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Segmental contributions to trunk control in children with moderate-to-severe cerebral palsy

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Abstract

Objective—To examine postural constraints in children with moderate-to-severe cerebral palsy using a segmental approach.

Design—quasi-experimental repeated measure study; case series

Setting—Motor control research laboratory

Participants—Fifteen children (4–16 years) with moderate (Gross Motor Function Classification System (GMFCS) IV; n=8; 4 males) or severe (GMFCS V; n=7; 4 males) cerebral palsy.

Interventions—Each child participated in three data collection sessions. During each session, we evaluated postural control for sitting using kinematics and clinical assessments.

Main Outcome Measures—Kinematic data were used to document head alignment and stabilization with external support at four levels (axillae, mid-rib, waist, and hip). Two clinical assessments, the Segmental Assessment of Trunk Control (SATCo) and behavioral assessment for stage of trunk control were also used to compare results for children with cerebral palsy to previous longitudinal data from typically developing (TD) infants (3–9 months of age).

Results—Children with GMFCS V had difficulty aligning and stabilizing their head along the medial-lateral and anterior-posterior axes. External support improved postural control for GMFCS

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V but not for children with GMFCS IV, who had opposite responses to support compared to TD infants.

Conclusions—Children with GMFCS V have limited trunk control but respond to support similarly to young typically developing infants suggesting delayed postural control. Response to external support for children with GMFCS IV suggests a unique strategy for trunk control not observed in typical infants. Overall a segmental approach offers new insights into development of trunk control in children with moderate-to-severe CP.

Keywords

sitting; posture; external support; segmental approach

Children with cerebral palsy (CP) who do not gain independent sitting balance by 4 years of age have poor prognosis for motor skill development^{1,2} and increased risk of secondary deficits³. Yet, very little research has examined postural constraints in children with moderate-to-severe CP.

Previous research exploring sitting performance in children with CP included analysis of: impairments in postural responses due to external perturbations^{4,5}, impairments in anticipatory postural responses during reaching^{6,7} and changes in ground reaction forces during postural adjustments⁸. Impairments such as spasticity, muscle weakness, excessive co-activation of agonist/antagonist muscles, decreased muscle coordination, and decreased response variability contribute to postural deficits in these children. These studies used a single segment model of trunk control and assessed posture with a global parameter (ground reaction force) or by using response to perturbations providing brief glimpses (2–10 sec) of reactive or anticipatory postural control. These paradigms were limited to participants with independent sitting or standing balance because the paradigm required that the participants be able to sit or stand with stability during data collection and prior to the perturbations.

While the information gained is helpful in understanding constraints on posture control in higher functioning children, there is limited applicability for children who have not achieved upright trunk control. These approaches do not tell us how children initially attain upright sitting nor do they provide intermediate measures of trunk control during its development. Innovation is necessary to improve outcomes for children with moderate-to-severe CP (Gross Motor Function Classification System⁹ (GMFCS) level IV-V); however these children are often excluded from posture research¹⁰.

Challenges in conducting research for these children include heterogeneity of the population with varying primary and secondary deficits, difficulty testing postural control in children without adequate control for traditional protocols, and difficulty communicating directions to children with limited language and cognition. Classification with GMFCS has helped overcome problems of heterogeneity while yielding relevant information regarding prognosis and secondary sequelae². Typically developing (TD) infants exhibit limitations of motor control, communication and cognition during the first months after birth that are similar to those seen in children with moderate-to-severe CP; thus we propose that research

designed to evaluate infants could be replicated in these children. Comparison with TD infants allows us to determine if trunk control is ‘delayed’ or ‘different’ in children with CP.

We previously used a segmental approach to evaluate changes in trunk control in TD infants prior to acquisition of sitting¹¹. Our simple, practical method of securing the hips and different trunk segments while evaluating the infant’s ability to vertically align and stabilize the trunk in space showed that developmental changes in stability were specific to the region of the trunk being investigated. For typical infants, the relationship between muscle activation and movement developed through a four stage process, changing from ballistic type movements to smoother muscle activation timed in response to sway, thus improving the maintenance of a vertical posture. In the current study we examine the applicability of this approach to children with moderate-to-severe CP. We sought to answer several questions. Do children with moderate-to-severe CP respond to external support like TD infants, indicating delayed development of trunk control or do they exhibit patterns that differ from TD infants suggesting different strategies for trunk control? Do children with CP, like TD infants, show segmental differences in trunk control?

Methods

To address these questions we stabilized the hips and lower regions of the trunk in vertical alignment and measured the child’s ability to align and stabilize the center-of-mass of the head over the base-of-support. Segmental levels of trunk control were assessed by altering the level of support (axillae, mid-ribs, waist and hips). Three-minute data sets at each support level captured each child’s postural skill repertoire. Analyses of pilot data from 1 data session for 4 subjects, 2 per GMFCS group (IV, V) yielded an average effect size of 0.38 for kinematic variables between levels of support. Using this effect size, an alpha of 0.05 and power of 0.80, G*power showed that a sample size of 12 (6 per group) should yield sufficient power to detect significant differences in the analyses proposed.

Fifteen children (4–16 years, median age 9 yr. 11 mo.) participated in this quasi-experimental repeated measures study. Information about the study was distributed via flyers to school therapists, pediatricians, newsletters and by word of mouth between families and teachers. Twenty-four families responded with interest in the study, 16 met the eligibility criteria (8 in each GMFCS group) and enrolled; however only 15 participated in all 3 data sessions. Eligibility criteria included: diagnosis of CP, GMFCS level IV or V, less than 18 years old, no surgical fixation of the spine, and no uncontrolled seizures. Children with these levels of severity were selected because they have postural control deficits that interfere with independent sitting^{2,10,14}. Participants were assessed using a neurologic and musculoskeletal exam by a neuro-developmental pediatrician (Table 1). The study was conducted in accordance with Declaration of Helsinki guidelines and had approval from the University of Oregon Human Subjects Committee. Written consent was obtained from participants and/or legal guardians before data collection. Data from a longitudinal study using the same protocol with eight TD infants were used for comparison¹¹.

Each child came to the laboratory for testing 3 times (median time between 1st and 3rd test=3 mos.). Kinematic data were collected in each session. Clinical tests of motor ability

(Gross Motor Function Measure, dimension A and B)¹² and the Segmental Assessment of Trunk Control (SATCo)¹³ were completed once for each child.

During kinematic tests, children were seated on a bench, with feet supported, facing a computer monitor. Pelvic strapping¹³ was used to ensure the pelvis remained vertical and was aligned directly below the rigid posterior support. This provided a secure upright position below the level of interest. The support was raised or lowered to allow evaluation of four different trunk segments (cervical-upper thoracic (axillae support), mid-thoracic (midrib support), thoracic-lumbar (waist support) and pelvis (hip support, strapping system only)¹¹ (Fig. 1). To control for operator variability with respect to the external level of fixation the first author always adjusted the support. Adjustment of the level of support required two researchers. One person provided manual support to hold the child's trunk upright and upper trunk aligned over the hips and pelvis. The other researcher adjusted the support device according to the same bony landmarks used for the SATCo. For this study we evaluated four segmental regions of control; cervical and upper thoracic (axillae support), midthoracic (mid-rib support), upper lumbar (waist support) and full trunk control (hip support)¹³. Children were entertained (e.g., video or visual distraction by parent/researcher) and encouraged to sit quietly with spine erect.

Magnetic tracking (Ascension Technology Corp, Burlington, VT) was used to record the child's position. One sensor attached to the forehead using a headband, documented head movement. A second sensor, taped to the spinous process of the 7th cervical vertebrae, documented trunk alignment. Two sensors in neoprene arm-bands were placed on the humerus above the elbow. Before data collection the edges of the trunk support were digitized to document location of the support in relation to head and trunk. Ear traegus position was digitized, allowing transformation of head sensor data to estimated center-of-mass of the head. Sampling frequency was 84 Hz, recording volume 1 m³ and spatial accuracy 1.8 mm.

Data reduction and Analysis

Kinematic data were digitized for off-line analysis using Matlab. Dependent variables were calculated from three minutes of data at each support level. There were four data sets for each of the 3 sessions for participants. In cases when children collapsed to the end of their range and could not right themselves, the researcher assisted return to vertical trunk alignment and released them again. For these trials dependent variables were calculated for each segment of unassisted data that was greater than 10 seconds. The final variable for that level of support was the average value for all unassisted segments. Due to technical problems, 1 child with GMFCS IV had missing data for axillae support during one session.

Data were filtered with a zero-lag fourth-order low-pass Butterworth filter (cut-off frequency 6 Hz) prior to calculating dependent variables. Postural orientation and stability of the trunk were measured by evaluating angular displacement of estimated center-of-mass of the head in relation to a vertical line located at the center of base-of-support (midline). Displacement-related measures [mean angle from midline (°), root mean square (**RMS**) (°)], and rate-related measures [mean speed (°/s), variability of speed (**VSP**) (°/s)], were calculated along the anterior-posterior (**AP**) and medial-lateral (**ML**) axes. Calculation of

angular displacement allowed normalization of data across levels of support and different participant heights. These postural sway parameters have been shown to describe physiologically meaningful features of postural control.²² They were used for analysis in the infant study; therefore using the same parameters will allow comparison between the two studies.

Statistical analysis

Due to repeated measurements for participants, the sessions cannot be assumed to be independent. For example, some participants may have poor ability to align while others have good alignment, regardless of the level of support. This would induce dependence within sessions associated with the same participant. To account for such dependence, a linear mixed model with a random participant intercept was used. The random-intercepts mixed model is an extension of linear regression that allows for dependent data¹⁴. Mixed models were fit using the lme4 package¹⁵ for R¹⁶. Random effects for participant and fixed effects for support and group were included in each model.

To answer the question of whether or not these children responded to external support similarly to TD infants, we tested two models, with and without interaction between group and level of support. If children with CP respond differently to support the interaction model will be stronger, while the no-interaction model will be stronger if there are only main effects of support or group. We used an F-test for nested models to compare the interaction and no-interaction models. Alpha was set at 0.05 for testing interaction models and 0.0125 for determining significance of posthoc tests (familywise error correction for group analysis because four TD groups were used to compare with GMFCS IV and again with GMFCS V).

Results

Results are divided into 3 sections. The first section reports statistical results of comparisons for kinematic measures along ML and AP axes (Table 2). This is followed by comparisons between groups on the segmental assessment of trunk control (SATCo). The final section provides comparison of individuals with CP to TD infants according to previously defined stages of trunk control¹¹. In all three sections we used the same outcome parameters that were used in the previous study of TD infants so that we would be able to compare the performance of children with CP to the trajectory of normal development of trunk control.

Medial-lateral axis

Interaction models were significantly better than non-interaction models for all kinematic variables along the ML axis ($p < 0.05$ for all comparisons). Interactions existed between group and support level along the medial-lateral axis for mean position ($p = 0.009$), mean speed ($p < 0.001$) and variability of position (RMS, $p = 0.011$) and speed (VSP, $p < 0.001$).

Post-hoc analysis revealed that effects of support differed depending on group (Table 3, Fig 1). The GMFCS IV children were aligned closer to midline with reduced variability (RMS and VSP) when support was at the waist or hips compared to axillae. Mean speed was not affected by support level.

Alignment and variability (RMS and VSP) were not significantly affected by support for GMFCS V. However, mean sway speed, similar to TD infants, was faster with support at the hips compared to axillae.

Alignment was not affected by support for TD infants who had achieved independent sitting (TD+1). All other TD groups were aligned closer to midline with support at the axillae compared to waist or hips. All TD groups swayed faster with increased variability (RMS and VSP) at lower support levels compared to axillae.

Thus, for movement along the ML axis, children classified GMFCS V had greater difficulty with alignment and stability than other groups. Like TD infants, children with GMFCS V had increased mean sway speed with support at the hip compared to axillae. The effects of support were opposite for GMFCS IV, who were better aligned and more stable with support at waist or hips compared to axillae while TD infants were more poorly aligned, with greater mean speed and variability at lower levels of support.

Anterior Posterior axis

Interaction models were better than non-interaction models for all kinematic variables along the AP axis ($p < 0.006$ for all). Interactions existed between group and support level along the AP axis for variability of position (RMS, $p < 0.001$), and mean speed ($p = 0.010$). Although the interaction model was better than the non-interaction model the interaction did not reach criteria for significance for mean position ($p = 0.05$) and variability of speed ($p = 0.34$).

Post-hoc analysis showed that mean speed increased with support at the hips compared to axillae for GMFCS V and all TD groups while speed did not change across support levels for GMFCS IV. Children with GMFCS IV had reduced RMS with support at mid-ribs, waist and hips compared to axillae, while RMS increased with hip support for TD-3, TD-2 and TD-1 groups (Table 3, Fig 1).

Thus, for movement along the AP axis, children with GMFCS V had greater difficulty with alignment and stability of the head than other groups. Like TD infants, children with GMFCS V had increased mean speed when support was at the hip compared to axillae. The effects of support were opposite for children with GMFCS IV, who had reduced RMS with lower levels of support while infants (TD-3, TD-2, and TD-1) showed increased RMS with support at the hip compared to axillae.

Segmental Assessment of Trunk Control

The GMFCS V group had significantly lower static SATCo scores than GMFCS IV and TD groups, lower active scores than TD groups and lower reactive scores than TD-2, TD-1 and TD+1. The GMFCS IV group had significantly lower static, active and reactive SATCo scores than TD-1 and TD+1 (Table 4). Thus, children with GMFCS V lost control at higher levels of the trunk than TD infants while GMFCS IV performed similarly to TD-3 and TD-2 and lost control at higher levels than TD-1 and TD +1.

Behavioral Analysis

Three minute long data sets allowed evaluation of each child's repertoire of responses to the gravitational field. We previously categorized four stages of upright control in TD infants when support was provided at the hip^{11,17}. Figure 2 shows examples of TD infants and children with CP who exhibit clear examples of each stage. Stage 1 consists of forward "collapse" of the trunk (Fig. 2A–B) when the child is released from a vertical position. In stage 2, "rise and fall" the head was primarily forward of midline with brief excursions towards midline (Fig. 2C–D). These children attempted an upright position but could not sustain it. During stage 3, "wobble", children sustained a partially upright position (Fig. 2E–F). Head position and postural activity were more consistent across the 3 minutes and range of movement was more restricted than in previous stages. In the final "functional" stage the head was primarily centered over midline with brief excursions from midline for environmental interactions (Fig. 2G–H).

Using video behavior coding and the AP path of head center-of-mass we categorized the behavioral stage of postural control for children during each session. Table 2 shows stage categorizations for each group. Children with GMFCS IV primarily demonstrated "wobble" similar to TD-1, while children with GMFCS V demonstrated "collapse" or "rise and fall" similar to TD-3.

Discussion

The goal of this study was to examine constraints on trunk control using a segmental approach in children with moderate-to-severe CP. We evaluated postural control as the ability to align and stabilize the center-of-mass of the head over the base of support during sitting. Specific spinal regions were evaluated by adjusting external support across four levels (axillae, mid-ribs, waist, and hips). We compared results for 15 children with CP who had moderate (n=8, GMFCS IV) or severe (n=7, GMFCS V) motor disability with data from TD infants (3–9 months of age) grouped according to developmental timeline (1, 2 or 3 months before onset of independent sitting and within 1 month of independent sitting; TD-3, TD-2, TD-1 and TD+1).

Children with GMFCS V had more difficulty than other groups aligning and stabilizing their head along the ML and AP-axes. Support did not improve their alignment; however their sway speed was reduced along both axes and variability of sway speed was reduced along the AP axis with axillae support compared to hip support. These children performed worse on the SATCo than all other groups, losing control in the cervical or upper thoracic region for static, active and reactive tests. They demonstrated earlier stages of control, similar to TD-3 group by either "collapsing" or attempting to "rise" but being unable to sustain a vertical position. This group of children exhibited delayed segmental postural control compared to TD progression. They showed similar patterns of sway to TD-3 with lower support levels, where TD infants showed greater instability.

Data from our previous infant study suggested that the critical constraint for achieving upright control was the infant's ability to anticipate and grade muscle responses to counteract gravitational torque. Thus, we hypothesized that by the time the "wobble" stage

emerged, and infants could maintain partial trunk verticality, it was evidence of the emergence of a functional network that included an internal representation of upright position. This network would allow infants to respond more quickly when they swayed closer to the edges of postural stability¹¹. The present results suggest that children classified as GMFCS V might not yet have an internal representation of upright position; thus they struggle with alignment regardless of the amount of external support provided. Alternatively, these children might have an internal sense of upright position but lack the motor control to achieve it. Previous studies have described levels of control similar to “collapse” or “rise and fall” in children with severe CP^{18–21}; however these studies were focused on seating systems not on control strategies and used a single-segment trunk model. No previous studies have evaluated segmental trunk control in children with this level of severity.

The effect of external support was opposite for children with GMFCS IV compared to TD infants along ML and AP axes. The GMFCS IV group had better alignment and reduced RMS with lower levels of support while mean sway speed did not change across support levels. In contrast TD infants showed increased sway speed and variability of position (RMS) and speed (VSP), at lower support levels. Children with GMFCS IV lost static, active and reactive control in the middle to lower thoracic region on the SATCo, similar to TD-3 and TD-2. Their postural behavior was predominantly categorized as “wobble”, similar to TD-1. This suggests children with GMFCS IV had developed a functional internal model or process for maintaining upright control; however they used a different strategy than TDs when attempting to sit. We believe these children used a stiffness strategy to remain upright. They demonstrated loss of control on the SATCo in the thoracic region, yet had better alignment and reduced RMS when external support was lower (waist or hips). Findings of reduced RMS at lower support levels without corresponding reductions in mean sway speed are consistent with active trunk stiffness^{22,23}. These findings are also consistent with research showing reduced response variability in children with CP compared to TD children²⁴. Since the children in the GMFCS IV group were predominantly children with spastic CP it is possible that the additional stiffness at lower levels of support could be due to increased muscle spasticity. Another contributing factor could be their use of a stiffness strategy of co-contracting trunk muscles to improve stability; this strategy is often used by individuals who are not proficient in skilled postural control.

Limitations

The age range of the children with CP was broad. However, the children were selected by GMFCS level and gross motor skills are not expected to change significantly in children with these levels of severity beyond 5 years of age². Differences between the GMFCS levels may have been influenced by heterogeneity of motor disorders in the two groups. Seven out of eight children in the GMFCS IV had spastic or mixed spastic dystonic movement disorders, while only four out of seven children in the GMFCS V group had spastic movement disorder. Future studies with larger cohorts may help to determine the contribution of different types of movement disorder to segmental development of trunk control. This study was descriptive, testing hypotheses about similarities and differences between TD infants and children with moderate to severe CP when trunk control was

examined segmentally. Nevertheless we believe it makes a strong contribution to rehabilitation research because it allows researchers to begin developing and testing hypotheses about the development of postural control prior to the onset of independent sitting.

Conclusions

Children with GMFCS V had limited trunk control but responded to support similarly to young typically developing infants suggesting delayed postural control. Response to external support for children with GMFCS IV suggested a unique strategy for trunk control not observed in typical infants. We believe these results provide support for further research using a segmental approach to evaluate trunk control in children with CP who are unable to sit independently. The segmental approach offers intermediate measures of trunk control and methods for comparison with TD infants.

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Abbreviations

AP	anterior-posterior
CP	Cerebral palsy
GMFCS	Gross Motor Function Classification System
ML	medial-lateral
RMS	root mean square
SATCo	Segmental Assessment of Trunk Control
TD	typically developing
VSP	variability of speed

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Figure 1.

Kinematic responses to different levels of external support for movement along the Medial-Lateral or Anterior-Posterior axis. Groups = children with cerebral palsy, GMFCS level IV or V; typically developing infants 3, 2 or 1 month before onset of independent sitting (TD-3, TD-2, TD-1) or and up to 1 month after onset of stable sitting (TD +1).

Figure 2.

Sway trajectory along AP axis for TD infants (A,C,E,G) and children with CP (B,D,F,H) demonstrating four stages of upright control. Shaded portions of trajectory for A, B indicate time when manual support was given to bring child back to vertical alignment.

Table 1

Participant characteristics.

Diagnosis	Age	GMFCS	MACS	Movement type	Distribution	Gestational Age	Etiology	Visual Deficit	Birth Weight
Cerebral Palsy	7 yrs 5 mo	4	3	Mixed spastic dystonic	quadriplegia	29 wks	Prematurity	Strabismus wears glasses for reading	3 lbs
Cerebral Palsy	8 yrs 10 mo	4	3	Spastic	diplegia	30.5 wks	Prematurity periventricular leukomalacia	Strabismus wears glasses for reading	3 lbs 3 oz
Cerebral Palsy	12 yrs 3 mo	4	3	Mixed spastic dystonic	quadriplegia	30 wks	Prematurity Perinatal asphyxia Listeria monocytogenes infection	Right exotropia	3 lbs 7 oz
Cerebral Palsy	15 yrs 3 mo	4	4	Mixed spastic dystonic	triplegia	28 wks	Prematurity	Strabismus corrected surgically	2 lbs 7 oz
Cerebral Palsy Seizure disorder	8 yrs 7 mo	4	4	Spastic	quadriplegia	27 wks	Prematurity periventricular leukomalacia	Esotropia	2 lbs
Cerebral Palsy Seizure disorder	12 yrs 5 mo	4	4	Spastic	quadriplegia	40 wks	Schizencephaly	wears glasses for myopia	7 lbs 11 oz
Cerebral Palsy	16 yrs 6 mo	4	5	extrapyramidal Dystonic	quadriplegia	42 wks	meconium aspiration Perinatal asphyxia	wears glasses for reading	7 lbs 10 oz
Cerebral Palsy	13 yrs 7 mo	4	5	Mixed spastic dystonic	quadriplegia	40 wks	unknown		8 lbs 10 oz
Cerebral Palsy	6 yrs 5 mo	5	4	Mixed spastic dystonic	quadriplegia	38.5 wks	Nuchal cord Perinatal hypoxia		5 lbs 15 oz
Cerebral Palsy Seizure disorder	11 yrs 1 mo	5	4	Spastic	quadriplegia	32 wks	Prematurity	CVI	5 lbs 10 oz
Cerebral Palsy Seizure disorder	8 yrs 1 mo	5	4	Spastic	quadriplegia	26 wks	Prematurity Intraventricular hemorrhage	Strabismus wears glasses	2 lbs 3 oz
Cerebral Palsy Seizure disorder	8 yrs 2 mo	5	5	Mixed spastic dystonic	quadriplegia	40 wks	meconium aspiration	wears glasses for myopia strabismus	6 lbs 10 oz
Cerebral Palsy Seizure disorder	4 yrs 2 mo	5	5	Hypotonic Mild dystonic	quadriplegia	40 wks	Infantile spasms at 6 mo of age	CVI	7 lbs 7 oz
Cerebral Palsy	9 yrs 10 mo	5	5	Mixed extrapyramidal spastic	quadriplegia	40 wks	Basal ganglia injury on MRI		7 lbs 2 oz

Diagnosis	Age	GMFCS	MACS	Movement type	Distribution	Gestational Age	Etiology	Visual Deficit	Birth Weight
Cerebral Palsy Seizure disorder	10 yrs 11 mo	5	5	Extrapyramidal Mixed spastic dystonic chorea	quadriplegia	41 wks	Birth injury		8 lbs 9 oz

GMFCS=gross motor function classification system, MACS = manual ability classification system, wks = weeks, MRI = magnetic resonance image, CVI = cortical visual impairment, lbs= pounds, oz= ounces

Table 2

Group means (**bold**) and standard deviations (*italics*) for kinematic variables by level of support and for Stage of control.

Group	GMFCS IV (n=8) 24 Sessions	GMFCS V (n=7) 21 Sessions	TD-3 (n=8) 18 Sessions	TD-2 (n=8) 16 Sessions	TD-1 (n=8) 16 Sessions	TD+1 (n=8) 16 Sessions
Median Age(range)	12y 6m (7y 5m –16y 4m)	8y 5m (4y 2m – 11y 9m)	4m 14d (97–177 d)	5m 16d (134–206 d)	6m 13d (155–237 d)	7m 12d (183–270 d)
ML axis						
Mean Head Position (° from midline)	L1	6.7 (3.6)	4.1 (2.7)	4.4 (2.3)	3.8 (2.1)	5.3 (2.9)
	L2	7.1 (4.2)	14.3 (10.4)	6.0 (4.4)	5.3 (1.7)	5.7 (1.7)
	L3	5.2 (2.0)	13.1 (6.3)	9.2 (6.4)	5.6 (2.3)	5.5 (2.6)
	L4	4.1 (2.3)	12.8 (5.6)	8.6 (4.3)	6.4 (2.3)	5.9 (2.6)
Variability of position (RMS) (°)	L1	7.6 (3.7)	15.1 (13.3)	6.1 (5.3)	6.6 (4.9)	4.6 (3.4)
	L2	8.1 (4.2)	15.8 (9.9)	10.1 (9.2)	6.8 (3.4)	8.9 (4.0)
	L3	6.5 (2.4)	15.0 (6.2)	15.4 (14.1)	9.3 (4.2)	9.1 (5.4)
	L4	5.2 (2.6)	14.5 (5.8)	13.5 (9.7)	8.2 (2.1)	8.0 (4.6)
Mean speed (°/s)	L1	2.4 (1.6)	5.5 (3.3)	2.5 (1.3)	2.4 (1.0)	2.4 (1.0)
	L2	2.6 (1.6)	6.6 (3.7)	3.0 (1.3)	3.1 (1.0)	3.5 (1.2)
	L3	2.7 (1.5)	6.3 (3.1)	4.1 (1.7)	3.8 (0.8)	3.8 (1.3)
	L4	2.4 (1.1)	7.5 (3.5)	8.5 (2.4)	7.2 (2.0)	5.0 (1.6)
Variability of speed (VSP) (°/s)	L1	4.7 (2.8)	9.7 (5.1)	3.9 (1.7)	3.8 (1.4)	3.9 (1.4)
	L2	4.9 (2.4)	11.1 (5.7)	4.5 (1.8)	4.4 (1.0)	5.6 (2.4)
	L3	4.2 (2.1)	9.8 (4.9)	5.6 (2.2)	4.6 (1.1)	4.8 (1.1)
	L4	3.7 (1.5)	11.2 (5.2)	9.2 (2.5)	7.8 (2.2)	5.5 (1.7)
AP axis						
Mean Head Position (° from midline)	L1	23.4 (8.0)	29.1 (11.7)	19.2 (7.6)	17.7 (6.2)	15.0 (5.3)
	L2	17.4 (7.7)	24.3 (9.7)	15.8 (6.7)	13.9 (5.9)	13.7 (5.3)
	L3	14.1 (7.9)	23.3 (10.2)	12.6 (5.4)	9.2 (2.4)	7.9 (3.4)
	L4	15.6 (6.2)	28.8 (10.5)	23.1 (10.1)	19.3 (5.8)	8.3 (3.0)
Variability of position (RMS) (°)	L1	24.7 (7.7)	30.4 (11.0)	5.3 (1.8)	5.8 (3.2)	7.7 (2.7)
	L2	19.2 (7.5)	26.0 (9.2)	5.9 (4.4)	5.8 (2.0)	7.3 (2.8)
	L3	15.7 (7.9)	25.1 (10.0)	5.8 (2.3)	8.0 (3.8)	8.9 (3.7)

Group	GMFCS IV (n=8) 24 Sessions	GMFCS V (n=7) 21 Sessions	TD-3 (n=8) 18 Sessions	TD-2 (n=8) 16 Sessions	TD-1 (n=8) 16 Sessions	TD+1 (n=8) 16 Sessions
Median Age(range)	12y 6m (7y 5m –16y 4m)	8y 5m (4y 2m – 11y 9m)	4m 14d (97–177 d)	5m 16d (134–206 d)	6m 13d (155–237 d)	7m 12d (183–270 d)
Mean speed (°/s)	L4	16.8 (6.4)	12.9 (5.8)	13.5 (5.7)	9.9 (4.0)	9.7 (4.1)
	L1	2.7 (1.7)	3.7 (1.6)	3.7 (1.6)	3.2 (1.2)	4.3 (1.6)
	L2	3.0 (1.8)	4.1 (1.6)	4.1 (1.4)	4.3 (1.5)	5.0 (1.7)
	L3	3.2 (1.6)	5.0 (2.0)	4.9 (1.7)	4.8 (1.3)	5.1 (1.8)
	L4	3.2 (1.6)	9.6 (4.1)	9.4 (4.3)	7.1 (2.3)	6.8 (2.6)
Variability of speed (VSP) (°/s)	L1	5.1 (2.7)	5.7 (2.0)	5.6 (2.0)	5.2 (1.7)	7.6 (2.7)
	L2	5.4 (2.8)	5.7 (2.1)	5.5 (1.8)	6.1 (2.6)	7.6 (3.3)
	L3	5.3 (2.5)	6.5 (2.4)	6.2 (3.6)	6.0 (1.6)	7.2 (3.2)
	L4	5.1 (2.2)	12.4 (5.7)	11.9 (5.7)	8.1 (2.3)	8.4 (3.4)
Stage of Control						
Collapse		5	6			
Rise & Fall	2	16	11	11	3	1
Wobble	20		1	5	10	8
Functional	2				3	7

GMFCS = Gross Motor Function Classification System. TD-3, TD-2, TD-1 = infants 3, 2 or 1 months before onset of independent sitting. TD+1 = infants within 1 month of achieving independent sitting. ML=medial-lateral; AP=anterior-posterior; Support levels: axillae (L1); midribs (L2), waist (L3) and hips (L4).

Table 3

Post hoc statistical results for group*support interaction. For each group kinematic parameters with support at axillae (L1) were compared to support at midribs (L2), waist (L3) and hips (L4). p-value < 0.0125 is shown in bold font.

Medial Lateral Axis												
Group	Mean angle from midline (°)			Root Mean Square (RMS) (°)			Mean speed (°/s)			Variability of speed (VSP) (°/s)		
	Confidence Interval		p-value	Confidence Interval		p-value	Confidence Interval		p-value	Confidence Interval		p-value
	lower	upper		lower	upper		lower	upper				
GMFCS IV	-1.24	1.74 (L2)	0.74	-0.99	2.04 (L2)	0.53	-0.33	0.58 (L2)	-0.59	-0.71	0.71 (L2)	0.97
	-3.54	-0.47 (L3)	0.008	-3.20	0.004 (L3)	0.038	-0.39	0.54 (L3)	0.73	-1.55	0.084 (L3)	0.033
	-4.27	-1.30 (L4)	<0.001	-4.11	-1.02 (L4)	<0.001	-0.52	0.40 (L4)	0.71	-1.87	-0.44 (L4)	0.003
GMFCS V	-4.45	4.68 (L2)	0.98	-3.78	5.18 (L2)	0.82	-0.44	2.16 (L2)	0.17	-0.69	2.98 (L2)	0.24
	-4.43	4.79 (L3)	0.95	-3.60	5.45 (L3)	0.69	-0.15	2.45 (L3)	0.086	-1.06	2.64 (L3)	0.37
	-4.93	3.72 (L4)	0.88	-4.02	4.52 (L4)	0.93	0.78	3.14 (L4)	0.002	-0.15	3.33 (L4)	0.078
TD-3	-1.69	4.43 (L2)	0.39	-3.68	10.37 (L2)	0.34	-0.55	1.68 (L2)	0.30	-0.65	2.06 (L2)	0.31
	2.75	8.78 (L3)	<0.001	3.24	16.91 (L3)	0.005	0.54	2.73 (L3)	0.003	0.59	3.24 (L3)	0.006
	1.51	7.51 (L4)	0.003	0.10	13.84 (L4)	0.037	5.33	7.50 (L4)	<0.001	4.54	7.23 (L4)	<0.001
TD-2	-0.40	2.35 (L2)	0.15	-1.30	3.85 (L2)	0.31	-0.09	1.64 (L2)	0.073	-0.33	1.76 (L2)	0.16
	0.36	3.10 (L3)	0.012	0.99	6.15 (L3)	0.008	0.25	1.97 (L3)	0.011	-0.28	1.76 (L3)	0.16
	0.82	3.51 (L4)	0.002	-0.36	4.72 (L4)	0.10	3.77	5.45 (L4)	<0.001	2.74	4.78 (L4)	<0.001
TD-1	-0.13	3.42 (L2)	0.68	-1.27	4.91 (L2)	0.230	0.20	1.66 (L2)	0.015	-0.17	1.52 (L2)	0.12
	-0.13	3.57 (L3)	0.64	0.34	6.72 (L3)	0.035	0.81	2.37 (L3)	<0.001	-0.14	1.64 (L3)	0.11
	0.65	4.36 (L4)	0.010	-1.29	5.16 (L4)	0.236	2.88	4.42 (L4)	<0.001	1.54	3.34 (L4)	<0.001
TD+1	-2.00	1.46 (L2)	0.75	1.16	7.28 (L2)	0.006	0.08	1.37 (L2)	0.026	0.31	2.07 (L2)	0.007
	-1.61	1.92 (L3)	0.93	2.50	8.44 (L3)	0.001	0.75	1.99 (L3)	<0.001	-0.04	1.62 (L3)	0.061
	-1.80	1.73 (L4)	0.95	0.34	6.38	0.029	1.93	3.19 (L4)	<0.001	0.59	2.29 (L4)	0.001

Anterior Posterior Axis												
Group	Mean angle from midline (°)			Root Mean Square (RMS) (°)			Mean speed (°/s)			Variability of speed (VSP) (°/s)		
	Confidence Interval		p-value	Confidence Interval		p-value	Confidence Interval		p-value	Confidence Interval		p-value
	lower	upper		lower	upper		lower	upper		lower	upper	
GMFCS IV	-9.26	-3.74 (L2)	<0.001	-8.52	-3.29 (L2)	<0.001	-0.30	0.68 (L2)	0.41	-0.74	0.790 (L2)	0.926
	-12.15	-6.37 (L3)	<0.001	-11.72	-6.39 (L3)	<0.001	-0.21	0.78 (L3)	0.26	-1.03	0.53 (L3)	0.50
	-10.72	-5.13 (L4)	<0.001	-10.39	-5.17 (L4)	<0.001	0.09	1.08 (L4)	0.021	-0.85	0.674 (L4)	0.808
GMFCS V	-10.36	-0.34 (L2)	0.030	-9.77	-0.27 (L2)	0.032	0.064	3.65 (L2)	0.051	-0.44	5.44 (L2)	0.11
	-9.83	0.25 (L3)	0.064	-9.89	0.034 (L3)	0.057	0.017	3.67 (L3)	0.056	-0.51	5.54 (L3)	0.12
	-4.46	4.99 (L4)	0.90	-4.54	4.46 (L4)	0.949	1.51	4.94 (L4)	<0.001	0.84	6.42 (L4)	0.013
TD-3	-7.91	2.09 (L2)	0.249	-2.58	1.97 (L2)	0.75	-1.56	1.81 (L2)	0.85	-2.56	2.05 (L2)	0.80
	-10.16	-0.39 (L3)	0.039	-1.64	2.80 (L3)	0.62	-0.37	2.93 (L3)	0.12	-1.26	3.23 (L3)	0.41
	0.55	10.48 (L4)	0.041	5.60	10.12 (L4)	<0.001	4.58	7.85 (L4)	<0.001	4.88	9.31 (L4)	<0.001
TD-2	-7.33	0.19 (L2)	0.06	-2.58	2.25 (L2)	0.83	-1.08	2.11 (L2)	0.53	-2.19	2.27 (L2)	0.93
	-12.54	-5.00 (L3)	<0.001	-0.79	3.94 (L3)	0.19	-0.54	2.70 (L3)	0.17	-1.58	2.83 (L3)	0.54
	-3.34	4.16 (L4)	0.88	4.64	9.36 (L4)	<0.001	4.05	7.22 (L4)	<0.001	3.87	8.23 (L4)	<0.001
TD-1	-6.70	-0.27 (L2)	0.033	-0.67	2.83 (L2)	0.23	0.09	2.15 (L2)	0.031	-0.40	2.27 (L2)	0.19
	-12.62	-5.74 (L3)	<0.001	0.22	3.97 (L3)	0.021	0.46	2.57 (L3)	0.006	-0.99	1.81 (L3)	0.48
	-8.39	-1.53 (L4)	0.005	2.33	6.03 (L4)	<0.001	2.66	4.82 (L4)	<0.001	1.52	4.37 (L4)	<0.001
TD+1	-3.85	2.00 (L2)	0.51	-3.10	0.83 (L2)	0.26	-0.91	1.21 (L2)	0.75	-2.47	0.76 (L2)	0.31
	-9.87	-4.10 (L3)	<0.001	-0.94	2.88 (L3)	0.29	-0.30	1.76 (L3)	0.18	-2.13	0.97 (L3)	0.42
	-10.07	-4.26 (L4)	<0.001	-0.41	3.41 (L4)	0.13	1.14	3.26 (L4)	<0.001	-1.11	2.07 (L4)	0.51

GMFCS = Gross Motor Function Classification Scale; TD-3, TD-2, TD-1 = infants 3 or more, 2 or 1 months before onset of independent sitting, TD+1 = infants within 1 month of achieving independent sitting defined as ability to sit with hands free of support for 60 seconds or more.

Table 4
Segmental Assessment of Trunk Control (SATCo) scores for participants in each group across all data sessions.

Control Type	GMFCS IV (n=8)	GMFCS V (n=7)	TD-2 (n=8)	TD-1 (n=8)	TD+1 (n=8)	GMFCS IV vs. TD	GMFCS V vs. TD
Static	4.0 (1.1)	2.2 (1.0)	4.7 (1.4)	5.9 (1.2)	7.6 (0.7)	p=0.66 (TD-3) p=0.097 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)	p=0.001 (TD-3) p<0.001 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)
Active	3.0 (1.0)	1.9 (0.9)	4.0 (1.4)	5.2 (1.6)	7.0 (1.3)	p=0.021 (TD-3) p=0.027 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)	p=0.009 (TD-3) p<0.001 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)
Reactive	3.3 (1.0)	2.2 (1.1)	4.3 (1.3)	5.7 (1.0)	6.7 (1.4)	p=0.022 (TD-3) p=0.011 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)	p=0.015 (TD-3) p<0.001 (TD-2) p<0.001 (TD-1) p<0.001 (TD+1)

Static = ability to maintain vertical alignment for 5 sec. or more; Active=ability to maintain vertical alignment while turning the head or reaching with arms; Reactive = ability to maintain or quickly return to vertical when given a nudge. Numerical values are used to indicate group means (**bold**) and standard deviations (*italics*), however SATCo scores are not intended to be numerical evaluations, each number indicates an anatomical segment where control was lost. The values reflect loss of control in the following segments: 1= cervical, 2 = upper thoracic, 3=mid-thoracic, 4= lower thoracic, 5= upper lumbar, 6= lower lumbar, 7 = loss of control with no support, 8= no loss of control.