.

Results

Figure 2 shows group means for each dependent variable as well as statistical results for group effects. For all variables the group effect was due to significant differences between children with CP and adults.

Sagittal Plane

All variables for sagittal plane motion had a main effect of support (AP_MV: $F_{(2,92)}=11.05$ $p<.0005$, $\eta^2=.194$; AP_RMSV: $F_{(2,92)}=4.289$ $p=.024$, $\eta^2=.085$; AP_RMS: $F_{(2,92)}=8.814$ $p<.0005$, $\eta^2=.092$, AP_P95: $F_{(2,92)}=8.204$, $p=.001$, $\eta^2=.151$) and all variables except frequency had a main effect of group (Fig. 2). There were no interactions and no effect of vision. Across all groups and visual conditions, variability of displacement (AP_RMS) and variability of velocity (AP_RMSV) decreased progressively as additional support was provided (AP_RMS: Linear contrast $F_{(1,46)}=13.280$ $p=.001$, $\eta^2=.224$; AP_RMSV: Linear contrast $F_{(1,46)}=7.268$ $p=.01$, $\eta^2=.136$). Speed (AP_MV) and frequency of sway (AP_P95) had similar values for No Support and Pelvic Support and reduced values for Torso Support (AP_MV: Linear contrast $F_{(1,46)}=16.739$ $p<.0005$, $\eta^2=.267$, quadratic contrast $F_{(1,46)}=4.810$ $p=.033$, $\eta^2=.095$; AP_P95: Linear contrast $F_{(1,46)}=8.461$ $p=.006$, $\eta^2=.155$, quadratic contrast $F_{(1,46)}=7.909$ $p=.007$, $\eta^2=.147$).

Overall these results show that for the sagittal plane, measures of variability (AP_RMS and AP_RMSV) decreased progressively as external support was increased while frequency distribution (AP_P95) and speed (AP_MV) decreased primarily in the Torso Support condition. Vision did not influence head stability in the sagittal plane. Children with CP had greater displacement and speed of movement but similar frequency distribution in the sagittal plane when compared to typical subjects (Fig. 2). They were affected similarly to typical subjects by external support and vision.

Frontal Plane

All variables for the frontal plane had interactions except frequency, which had a main effect of support (ML_P95: $F_{(2,92)}=4.388$, $p=.015$, $\eta^2=.087$, quadratic contrast $F_{(1,46)}=5.032$ $p=.03$, $\eta^2=.099$) and no other main effects or interactions.

Across all groups, the effect of support on rate related measures (ML_MV, ML_RMSV) differed depending on vision (support*vision interaction: ML_MV: $F_{(2,92)}=6.084$ $p=.003$, $\eta^2=.117$; ML_RMSV: $F_{(2,92)}=4.853$ $p=.015$, $\eta^2=.095$). Figure 3 shows the mean sway across all groups, demonstrating the vision by support interaction. Head stability improved (all variables decreased) progressively with additional support when vision was present (eyes open: ML_MV: Linear contrast $F_{(1,46)}=32.272$ $p<.0005$, $\eta^2=.412$; ML_RMSV: Linear contrast $F_{(1,46)}=21.132$ $p<.0005$, $\eta^2=.315$) and decreased primarily at the torso level of support when vision was absent (eyes closed: ML_MV: Linear contrast $F_{(1,46)}=7.567$, $p=.008$, $\eta^2=.146$, quadratic contrast $F_{(1,46)}=12.102$ $p=.001$, $\eta^2=.197$; ML_RMSV: Linear contrast $F_{(1,46)}=6.196$, $p=.016$, $\eta^2=.119$, quadratic contrast $F_{(1,46)}=8.555$ $p=.005$, $\eta^2=.166$).

Frontal plane ML_RMS was more complex (Fig. 4a). For this variable the interaction between support and vision differed depending on group (group*support*vision interaction: $F_{(10,92)}=3.596$, $p<.0005$, $\eta^2=.281$). Examination of the data revealed that this was the result of a 2-way interaction (group*vision) that differed depending on the level of support. With No Support the effect of vision depended on group (group*vision interaction: $F_{(5,46)}=2.89$, $p<.025$, $\eta^2=.201$). Paired t-tests revealed that the adults had significantly reduced ML_RMS with eyes closed at this level of support (adult: $t_{(10)}=5.792$, $p<.0005$). No other groups had significant differences in ML_RMS across visual conditions at this level of support. There was a main

effect of group, but there was not a main effect of vision ($p=.511$). In the Pelvic Support condition (Fig 4b) there was a main effect of vision ($F_{(1,46)}=8.254$, $p=.006$, $\eta^2=.152$), a main effect of group ($F_{(5,46)}=5.822$, $p<.0005$, $\eta^2=.388$) and an interaction (group*vision: $F_{(5,46)}=5.246$, $p=.001$, $\eta^2=.363$). Examination of means indicates that younger children (TD4–6, TD7–9 and CP6–9) had increased ML_RMS with eyes closed, while older children (TD10–14, CP10–16) and adults had decreased ML_RMS with eyes closed (Fig. 4b). However, paired t-tests failed to reach significance between vision and no vision for any of the individual groups (TD 4–6 ($t_{(8)}=-1.15$, $p=.13$); TD 7–9 ($t_{(9)}=-.545$, $p=.6$); TD 10–14 ($t_{(6)}=.962$, $p=.37$); adult ($t_{(10)}=.712$, $p=.49$); CP 6–9 ($t_{(4)}=-2.497$, $p=.067$); CP 10–16 ($t_{(9)}=.208$, $p=.84$)). Finally, in the Torso Support condition (Fig. 4c) there was a main effect of vision ($F_{(1,46)}=10.639$, $p=.002$, $\eta^2=.188$), but the interaction and main effect of group failed to reach significance (group*vision: $F_{(5,46)}=2.21$, $p=.07$, $\eta^2=.247$; group $F_{(5,46)}=2.247$, $p=.065$, $\eta^2=.196$). Paired t-tests revealed decreased ML_RMS with eyes closed for the two oldest groups of TD children (TD7–9: ($t_{(9)}=2.892$, $p=.018$); TD10–14: ($t_{(6)}=3.178$, $p=.019$)).

Over all, these results indicate that head stability in the frontal plane is more responsive than that in the sagittal plane to constraints of postural control and vision during quiet sitting. Like the sagittal plane, the pelvic support condition combined with lack of vision was most challenging to head stability (Fig. 3). Head displacement (RMS) most clearly differentiated age- and diagnosis-related differences in the effect of vision and external support. Across visual conditions, children with CP had significantly greater RMS than adults during No Support and Pelvic Support conditions but did not differ significantly with Torso Support. Lack of vision reduced RMS in adults (No Support), TD 7–9 year olds (Torso Support) and TD 10–14 year olds (Torso Support).

Results for children with CP grouped by movement disorder

We grouped children in this study according to age; however one of the hallmarks of CP is heterogeneity and our age groups contained children with a variety of movement disorders. The CP group consisted of eight children with spastic CP (3 hemiplegia, 5 diplegia), four children with ataxic CP, 2 children with dyskinetic CP and one child with mixed spastic and ataxic CP. All of these children had mild to moderate motor disability (GMFCS I, II, or III). Since it is likely that postural control mechanisms vary with the type of movement disorder we investigated the characteristics of head stability within the CP group by repeating the statistical analysis with children grouped according to movement disorder. Since this analysis increases the number of comparisons using the same data we adjusted our alpha to accommodate family-wise error ($.05/3=.0167$). For this analysis group differences were considered significant if p value was .0167 or below. Figure 2 shows group means and group effects for children with CP grouped by diagnosis (*white bars*). Of interest to this study is whether trunk support or vision affect children with CP differently based on their movement disorder.

When grouped by diagnostic category, the main effects of support in sagittal plane and vision*support interactions in the frontal plane were the same as those reported above for the full study in which children with CP were grouped by age (p values ranged from $<.0005$ to .042, effect sizes ranged from .234 to .646). The only difference found in the analysis was for RMS in the frontal plane. For this variable there was a vision by group interaction (ML_RMS: vision*dx_grp interaction, $F_{(2,11)}=13.232$, $p=.001$, $\eta^2=.477$), group, support by vision and support did not reach significance at the adjusted level of $p=.0167$. Figure 5 shows the effect of vision for each group across all levels of support. Since this interaction is well below the necessary corrected alpha of .0167 we evaluated it further. Paired t-tests revealed that RMS decreased for children with spastic CP when vision was present ($t(7)=-2.639$, $p=.033$), while the opposite effect occurred in children with dyskinetic CP and the child with mixed spastic/

ataxic CP. RMS increased in these children when vision was present. However with only 2 children having dyskinetic type movement disorders all information for the dyskinetic group can only be considered descriptive. The children with ataxic CP had no change in RMS across visual conditions ($t(3)=-.313$, $p=.775$).

Overall this additional analysis indicates that spinal control and vision contribute differently to head stability in children with CP depending on the type of movement disorder.

Discussion

Our primary motivation in this study was to investigate the constraints of trunk control on head stability and to determine whether children with CP differed from TD individuals at this basic level of postural control. Children with CP are known to have deficits in head stability during dynamic tasks and to have deficits in postural control during sitting. Our results confirm and expand these findings by providing evidence that children with CP have deficits in head stability even during quiet sitting and that these deficits are modulated by external postural support and vision. In what follows we discuss how the manipulation of postural support and vision affected head stability and how these results relate to previous studies of postural deficits in CP.

EFFECT OF SUPPORT

We predicted that children with CP would have immature or deficient trunk control and that this would result in greater instability of the head in No Support or Pelvic Support conditions and no difference from typically developing peers or adults in head stability when support was provided at the torso. Our prediction was correct for the frontal plane however children with CP had significantly greater amplitude and velocity of head movement in the sagittal plane even with Torso Support. Nevertheless the effect of support was similar. Across all subjects and both planes there was a significant effect of support, with reduced amplitude and velocity of head movement during Torso Support and evidence of active stiffness strategy during Pelvic Support.

Maurer and Peterka (2005) have shown that an increase in active stiffness is associated with decreased amplitude (RMS), paired with increased mean velocity (MV). Our results from the sagittal plane, Pelvic Support condition are consistent with this effect. Across all groups providing such support led to decreased RMS relative to the no support condition while mean velocity (MV) either increased or remained the same. In the frontal plane there was similar evidence of active stiffness during pelvic support with eyes closed for adults and older children (TD 10–14, CP 10–16) but not for younger children (TD 4–6, TD 7–9, CP 6–9) and not for any groups with eyes open. This indicates that vision was adequate to stabilize frontal plane head movement during the pelvic support condition, and that there may be a developmental progression in the ability to use active stiffness for frontal plane stability. It is interesting to note that this is a developmental effect and not related specifically to CP. This may reflect somatosensory or vestibular inefficiency in younger children, or it may imply that the active stiffness strategy in the frontal plane is a more complex motor skill that has not yet fully developed in young children.

Indeed there is support in the literature for sensory developmental refinement of proprioceptive control during stable situations in TD children (Steindl et al 2006, Vaugoyeau et al 2008, Viel et al 2009). Deficits in kinesthesia have been reported in children with CP (Cooper et al 1995, Lesny et al 1993), however a developmental trend for somatosensory refinement has not been demonstrated in children with CP. To our knowledge, the ability to use muscle co-activation for medial-lateral stability has not been investigated in children with or without CP.

It is possible that the command “sit still like a statue” may have increased trunk muscle co-activation and thus increased active stiffness. However, the same command was given to all participants and for all support conditions. Nevertheless, the active stiffness was present only for the pelvic support condition and was present across all groups for the sagittal plane and only the older subjects (adults, TD (10–14), CP (10–16)) for the frontal plane. Thus, we believe that the postural challenge of vertical trunk alignment and not the instruction contributed to the active stiffness strategy.

All measures of head sway (displacement, rate and frequency) were reduced in the Torso Support condition compared to No Support or Pelvic Support across all groups and both planes. We propose that the reduction in sway resulted from biomechanical factors (reduced degrees of freedom, shorter lever arm, reduced intrinsic perturbations that result from respiration, and increased passive stiffness) as well as enhanced somatosensory information through tactile input from the support device (Jeka et al 1994). In spite of reduced biomechanical challenges, children with CP continued to have significantly greater amplitude and velocity of head movement than adults in the sagittal but not the frontal plane. This suggests to us that basic postural mechanisms for head stability in the sagittal plane may be deficient in children with CP and that these deficits are in central control mechanisms, not just related to biomechanical challenges or to trunk motor control.

Evidence exists that children with CP may have deficits in the primary sensory systems that contribute to postural control. In addition to kinesthetic deficits mentioned above, and visual deficits addressed in the next section, there is evidence that children with CP may have vestibular hypofunction (Secretan, 1972; Bodensteiner et al 2003; Chee et al 1978). It has been consistently demonstrated during posturography that sensory conditions in which children must rely primarily on vestibular cues cause instability and frequent falling in children with spastic CP (Cherng et al 1999; Liao et al 1997, 2003; Nashner et al 1983). Postural sway during quiet sitting should be below the sensory threshold for semi-circular canals, however, input from the vestibular otoliths contributes significantly to stability of the head during sitting with eyes closed (Blouin et al 2007). While this data suggests that vestibular sensitivity may constrain postural stability, we are not aware of any research explicitly examining otolith function in children with CP.

In contrast to the sagittal plane, our results for the frontal plane provide evidence that children with CP have deficits in medial-lateral trunk control. These children are capable of better frontal plane head stability when the demands for trunk control are reduced. Previous studies using global (COP) measures of postural control demonstrated greater instability in the frontal plane for children with CP compared to TD peers during quiet sitting and quiet standing (Liao et al 2003b; Ferdjallah et al 2002). Our results expand these findings by demonstrating that medial-lateral trunk movement contributes to increased sway.

EFFECT OF VISION

We predicted that lack of vision would increase postural sway and that subjects who depended strongly on visual input (young TD children and children with CP) would have significantly greater instability of the head when vision was absent. Vision did not affect head stability in the sagittal plane; however, for the frontal plane the response to vision differed depending on level of support and group. We found that vision did not affect head stability for the youngest TD group (Fig. 4) or children with ataxic CP (Fig. 5) at any level of support. Lack of vision resulted in less, not more, sway in the adults and older TD groups with No Support or Torso Support respectively (Fig. 4). A similar effect of reduced sway amplitude with eyes closed was seen in children with dyskinetic CP, while children with spastic CP had increased amplitude of head movement with eyes closed across all levels of support (Fig. 5). This differential effect of vision on sway in children with CP has not previously been reported. It must not be overstated

at this time because of small sample sizes; however, the effect sizes are large and the concept is worthy of future investigation.

Riach & Hayes (1987) showed that young children (< 6 years), unlike older children and adults, swayed less with eyes closed than with visual fixation. They attributed this phenomenon not to improved postural control with eyes closed but to increased sway with eyes open due to difficulty maintaining visual fixation. We suggest that this explanation also applies to our findings of reduced sway with eyes closed in children with dyskinesia. Children with dyskinetic CP have been shown to have dyskinetic eye movements and the additional effort of attempting to control their vision results in increased movement of the body (Jan et al 2001).

While we had predicted increased sway with eyes closed it is interesting to note that only the children with spastic CP had this effect; while TD children had no difference or reduced amplitude of head movements with eyes closed in sitting. This raises questions regarding the efficiency of postural control in children with spastic CP. Could deficits in primary sensory systems for postural control be affecting head stability in children with spastic CP at this foundational level? The stable sitting surface in addition to external supports should have enhanced somatosensory processing, yet children with spastic CP had increased sway with eyes closed across all levels of support, suggesting the possibility of deficits in this system or in the vestibular system. As noted above, longitudinal quantitative studies of sensory perception are lacking in children with CP.

It is known that head stability varies depending on the demands of the task (Assaiante & Amblard 1993, Buchanan & Horak 1999, Keshner et al. 1999). Moving during a static position could be a good strategy to constantly update the stability limits especially when the eyes are closed. However, we have been interpreting less sway as an indication of better control throughout this discussion. We believe that our task instruction of “sit still like a statue” encouraged reduction of sway if it was possible for the control system. In addition we use the response of the adult subjects as a representation the “gold standard” of postural control. Thus, in conditions when adults had reduced sway we use reduced sway as an indication of better control.

Clinical Significance

This study produced new information regarding the effects of vision and postural support on fundamental levels of postural control in children with mild to moderate CP. Recording head kinematics provided more specific information about the mechanisms of trunk control in children with CP and has direct implications for visuomotor skills. Since head movement directly influences visual acuity (Braswell & Rine 2006) we hypothesize that the ability of children to attenuate head movement will have a significant impact on reading, writing and other academic skills. Our results suggest that children with mild to moderate CP may be working harder than their peers to stabilize their vision for academics. Most ophthalmologists evaluate and adjust prescriptions based on head fixed testing. It may be necessary to confirm visual acuity with head free testing to account for the contributions of postural control to acuity in children with mild to moderate CP.

In children with dyskinetic CP oculomotor control may be a primary postural constraint. Assessing postural sway with eyes open and eyes closed may help differentiate those children who are most likely to benefit from training of visual motor skills. Specifically, training visual fixation in children who have reduced sway with eyes closed may contribute to improved head stability and thus to improved postural control.

The Pelvic Support condition used in this study offers a good position from which to assess postural control in children with CP. Previous studies of sitting in children with CP have used

different postures of the legs (straight or crisscross, to accommodate tight hip muscles in children with CP) (Brogren et al 1996, 2001) or different seat inclination angles (Hadders-Algra et al 2007); however, these did not guarantee a vertical alignment of the spine. The current technique gives solid vertical alignment without decreasing the degrees of freedom. It is comfortable and well tolerated by children because it does not require significant hip muscle range of movement.

Limitations

The model of postural control (Maurer & Peterka 2005) that we used in interpreting the physiological meaning of our results was created using sway parameters acquired from COP in standing subjects. We used a smaller pendulum (sitting vs standing) however Reeves and colleagues (2006) also used sitting and showed results consistent with Maurer and Peterka's model for active stiffness. We used a kinematic marker for specific information about head stability while Maurer and Peterka (2005) and Reeves and colleagues (2006) used COP or COM of the entire body. Our interpretation assumes that the relationship amongst the sway variables would be similar whether they were measured globally or locally at the head.

The children evaluated in this study were children with less severe motor deficits (GMFCS I, II and III). Nevertheless these children exhibit deficits in head stability during quiet sitting. It is frequently assumed that children with poor trunk control benefit from additional external support. Further studies are currently under way in our lab to assess the influence of external support on head stability in children with more severe motor deficits (GMFCS IV and V).

Another limitation is that our results are confounded by small sample size and from resampling the data for further exploration of CP postural control mechanisms. Nevertheless the effect sizes are relatively large for these variables, suggesting that robust differences exist. As such, these data support the need for further studies examining basic postural mechanisms for head stability and trunk control in children with CP.

Conclusions

Previous studies have examined postural control in children with CP using global measures of stability. We examined the influence of trunk control on head stability in children with and without CP. To our knowledge, no other studies have looked at such a basic level of postural control. Our results suggest that children with CP may have deficits in basic postural mechanisms for head stability in the sagittal plane and deficits in trunk control that affect head stability in the frontal plane. In addition the influence of vision on frontal plane head stability in children with CP depends on the type of movement disorder (spastic, ataxic, dyskinetic).

Abbreviations

CP	cerebral palsy
TD	typically developing

Acknowledgments

The authors wish to thank Cooper Boydston for providing computer support, Claudia Vincent for providing statistical consultation and Robert Nickel, MD, for neurologic evaluation of subjects. This work was supported by NIH Grant R01NS038714, Marjorie Woollacott, PI.

References

- Assaiante C, Amblard B. Ontogeny of head stabilization in space during locomotion in children- influence of visual cues. *Exp Brain Res* 1993;93(3):499–515. [PubMed: 8519339]
- Assaiante C, Amblard B. An ontogenetic model for the sensorimotor organization of balance control in humans. *Hum Mov Sci* 1995;14:13–43.
- Assaiante C. Development of locomotor balance control in healthy children. *Neuroscience Biobehav Reviews* 1998;22(4):527–532.
- Bax M, Goldstein M, Rosenbaum P, Leviton A, Paneth N, Dan B, Jacobsson B, Damiano D. Proposed definition and classification of cerebral palsy, April 2005. *Dev Med Child Neurol* 2005;47:571–576. [PubMed: 16108461]
- Bernstein, NA. The co-ordination and regulation of movement. In: Whiting, editor. *Human Motor Actions Bernstein Reassessed*. Amsterdam, The Netherlands: Elsevier Science Publishers BV; 1984.
- Bertenthal BI, Boker SM, Xu M. Analysis of the perception-action cycle for visually induced postural sway in 9-month-old infants. *Infant Behav Dev* 2000;23:299–315.
- Blouin J, Teasdale N, Mouchnino L. Vestibular signal processing in a subject with somatosensory deafferentation: the case of sitting posture. *BMC Neurol* 2007;7:25. [PubMed: 17727717]
- Bodensteiner JB, Smith SD, Schaefer GB. Hypotonia, congenital hearing loss, and hypoactive labyrinths. *J Child Neurol* 2003;18(3):171–173. [PubMed: 12731641]
- Braswell J, Rine RM. Evidence that vestibular hypofunction affects reading acuity in children. *Int J of Ped Otorhinolaryngology* 2006;70(11):1957–1965.
- Brogren E, Hadders-Algra M, Forssberg H. Postural control in children with spastic diplegia: Muscle activity during perturbations in sitting. *Dev Med Child Neurol* 1996;38(5):379–388. [PubMed: 8698146]
- Brogren E, Forssberg H, Hadders-Algra M. Influence of two different sitting positions on postural adjustments in children with spastic diplegia. *Dev Med Child Neurol* 2001;43(8):534–546. [PubMed: 11508919]
- Buchanan JJ, Horak FB. Emergence of postural patterns as a function of vision and translation frequency. *J Neurophysiol* 1999;81(5):2325–2339. [PubMed: 10322069]
- Chen LC, Metcalfe JS, Chang TY, Jeka JJ, Clark JE. The development of infant upright posture: sway less or sway differently? *Exp Brain Res* 2008;186:293–303. [PubMed: 18057920]
- Cherng RJ, Su FC, Chen JJ, Kuan TS. Performance of static standing balance in children with spastic diplegic cerebral palsy under altered sensory environments. *Am J Phys Med Rehabil* 1999;78:336–343. [PubMed: 10418839]
- Cherng RJ, Chen JJ, Su FC. Vestibular systems in performance of standing balance of children and young adults under altered sensory conditions. *Percept Motor Skill* 2001;92(3):1167–1179.
- Cooper J, Majnemer A, Rosenblatt B, Birnbaum R. The determination of sensory deficits in children with hemiplegic cerebral palsy. *J Child Neurol* 1995;10(4):300–309. [PubMed: 7594266]
- Dan B, Bouillot E, Bengoetxea A, Noel P, Kahn A, Cheron G. Head stability during whole body movements in spastic diplegia. *Brain and Dev* 2000;22:99–101.
- de Seze M, Falgairolle M, Viel S, Assaiante C, Cazalets JR. Sequential activation of axial muscles during different forms of rhythmic behavior in man. *Exp Brain Res* 2008;185:237–247. [PubMed: 17940760]
- Donker SF, Ledebt A, Roerdink M, Savelsbergh GJP, Beek PJ. Children with cerebral palsy exhibit greater and more regular postural sway than typically developing children. *Exp Brain Res* 2008;184:363–370. [PubMed: 17909773]
- Ferdjallah M, Harris GF, Smith P, Wertsch JJ. Analysis of postural control synergies during quiet standing in healthy children and children with cerebral palsy. *Clin Biomech* 2002;17:203–210.
- Good WV, Jan JE, Burden SK, Skoczinski A, Candy R. Recent advances in cortical visual impairment. *Dev Med Child Neurol* 2001;43:56–60. [PubMed: 11201425]
- Hadders-Algra M, van der Heide JC, Fock JM, Stremmelaar E, van Eykern LA, Otten B. Effect of seat surface inclination on postural control during reaching in preterm children with cerebral palsy. *Phys Ther* 2007;87:861–871. [PubMed: 17472949]

- Hay L. The effects of amplitude and accuracy requirements on movement time in children. *J Mot Behav* 1981;13:177–186. [PubMed: 15213015]
- Hsu WL, Scholz JP, Shoner G, Jeka JJ, Kiemel T. Control and estimation of posture during quiet stance depends on multijoint coordination. *J Neurophysiol* 2007;97(4):3024–3025. [PubMed: 17314243]
- Jacobson LK, Dutton GN. Periventricular leukomalacia: an important cause of visual and ocular motility dysfunction in children. *Survey of Ophthalmology* 2000;45:1–13.
- Jan JE, Lyons CJ, Heaven KB. Visual impairment due to a dyskinetic eye movement disorder in children with dyskinetic cerebral palsy. *Dev Med Child Neurol* 2001;43(2):108–112. [PubMed: 11221897]
- Jeka JJ, Lackner JR. Fingertip contact influences human postural control. *Exp Brain Res* 1994;100:495–502. [PubMed: 7813685]
- Keshner EA, Hain TC, Chen KJ. Predicting control mechanisms for human head stabilization by altering the passive mechanics. *J Vestib Res* 1999;9:423–434. [PubMed: 10639027]
- Kirschenbaum N, Riach CL, Starkes JL. Non-linear development of postural control and strategy use in young children: a longitudinal study. *Exp Brain Res* 2001;140:410–431.
- Ledebt A, Bril B, Wiener-Vacher S. Trunk and head stabilization during the first months of independent walking. *Neuroreport* 1995;6:1737–1740. [PubMed: 8541471]
- Lesny I, Stehlik A, Tomasek J, Tomankova A, Havlicek I. Sensory disorders in cerebral palsy: 2-point discrimination. *Dev Med Child Neurol* 1993;35(5):402–405. [PubMed: 8495821]
- Liao HF, Hwang AW. Relations of balance function and gross motor ability for children with cerebral palsy. *Percept Mot Skills* 2003a;96:1173–1184. [PubMed: 12929770]
- Liao S-F, Yang TF, Hsu TC, Chan RC, Wei TS. Differences in seated postural control in children with spastic cerebral palsy and children who are typically developing. *Am J Phys Med Rehabil* 2003b;82(8):622–626. [PubMed: 12872019]
- Maurer C, Peterka RJ. A new interpretation of spontaneous sway measures based on a simple model of human postural control. *J Neurophysiol* 2005;93:189–200. [PubMed: 15331614]
- Nadeau S, Amblard B, Mesure S, Bourbonnais D. Head and trunk stabilization strategies during forward and backward walking in healthy adults. *Gait Posture* 2003;18:134–142. [PubMed: 14667946]
- Nashner LM. Strategies for organization of human posture. In: Igarashi, M.; Black, FO., editors. *Vestibular and visual control of posture and locomotor equilibrium*. Basel: S Karger; 1985. 1985
- Nashner LM, Shumway-Cook A, Marin O. Stance posture control in select groups of children with cerebral palsy: deficits in sensory organization and muscular coordination. *Exp Brain Res* 1983;49:393–409. [PubMed: 6641837]
- Palisano RJ, Rosenbaum P, Bartlett D, Livingston MH. Construct validity of the expanded and revised Gross Motor Function Classification System. *Dev Med Child Neurol* 2008;50:744–750. [PubMed: 18834387]
- Pozzo T, Berthoz A, Lefort L. Head stabilization during various locomotor tasks in humans: I. Normal subjects. *Exp Brain Res* 1990;82:97–106. [PubMed: 2257917]
- Pozzo T, Berthoz A, Vitte E, Lefort L. Head stabilization during locomotion. Perturbations induced by vestibular disorders. *Acta Otolaryngol S* 1991;481:322–327.
- Prince F, Winter DA, Stergiou P, Walt SE. Anticipatory control of upper body balance during human locomotion. *Gait & Posture* 1994;2:19–25.
- Reeves NP, Everding VQ, Cholewicki J, Morrisette DC. The effects of trunk stiffness on postural control during unstable seated balance. *Exp Brain Res* 2006;174:694–700. [PubMed: 16724177]
- Rose J, Wolff DR, Jones VK, Bloch DA, Oehlert JW, Gamble JG. Postural balance in children with cerebral palsy. *Dev Med Child Neurol* 2002;44:58–63. [PubMed: 11811652]
- Rosenbaum PL, Walter SD, Hanna SE, Palisano RJ, Russell DJ, Raina P, Wood E, Bartlett DJ, Galuppi BE. Prognosis for gross motor function in cerebral palsy. creation of motor development curves. *JAMA* 2002;288(11):1357–1363. [PubMed: 12234229]
- Saavedra S, Joshi A, Woollacott M, van Donkelaar P. Eye-hand coordination in children with cerebral palsy. *Exp Brain Res* 2009;192(2):155–165. [PubMed: 18830589]
- Secretan JP. Vestibular function in cerebral-palsy children. *J Oto-rhinolaryngology* 1972;34(2):111–116.
- Shumway-Cook A, Woollacott MH. The growth of stability: postural control from a developmental perspective. *J Motor Behav* 1985;17(2):131–147.

- Silvies SP, Cholewicki J, Radebold A. The effects of visual input on postural control of the lumbar spine in unstable sitting. *Hum Mov Sci* 2003;22(3):237–252. [PubMed: 12967756]
- Steindl R, Kunz K, Schrott-Fischer A, Scholtz AW. Effect of age and sex on maturation of sensory systems and balance control. *Dev Med Child Neurol* 2006;48:477–482. [PubMed: 16700940]
- Stoffregen TA, Smart LJ, Bardy BG, Pagulayan RJ. Postural stabilization of looking. *J Exp Psych Hum Percept Perform* 1999;25(6):1641–1658.
- Thelen E, Spencer JP. Postural control during reaching in young infants: A dynamic systems approach. *Neuroscience and Biobehavioral Reviews* 1998;22:507–514. [PubMed: 9595562]
- UCLA: Academic Technology Services, Statistical Consulting Group. SPSS FAQ How can I explain a three-way interaction in ANOVA?. [accessed January 9, 2009]. From http://www.ats.ucla.edu/stat/faq/threeway_hand.htm
- Vaugoyeau M, Viel S, Amblard B, Axulay JP, Assaiante C. Proprioceptive contribution of postural control as assessed from very slow oscillations of the support in healthy humans. *Gait Posture* 2008;27:294–302. [PubMed: 17509884]
- Viel S, Vaugoyeau M, Assaiante C. Adolescence: a transient period of proprioceptive neglect in sensory integration of postural control. *Motor Control* 2009;13(1):25–42. [PubMed: 19246776]
- Winter, DA. A.B.C. (Anatomy, biomechanics and Control) of Balance During Standing and Walking. Waterloo Biomechanics, bound at Graphic Services. University of Waterloo; 1995.

1)

Figure 1.

Experimental setup: Children sat in front of a computer monitor in a darkened room, hands folded across their shoulders. Torso Support included hip straps that keep the pelvis aligned vertically and a rigid support around the thoracic spine ~ 1 inch below arm pit. The support bar was removed for Pelvic Support and the straps were released for No Support. Magnetic sensor was attached to a headband.

Figure 2.

Group effects. Group means (across all levels of support and both visual conditions) for all sway parameters in sagittal (left) and frontal (right) planes. Head movement for control group (light gray bars) and children with CP grouped by age (dark gray bars) or grouped by movement disorder (white bars). Error bars, intersubject SE. * indicates $p < .05$.

Figure 3.

Vision by support interaction. Mean sway velocity across all groups, with eyes open (*unfilled circles*) and with eyes closed (*filled squares*) at each level of support. *Error bars*, intersubject SE.

Figure 4. Group means for head displacement (RMS) during a) No Support, b) Pelvic Support and c) Torso Support with eyes open (dark bars) and eyes closed (light bars). Error bars, intersubject SE. * indicates $p < .05$.

Figure 5.

Group means showing effect of vision on sway amplitude across all levels of support. Comparing children with CP grouped by diagnosis with TD children and adults. Eyes open (*light bars*) and eyes closed (*dark bars*). Children with CP grouped by movement disorder, spastic CP (S_CP), ataxic CP (A_CP) and mixed CP with dyskinesia (D_CP). *Error bars*, intersubject SE. * indicates $p < .05$.

Table 1

Demographic data

Subject	age	Sex	Diagnosis	Gestational age	Etiology	GMFCS
1	6 yr 6 mo	F	ataxia	term	unknown	I
2	6 yr 8mo	F	ataxia	term	neonatal seizures, probable neonatal stroke	I
3	15 yr 6 mo	M	ataxia	38 weeks	perinatal asphyxia	I
4	16 yr 8 mo	F	ataxia	term	unknown	III
5	7 yr 2 mo	M	spastic hemiplegia	term	unknown	I
6	7 yr 3 mo	F	spastic hemiplegia	term	perinatal stroke	I
7	9 yr 1 mo	M	spastic hemiplegia	36 wks	Invagination Right hemisphere white matter	I
8	11 yr 7 mo	F	spastic diplegia	premature	unknown	III
9	11 yr 8 mo	M	spastic diplegia	33 wks	Intraventricular hemorrhage	I
10	12 yr 11 mo	F	spastic diplegia	premature	unknown	II
11	14 yr	F	spastic diplegia	premature	Intraventricular hemorrhage	II
12	15 yr 4mo	M	spastic diplegia	premature	Periventricular leukomalacia	I
13	14 yr 6 mo	F	dystonia	unknown	unknown	I
14	15 yr 11mo	M	mixed spastic diplegia/chorea/dystonia	term	post cardiotomy	III
15	11 yr 11 mo	F	mixed spastic hemiplegia /ataxia	36 weeks	third trimester stroke	I