CONTRIBUTION OF SPINAL SEGMENTS TO CONTROL OF POSTURE DURING TYPICAL AND ATYPICAL DEVELOPMENT

by

SANDRA LEE SAAVEDRA

A DISSERTATION

Presented to the Department of Human Physiology
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

March 2010

UMI Number: 3406850

All rights reserved

INFORMATION TO ALL USERS
The quality of this reproduction is dependent upon the quality of the copy submitted.

In the unlikely event that the author did not send a complete manuscript
and there are missing pages, these will be noted. Also, if material had to be removed,
a note will indicate the deletion.

UMI 3406850
Copyright 2010 by ProQuest LLC.
All rights reserved. This edition of the work is protected against
unauthorized copying under Title 17, United States Code.

ProQuest LLC
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106-1346

University of Oregon Graduate School

Confirmation of Approval and Acceptance of Dissertation prepared by:

Sandra Saavedra

Title:

"Contribution of Spinal Segments to Control of Posture during Typical and Atypical Development,"

This dissertation has been accepted and approved in partial fulfillment of the requirements for the Doctor of Philosophy degree in the Department of Human Physiology by:

Marjorie Woollacott, Chairperson, Human Physiology
Paul van Donkelaar, Member, Human Physiology
Andrew Karduna, Member, Human Physiology
Shawn Lockery, Outside Member, Biology

and Richard Linton, Vice President for Research and Graduate Studies/Dean of the Graduate School for the University of Oregon.

March 20, 2010

Original approval signatures are on file with the Graduate School and the University of Oregon Libraries.

© 2010 Sandra Lee Saavedra

An Abstract of the Dissertation of

Sandra Lee Saavedra for the degree of Doctor of Philosophy

in the Department of Human Physiology to be taken March 2010

Title: CONTRIBUTION OF SPINAL SEGMENTS TO CONTROL OF POSTURE DURING TYPICAL AND ATYPICAL DEVELOPMENT

Approved:____
Dr. Marjorie Woollacott

Trunk control is critical for all functional movement, yet little is known about the development of trunk stability. Previous research considered the trunk to be one rigid segment ignoring the complexity of multiple spinal segments. In healthy adults spinal control is so well orchestrated that this assumption is reasonable; however during development and more specifically in pathological conditions in which spinal control is immature or compromised, this assumption may prevent accurate analysis and/or treatment of the condition.

This dissertation investigates the mechanisms used by typical infants in gaining postural control of spinal segments for independent sitting. Infant data were compared to data from children with cerebral palsy (CP). The contribution of spinal segments was assessed by stabilizing the trunk in vertical alignment with four levels of support (axillae, mid-ribs, waist or hips). Documentation of postural sway of the head reflected the motor control available in the free segments of the spine. Kinematic data were collected bimonthly from 3 to 9 months of age in typically developing infants and 3-4 times over a 4 month time span in children with CP.

The infants' response to external support changed in a non-linear, stage-like fashion as they transitioned from immature to mature spinal control. Head stability emerged first at higher levels of trunk support and gradually progressed in a cephalo-caudal pattern to lower levels of support. Emergence of functional sitting was associated with mastery of postural control in the lower lumbar and pelvic regions of the spine. The severity of CP was related to the level of spinal control achieved. Children with severe CP had control in the cervical or upper thoracic spine while those with moderate CP had control into the mid to lower thoracic spine. In addition, behavioral patterns seen in children with CP were consistent with developmental stages seen in typical infants during acquisition of vertical alignment. These findings challenge the existing clinical practice of evaluating and treating the trunk as a single segment, offer intermediate measures of progression of spinal control and propose that a more specific approach may create the foundation for improved motor outcomes in pathological populations.

CURRICULUM VITAE

NAME OF AUTHOR: Sandra Lee Saavedra

PLACE OF BIRTH: Enterprise, Oregon

DATE OF BIRTH: April 28, 1952

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene
University of Southern California, Los Angeles
Eastern Oregon University, LaGrande

DEGREES AWARDED:

Doctor of Philosophy in Human Physiology, 2010, University of Oregon
Master of Science in Physical Therapy, 1979, University of Southern California
Bachelor of Science in Biology, 1975, University of Oregon

AREAS OF SPECIAL INTEREST:

Rehabilitation of Children with Moderate to Severe Motor Deficits
Typical and Atypical Development of Postural Control

PROFESSIONAL EXPERIENCE:

2006-present *Research Collaboration*: The Movement Foundation, Oswestry, UK, Penelope Butler, PhD. Clinical training study examining effects of Targeted Training for Trunk Control in children with cerebral palsy.

2005-present *Research Collaboration*: University of Queensland, Australia, Sandy Brauer, PhD. Multicenter study of attentional networks in children with cerebral palsy initiated following presentation in Marseille June 2005

2004-2009 Research fellow, University of Oregon, Eugene, OR

2004 Clinical case studies: HORSES, therapeutic riding for children with CP (n=11)

2003 Clinical case studies: "summer camp for lefty", constraint induced movement for children with upper extremity hemiparesis (n=8)

2002 Clinical case studies: body weight support treadmill training for children with CP (n=7)

1997-2002 Clinical case studies: night time threshold electrical stimulation for children with CP (n=5)

1978-2005 Staff therapist positions at: Grande Ronde Hospital in LaGrande OR; Children's Hospital and Medical Center in Seattle, WA; Educational Service Districts in Spokane and Kelso WA, and Salem OR; private children's clinics in Salem, OR and Vancouver WA

GRANTS, AWARDS AND HONORS:

2009 AACPDM student travel scholarship September 2009

2009 Invited speaker, Danish Fysiotherapy conference, Odense, Denmark March 26-28, 2009.

2008 Betty Foster McCue Fellowship May 2008

2007 Oregon Chapter Society for Neuroscience travel award. November 2007

2007 Neuron Award winner Oregon Society for Neuroscience Annual Chapter Meeting. March 2007

2006 National Institute of Health NRSA individual pre-doctoral fellowship through National Institute of Neurologic Disease and Stroke. September, 2006-September 2009

2005 Finalist, Esther Thelen Award for "young and promising researcher" in the field of Developmental Posture Research, ISPGR Marseille, France. June, 2005

PUBLICATIONS:

Butler PB, Saavedra S, Sofranc M, Jarvis S,Woollacott M. (in press), ‘Reliability and validity of the Segmental Assessment of Trunk Control’, *Pediatric Physical Therapy*

Saavedra S, Woollacott M H. 2009, ‘Spinal control in children with cerebral palsy (CP): evidence for specific segmental deficits’, *Developmental Medicine and Child Neurology*, vol. 51, no. S5, pp. 81-82.

Saavedra S, Woollacott M H. 2009, ‘Contributions of spinal segments to trunk postural control during typical development’, *Developmental Medicine and Child Neurology*, vol. 51, no. S5, pp. 82.

Saavedra S, Woollacott M, van Donkelaar P. 2009, ‘Head stability during quiet sitting in children with cerebral palsy: effect of vision and trunk support’, *Experimental Brain Research,* DOI: 10.1007/s00221-009-2001-4.

Saavedra S, Woollacott M H, Sofranac M, Butler P, Jarvis S. 2009, ‘Reliability of the Segmental Assessment of Spinal Control (SASCo)’, *Pediatric Physical Therapy*, vol. 21, no. 1, pp. 128-129.

Saavedra S, Woollacott M, van Donkelaar P. 2009, ‘Eye-Hand Coordination in Children with Cerebral Palsy’, *Experimental Brain Research,* vol. 192, no. 2, pp. 155-165.

Reilly D, van Donkelaar P, Saavedra S, Woollacott MH. 2008, ‘The effects of dual task conditions: the interaction between the development of postural control and executive attention’, *Journal of Motor Behavior,* vol. 40, no. 2, pp. 90-102.

Reilly D, Woollacott MH, van Donkelaar P, Saavedra S. 2008, ‘Dual task effects on postural control in children with cerebral palsy: static stance’, *Archives of Physical Medicine and Rehabilitation,* vol. 89, pp. 834-842.

Van Donkelaar P, Saavedra S, Woollacott MH. 2007, ‘Multiple Saccades are more automatic than single saccades’, *Journal of Neurophysiology,* vol. 97, pp. 3148-3151.

Saavedra S, Woollacott MH, van Donkelaar P. 2007, ‘Effects of Postural Support on Eye Hand Interactions Across Development’, *Experimental Brain Research,* vol. 180, no. 3, pp. 557-567.

Saavedra S, Woollacott M H, van Donkelaar P. 2005, ‘Attentional networks contributing to postural stability during dual tasks in typically developing children and children with cerebral palsy’, *Gait and Posture,* no. 21, pp. S88.

Woollacott MH, Reilly D, Saavedra S, van Donkelaar P. 2005, ‘Attention demands of postural control in typically developing children’, *Gait and Posture,* vol. 21, pp. S4.

ACKNOWLEDGEMENTS

"Whatever you can do or dream you can, begin it.
Boldness has genius, power and magic in it!" --Goethe

The completion of this degree attests to the power and magic of beginning, even if it looks impossible. It is with genuine gratitude and humiliation that I recognize and acknowledge the dedication of so many people who supported me in accomplishing this project. First and foremost my gratitude is extended to my committee. Marjorie Woollacott (my advisor) set a wonderful example with her calm approach, consistent responsiveness, enthusiasm and dedication to helping me accomplish this body of work. Paul van Donkelaar helped me prioritize on those days when it all seemed impossible by convincing me that I can only do two things really well at a time. Andy Karduna brought a sense of humor and perspective to my many moments of panic over not understanding something. Shawn Lockery stepped outside the controlled world of cellular biology and offered tremendously helpful insights into this project. His tireless enthusiasm for science and willingness to invest critical thinking and insights into this project set an example I will spend years striving to emulate. The inspiration for this project came from the work of Penny Butler and Richard Major. I thank them for their willingness to share their ideas and offer critique as the project unfolded. My father Jack Duckett (machinest and inventor) and my friend Bob Collins, (orthotist-prosthetist) were instrumental in helping me design and fabricate the prototype trunk support device. David Senkovitch and Kris Johnson used the prototype to design and create the final fiberglass trunk support that was used in the study. I am deeply grateful for generous assistance from Cooper Boydston, Wayne Manselle, Mike McHorse and Don Pate in helping me resolve numerous computer and technical issues. Bill Roberts, Kip Kellar and Liz Whitchurch devoted time and expertise tutoring me in signal processing. Current and previous members of the motor control lab were generous with advice and support. A special thanks to Jeanne Langan for patience and perseverance in the early years when I needed an abundance of mentoring. These projects would not have been possible without the dedication of my research assistants, especially Francine Porter. A special thank you also goes to Eric Stewart who consistently counseled me to release my ego and stay focused on my purpose and goals. A project of this size takes tremendous dedication and time. That time has to come from somewhere and it is usually from family. This project would not have been worthwhile without the understanding and support of my children, Christina, Miguel and Marisa, my parents and my sisters. They forgave me when I was too busy to attend family events and during my frequent mental absence when we were together. Above all I owe a tremendous debt of gratitude to the parents, infants and children who participated in the lengthy data collection process.

The studies presented in this dissertation were supported through two grants from the National Institute of Health, R01NS038714 to Marjorie Woollocott and an NRSA pre-doctoral fellowship, F31NS056726, to myself. In addition, I received support from a Betty Foster McCue Fellowship and from The Movement Foundation to extend the work for clinical testing.

Dedicated to my father for teaching me the joy of problem solving,
to my children for teaching me to relax and trust what I cannot control,
and to my mother for teaching me not to give up.

TABLE OF CONTENTS

Chapter Page

Chapter Page

Chapter Page

LIST OF FIGURES

Figure Page

CHAPTER V

LIST OF TABLES

Table Page

CHAPTER I

DEVELOPMENT OF TRUNK CONTROL

Imagine sitting at your desk, reading a book and taking notes on your computer. A co-worker walks by with a memo that needs your signature. You look up and exchange greetings, take the memo, sign it and hand it back. Then you reach for your coffee take a sip and return to your work. These “simple” acts of reaching towards an object or shifting gaze from a book to a computer or to the face of a co-worker are carried out effortlessly many times daily. Yet, the ease with which we accomplish these common tasks belies the underlying complexity of sensorimotor transformation necessary in the brain (Ting, 2007). Neuroscientists know that the upright position is never completely stationary, but instead consists of a series of small fluctuations termed postural sway. The dynamics of this sway are modified depending on the task. For instance the visual acuity needed to read small print in a book will result in decreased amplitude and velocity of sway while focusing on a more distant target like the computer screen or our coworker’s face will result in subtle increases in amplitude and velocity of sway (Stoffregen et al., 1998). As our coworker approaches peripheral visual information is transformed from eye-centered to head-centered, body-centered, and finally hand-centered frames of reference (Snyder et al., 2000), allowing us to reorient our face and body towards their approach and to accurately time our reach to coincide with the reach of our co-worker in exchanging the memo. Accurate reaching movements are constrained by the ability to make predictive postural adjustments with the muscles of the trunk to compensate for the forces imposed on the body induced by the displacement of the arm (Bertenthal & von Hofsten, 1998). The end result is a smooth adjustment from focusing on our book to reaching out with accuracy and appropriate timing to grasp the memo at exactly the right moment for hand-off. Indeed, multiple modifications are frequently made to allow for the displacement of the upper extremities as they shift between tasks of turning pages in the book, typing on the keyboard, reaching accurately for the memo or grasping and lifting a cup of coffee. Any instability in the postural responses may end in a dropped memo, missed key stroke or spilt cup of coffee.

Researchers have argued for two primary sensori-motor strategies in solving these task requirements. Both probably operate in conjunction, with the task determining the higher priority. A "top down" organization using visual, vestibular and neck muscle feedback is necessary in order to stabilize the head in space for visual acuity and a "bottom up" organization that uses touch, pressure and muscle feedback from the trunk and extremities is necessary to determine and stabilize the position of the body with regard to the support surface. Interposed between these two extremes of sensory input is the spine. The spine's structure is designed for maximum flexibility, yet it serves as the central core of postural stability. Postural control of the spine creates the foundation not only for the sitting tasks just described but for all upright activities. This critical structure has no inherent mechanical stability and is unable to remain upright without the precise choreography of dozens of active muscles.

In adults and typically developing children, the sensori-motor control of the spine is so well orchestrated that it is an accepted practice to model the trunk as a single segment in postural control studies (Winter, 1995). Thus postural control studies have rarely addressed the musculoskeletal complexity necessary for upright control of the spine. During development of sitting and more specifically in pathological conditions in which spinal stability is immature or compromised, lack of a more detailed analysis of trunk control has prevented accurate analysis and/or treatment of the condition.

This dissertation addresses the contribution of spinal segments to upright control in two groups of children. The normal developmental progression of trunk control is examined in a group of 8 typically developing infants, studied longitudinally from 3 months to 9 months of age. This is the time span during which typical infants learn to sit independently. These results are compared to those found during atypical development by examining upright control in a group of children with cerebral palsy (age 6-16) who have been unable to learn to sit independently. Thus, this dissertation offers some of the first insights into the acquisition of upright control.

Musculoskeletal Complexity of Trunk Control

While posture control research has predominantly modeled the trunk as a single segment, biomechanical studies addressing issues of back pain and injury have focused on the mechanisms influencing spinal stability in specific regions of the spine. These manuscripts form the basis of what is currently known regarding the complexity of sensori-motor interaction necessary for spinal postural control.

The human spine is a mechanically unstable structure that requires constant muscle activation to assume and retain an upright position. The coordination of muscular effort involves active muscle recruitment, active muscle stiffness and reflex responses (McGill, 1998; Panjabi et al., 1989). The recruitment patterns must continually change depending on postural alignment and task (Stokes & Gardner Morse, 2003; Hodges & Gandevia, 2000). The synchrony of balanced stiffness produced by the motor control system is absolutely critical; any one muscle with inappropriate activation amplitude or timing may produce instability. However, just as insufficient stiffness renders the spine unstable, too much stiffness and co-activation imposes excessive forces on the joints and prevents motion (Gardner-Morse & Stokes, 1998). Studies of spinal control in adults have demonstrated consistently recognizable activation patterns for trunk muscles during movements of the lumbar spine with symmetrical and asymmetrical activation of muscles on the left and right side of the body depending on the location of the muscles and the direction and speed of movement (McGill et al., 2003; Peach et al., 1998; Zedka et al., 1998). During dynamic activities the muscles of the spine are temporally activated and graded so as to attenuate accelerations at the head (Prince et al., 1994), thus providing a stable reference for visual and vestibular information.

Adding to the complexity of spinal stability is the fact that trunk muscles are unique in being multifunctional. Coordination of these muscles accomplishes a number of vital functions including: respiration, protective reflexes like sneezing, or coughing, stabilizing the body in space and adjusting that stability for positional changes as well as anticipating and responding to external load requirements, and providing the necessary base of support to stabilize vision. Coordination for these different tasks must allow more than one functional goal to be accomplished at the same time, often by the same muscle (Hodges & Gandevia, 2000; Iscoe, 1998).

Sensory Contributions to Posture Control

Just as there are multiple motor output schemes, there are multiple overlapping sensory inputs that contribute to upright postural control. The three primary sensory systems involved with postural control are the visual system, the vestibular system and the somatosensory system (including joint and tendon receptors, muscle spindles, and cutaneous receptors for touch and pressure). Redundant sensory input is necessary to create stable postural control. No single sensory system is able to unambiguously determine postural information for all dynamic activities. For example, the visual system is capable of relaying information about movement; however if the entire visual field is in motion the visual system is not able to discern whether the body is moving in space or if the body is remaining stationary and the environment is moving past the body. Additional information is necessary from the vestibular system to make this distinction. Likewise if the visual field is not vertically aligned, the visual system cannot independently determine if the body is misaligned, if the head is misaligned, or if the environment is misaligned. Information is required from muscle, joint and tactile pressure receptors to make this distinction. Exactly how the CNS prioritizes information from multiple sensory systems for postural control is unknown (Peterka, 2003; Nashner, 1985; Keshner et al., 1995; Maurer et al., 2006). However, it is known that conflicting sensory information destabilizes posture and can result in aberrant postural adjustments and loss of stability (Lee & Lishman, 1975; Nashner, 1985).

For most of us, the sensory and motor systems of the spine work together with precision, smoothly shifting and adjusting forces from overlapping regions into a seamless, accurate performance. But how does this well orchestrated sensori-motor coordination develop?

Normal Development of Postural Control

Considering the complexity of redundant sensory and motor systems and the lack of mechanical stability in the spine, it is clear that acquisition of upright control is a non-trivial task. Yet typically developing infants master the basics of this control during the span of a mere 6 months.

Previous studies of postural development in infants have focused on three primary areas when assessing motor control; 1) development of muscle synergies for reactive balance responses to external perturbations (Hedberg et al., 2005; Hadders-Algra et al., 1996; Sveistrup & Woollacott, 1996; Woollacott et al., 1987; Harbourne, 1993; Hirschfeld & Forssberg, 1994; Bertenthal et al., 1997), 2) development of muscle synergies for anticipatory balance during learning to reach (van der Fits et al., 1998, 1999; Witherington et al., 2002; Thelen & Spencer, 1998) and 3) development of ground reaction forces for stabilizing the center of mass over the base of support (Harbourne & Stergiou, 2003, 2009). These studies have demonstrated a developmental sequence beginning with highly variable uncoordinated responses in the youngest infants (Hedberg et al., 2004, 2005; Harboune & Stergiou, 2003, 2009; Woollacott et al., 1987). Between

5 and 7 months of age motor responses progress to more consistent activation of synergists, with increased tonic activation and co-activation of agonists and antagonists (Woollacott et al., 1987; Hedberg et al., 2005; Hadders-Algra et al., 1996; Washington et al., 2001). The resulting spinal stiffness is accompanied by decreased amplitude (Bertenthal et al., 1997) and dimensionality (a measure of the number of degrees of freedom in a moving system) (Harbourne & Stergiou, 2003, 2009) of sway and by decreased adaptation to visual perturbation (Bertenthal et al., 1997). By 9-10 months of age infants begin to show phasic responses with increased consistency of adult-like postural synergies (Hadders-Algra et al., 1996; Washington et al., 2001; Woollacott et al., 1987) and are able to adjust these responses according to the speed of perturbation (Hadders-Algra et al., 1996; Bertenthal et al., 1997). All of these studies have considered the trunk to move as a single segment. They have dealt with the lack of trunk control in their subjects by using reclined seating (Woollacott et al., 1987; Bertenthal et al., 1997; van der Fits et al., 1998; 1999a, b), propping on arms (Harbourne & Stergiou, 2003), allowing the infant's spine to collapse and /or holding them up from the chest and releasing the support (Harbourne, 1993, Harbourne & Stergiou, 2003) just prior to surface perturbation (Hedberg et al., 2004, 2005). Therefore these studies have not provided information about how postural control develops within the spinal column.

Thus the exact mechanisms by which typical infants acquire upright stability is unknown. Previous single segment trunk models have not addressed the complexity of sensori-motor learning necessary to control the multiple segments of the spine. None of these studies have examined the development of the "top down" strategy, that is, the ability of the infant to stabilize the head in space. Stability and predictability of head movement is necessary to allow sensory feedback from visual and vestibular systems to build internal frames of reference (Massion, 1998). Therefore assessing the ability of the infant to align and stabilize the head over the base of support is critical to understanding the development of postural control.

The goal of the first study was to examine how postural control was acquired across multiple spinal segments during typical development of sitting balance. Using stability of the head in space as a measure of upright control and an external support device to align the infants vertically and isolate specific spinal segments, changes in postural control were evaluated longitudinally in a group of typically developing infants.

Etiology of Cerebral Palsy

The act of sitting quietly is so stable for most people that they don't consider it a motor activity at all. Imagine not being able to hold your body steady enough to read, to eat or reach for an object or even to make eye contact with your friend. This is nearly unimaginable to most of us. It is the daily experience of children with moderate to severe cerebral palsy (CP).

Cerebral palsy is the most common cause of motor disability in children, with an incidence of 2 to 2.5/1000 live births (Odding et al., 2006; Cans et al., 2004). CP is an "umbrella term" covering a heterogeneous group of motor deficits that occur during the early years of life. Defined as a sensorimotor disorder, CP affects movement and posture; it is due to a "non-progressive disorder of the brain, the result of interference during its development" (Bax et al., 2005). Variability within this population results from extent of injury to the maturing brain, location of damage, developmental time of damage, and life experience.

Several classification systems have been developed to define motor impairment and function within this population. The most broadly used classifications are based on type of motor impairment, topography of limb motor dysfunction (hemiplegia (unilateral impairment of one arm and one leg), diplegia (both legs) and quadriplegia (both arms and both legs)), and severity of motor deficit (GMFCS).

The motor impairment classification is justified by association of injury in specific areas of the brain with specific motor impairment. Children with spastic CP (~70% of the population) usually exhibit damage to the white matter tracks of the corticospinal system often in the region of the internal capsule. These children have a predominant motor dysfunction of spasticity, a velocity dependent increase in motor response that results in increased tonic activation of specific muscle groups, usually extensor muscles in the lower extremity and flexor muscles in the upper extremity. Children with dyskinetic motor impairments (~20% of children with CP) often exhibit damage in the basal ganglia. These children may have mixed degrees of involuntary, writhing type movements, rapid jerking type involuntary movements, or sustained abnormal postures of the head, trunk and/or limbs as well as some degree of spasticity. Ataxic CP (~10% of children with CP) is associated with lesions in the cerebellum, and typically interferes with control of force production. These children characteristically have wide-based stumbling gait patterns and have difficulty with refined posture and balance (Cheney, 1997). In spite of the frequent occurrence of CP, clarification of the synaptic and systems dysfunctions underlying these conditions is not entirely clear (Filloux, 1996). Complicating the picture is the fact that damage to the brain during development is often diffuse, affecting more than one area. Children with CP frequently display characteristics of more than one type of motor impairment and in some cases there is no evidence of a specific brain lesion in a child who displays symptoms of cerebral palsy.

In each type of movement disorder there are deficits of voluntary motor control. Children with dyskinetic CP as well as those with spastic CP have been shown to have difficulty timing the activation of different muscle groups and often display co-activation of agonist/antagonist muscle pairs during postural perturbations. Children with ataxic CP have greater difficulty adapting to the strength of the perturbation and repeatedly over-respond to balance threats (Nashner et al., 1983).

Characterizing children with CP according to topography has been the most commonly used classification clinically. This classification characterizes children according to the parts of the body affected (Rosenbaum, 2002a). Hemiplegia refers to unilateral impairment of arm and leg on the same side. Diplegia consists of motor impairment primarily in the legs but can have some mild limitation in the arms. Quadriplegia has involvement of all four limbs and usually the trunk is functionally compromised. Children with more limb involvement tend to have greater severity of motor impairment.

Classification based on the severity of motor deficit using the Gross Motor Function Classification System (GMFCS) has a level of validity and reliability, which the movement disorder (spastic, ataxic, dyskinetic) and topographical (hemiplegia, diplegia, quadriplegia) classifications do not (Graham, 2001). The GMFCS provides a simple method of classifying children and youth with CP on the basis of functional ability with particular emphasis on sitting, walking, and wheeled mobility (Palisano et al., 1997). There are five levels of severity in the GMFCS ranging from mild impairment (Level I, in which children walk, run and are able to participate in most activities with typical peers) to severe impairment (Level V, in which children require assistance for all activities including mobility in a wheelchair). It is this classification that we find most helpful in examining the acquisition of upright control.

Previous studies of postural control in children with CP have focused on children with mild to moderate CP. They have excluded children at GMFCS level IV and V (nearly 30% of the CP population) from participation in studies because they did not have adequate independent sitting balance. It is these children who are most in need of postural research. The children with CP who participated in the second study of this dissertation all had a diagnosis of quadriplegic CP. Eight children were classified as GMFCS IV and 6 were classified as GMFCS V. Nine children had predominantly spastic CP while the other 5 had predominantly dyskinetic CP.

Development of Postural Control in Cerebral Palsy

Population studies have shown that for children with CP, development of independent sitting balance by 4 yrs of age is a key determinant of independent ambulation and future motor skill development (Wu et al., 2004). Spinal control is a necessary prerequisite to developing independent sitting balance. As such, development of spinal postural control and independent sitting balance is central to the quality of independent functioning that these individuals will achieve throughout their lifetime. Studies of developmental progression in children with CP demonstrate that motor development plateaus early in children with moderate to severe motor deficits (GMFCS level V at 2.8 yrs, GMFCS IV at 3.5 yrs, and GMFCS III at 3.7 yrs) (Rosenbaum et al., 2002b) regardless of the type of movement disorder. Most children with CP at GMFCS levels IV and V (30% of children with CP) are unable to achieve sitting balance.

Previous research that explored sitting performance in children with CP has included: (1) postural responses due to external perturbations (Brogren et al., 1998, 2001); (2) anticipatory postural responses during reaching (Hadders-Algra et al., 1999a,b; Van der Heide et al., 2004, 2005); and (3) changes in ground reaction forces during postural adjustments (Liao et al., 2003). Impairments such as spasticity (a velocity dependent increase in stretch reflexes), muscle weakness, excessive co-activation of agonist and antagonist muscles, decreased coordination of muscles, and decreased variability of responses have been found to constrain postural control in children with CP. While these studies have contributed important information regarding the motor control deficits in children with CP, none have controlled for or evaluated the contributions of different spinal segments to the control of sitting balance. Moreover, selection criteria for these studies included the ability to sit independently. Therefore studies have yet to address the specific constraints on sitting balance for children who have not achieved full postural control of the spine. These studies have in common the use of a single segment model of the trunk and they have all examined the interface of postural control with the environment from a bottom-up approach evaluating trunk and leg muscle reactions to intrinsic (anticipation of reaching) and extrinsic (support surface) perturbations. Acquisition of upright stability of the head, the contributions of spinal segments to trunk control and the specific constraints of postural control in children with moderate to severe disability have not yet been addressed.

Aims of the Dissertation

The overall goal of this research is to understand the mechanisms used by typically developing infants in gaining control of the multiple segments of the spine, to determine whether children with cerebral palsy use similar mechanisms and to apply that knowledge to improving treatment options for balance control in children with cerebral palsy.

The first study addresses the question of how typical infants manage the degrees of freedom problem biomechanically as they acquire upright control of their spine for sitting. Kinematic data were used to examine the acquisition of vertical alignment and development of postural stability along the medial-lateral (ML) and anterior-posterior (AP) axes. Contributions of different segments of the spine to postural control were assessed by using a stabilizing device that combined pelvic strapping with external support to the spinal column. The device blocked movement at and below the level of support while allowing full range of movement to the spinal segments above the support. Documentation of alignment and postural sway of the head reflected the motor control available in the free segments of the spine. Adjusting the height of the support (axillae, mid-ribs, waist, hips) allowed evaluation of specific regions of the spine. Data were collected continuously for 3 minutes at each level of support, thus allowing adequate data to examine the infant's repertoire of motor strategies.

The second study used a cross sectional design to examine the contributions of spinal segments to head stability in children with cerebral palsy who have not yet achieved postural control of the spine for independent sitting. The same methods were used for both studies. Results for children with CP were compared with those from typical infants to determine whether postural control deficits in CP represent developmental delay or unique patterns of motor control.

CHAPTER II

DISSERTATION DESIGN

Figure 1 is a schematic demonstrating our approach to the “problem” of quantifying seated postural control in infants and in children with CP. Following explanation of the experimental design, the implications of the Systems Theory of motor control in regard to this experimental paradigm and methods of interpretation of postural sway data will complete the framework necessary for interpretation of the results of these studies.

The overall goal of the first study was to characterize the progression of upright control in typically developing infants as they gained independent sitting balance. Trunk control requires interaction of a large number of muscles controlling the multi-segmented spine with regions of varying biomechanical complexity. Previous research looking at development of posture has not provided adequate information to allow researchers to understand the process used by typical infants in learning to deal with the biomechanical complexity of the spinal column. Likewise, previous research looking at neuromuscular control of posture has not provided adequate information to allow clinicians to devise effective treatment for children with neuromotor deficits who are not able to deal with the biomechanical complexity of the spinal column. Therefore the goal of the second study was to examine postural responses of children with CP to see the extent to which upright stability had developed in different anatomical regions of the spine and the manner in which this was influenced by the severity of disability.

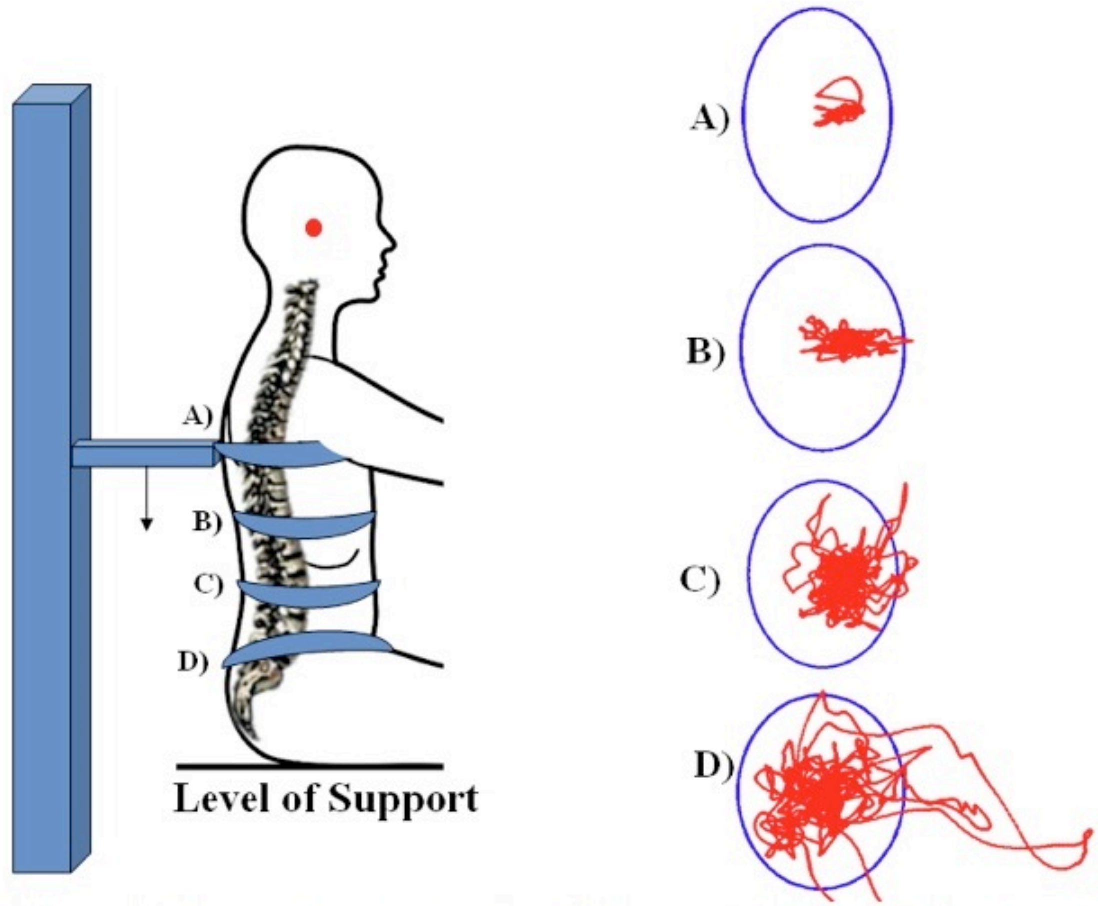

Figure 1. Schematic diagram of research paradigm. Data were collected for 3 minutes at each level of external support: A) axillae, B) mid-ribs, C) waist and D) hips. The number and type of vertebral units varied between levels of support. Center of mass (COM) plots (right column) show movement and alignment of the COM of the head with relation to the base of support *(ellipse)*. These plots were used to characterize upright spinal control at each level of support.

Principle Design Paradigm

In the analytical framework for the proposed study, the spine and head are the primary structures of interest. The initial goal of postural control for independent sitting is to align and stabilize the head vertically over the base of support. The two primary constraints on postural stability are the physical structure of the spinal column and the input from the neuromotor control system.

The physical structure includes the vertebral segments [cervical, thoracic and lumbar vertebrae], the connecting tissues, ligaments and the muscles. The number, shape and connections of the vertebrae determine the degrees of freedom that need to be managed. The alignment, direction of pull, location of attachment, and physical parameters such as the length, strength, stiffness and rate of response of the muscles determine the possible forces that can be used by the neuromotor system to create upright equilibrium. The physical structure was manipulated in this study by applying an external support to stabilize the spine (Fig. 1 A-D). The length of the unsupported spinal column was altered by adjusting the level of external support (at the axillae, mid-ribs, waist and hips). This had the effect of altering the degrees of freedom and placed specific regions of the spine in pivotal positions for controlling the upright column, thereby allowing indirect assessment of the contribution of specific regions to postural stability.

Control mechanism: To achieve the required stability at every instant in time, the neuromotor system must continuously and simultaneously monitor and adjust the forces in each muscle surrounding the spine. Instantaneous decisions must be made to redistribute the tension as the spine sways. Successful spinal control requires that the child activate his/her postural muscles with correct timing to move toward midline or to resist and reverse forces that are moving them away from midline. The stability of the system was affected by the speed and accuracy of postural adjustments as well as the coordination across the different segments. The COM plots in Figure 1 characterize the ability of the postural control system to align and stabilize the head over the base of support.

Systems Theory of Postural Control

Long-established maturational approaches to the study of both typical and atypical motor development used analysis that focused on the maturation of mainly reflex (e.g., spinal stretch reflexes) or voluntarily controlled neural subsystems. A current approach to motor development, the systems approach, extends the previous methods of analysis and considers these neural components in performance with other subsystems, such as the musculoskeletal systems, and also takes into account the relationship between task variables and the demonstrated behavior of the child. In this approach the developing child is considered to be a complex system and the child's behavior is viewed as emergent --being shaped by the changing states of the contributing subsystems and task or environmental components (Thelen & Spencer, 1998; Burtner et al., 1998, 1999, 2007). We used the systems perspective in our approach to the problem of acquisition of upright control or the spine. We manipulated the biomechanical complexity by placing support at different regions of the spine. If the infant is able to control upright posture, we know that visual, vestibular and proprioceptive systems are interacting functionally at that level of the spine. By sequentially manipulating the level of support we are able to examine postural control in different regions of the spine and with different amounts of biomechanical complexity. Thus, the systems perspective allows us to examine the contribution of spinal segments to trunk control across development.

Bernstein's Degrees of Freedom Problem

To maintain upright spinal control, the nervous system must confront the classic "degrees of freedom" problem posed by Nikolai Bernstein (Bernstein, 1967). Bernstein proposed this problem in which many different solutions to a task are available due to the large number of elements (giving many degrees of freedom) that need to be controlled in the system.

In order to remain upright, muscles and joints across the length of the spine must be coordinated to maintain the body's center of mass (COM) over the base of support. The many degrees of freedom afforded by the joints and muscles allow multiple successful solutions to the task of remaining upright. The nervous system has flexibility in choosing the specific muscle activation patterns for performing any given postural task. This redundancy poses a problem to the brain: the nervous system must choose from a large set of possible solutions because individual task requirements are not sufficient to uniquely specify how each joint should be controlled. Bernstein proposed a strategy for simplifying the control of multiple degrees of freedom by coupling, or grouping, output variables (neural commands) at the kinematic level (Bernstein 1967). This scheme was based on experimental observations that multiple joint angles appear to be controlled together, rather than independently, during motor tasks. Indeed task-variables such as the COM trajectory in postural control, and end point trajectory during finger pointing tasks have been shown to be more precisely controlled by the nervous system than individual joint angles (Scholz & Schoner, 1999; Scholz et al., 2000). Thus, the single segment model of trunk control has emerged from observations of adults and children who have achieved upright postural control of the spine. But how does this control develop? Bernstein hypothesized that learning a complex motor task resulted in a pattern of alternately "freezing and releasing" the degrees of freedom as motor control over the individual elements improved. One of the primary questions of this dissertation was to determine whether infants acquire upright control of the trunk by globally activating all muscles across the full length of the spine thereby coupling all joints (as in a single segment model), or if they gain control over a few individual segments at a time (multiple segment model) and gradually work their way across all segments of the spine.

Interpretation of Sway Data

It is well documented that upright static posture is not immobile but results in continual small oscillating movements around the midline. These movements are referred to as postural sway and are used as a measure of postural stability. Interpretation of change in postural sway parameters depends on intrinsic and extrinsic conditions. For example reduction in sway amplitude has been shown to accompany tasks that require precision in visual or manual control but has also been shown in persons with Parkinson's disease due to increased stiffness of muscle responses. Thus a decrease in amplitude of sway may be seen as a positive (improving the task efficiency) or a negative (decreasing flexibility of response) depending on task variables and neural conditions.

Maurer and Peterka (2005) created a simple model of postural sway that 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); they demonstrated that changes in postural sway parameters could be predicted by changes in the control parameters (passive stiffness, active stiffness, sensori-motor gain) of the postural sway model. Postural sway parameters included distance related measures and rate-related measure. Distance related measure included mean distance (MD), the mean absolute value of the time series representing the average distance from the mean, and the root mean square distance (RMS) from the mean (which is equivalent to the standard deviation of the time series from its mean). Rate-related measures included mean velocity (MV), the mean absolute value of the velocity (which was calculated by subtracting consecutive positions of the path and multiplying by the sampling rate), and the root mean square of velocity (RMSV), which is the standard deviation of the velocity time series.

It is possible, using Mauer and Peterka's model, to evaluate the contribution of active stiffness ("freezing degrees of freedom") during acquisition of upright spinal control. Their results demonstrated that distance related measures (MD and RMS) were positively correlated with time delay and noise level, but negatively correlated with stiffness, while velocity related measures (MV and RMSV) were positively correlated with stiffness, time delay and noise level. Active stiffness is unique in producing opposite changes in distance and rate related parameters. If active stiffness is used as a postural control strategy, postural sway parameters would be expected to show decreased RMS concurrent with increased MV. Thus it should be possible in the data from this paradigm to examine whether infants or children with CP actively "freeze" the degrees of freedom of their spine in response to challenging levels of external support.

This information can be used to compare the strategies used by typical infants with those used by children with CP. We used a different MD than that used by Mauer and Peterka. We were interested in understanding how well children are able to align the trunk and head to vertical. Thus we examined the mean position of the COM of the head with regard to the center of the base of support, instead of the mean with relation to the range in the data series. Therefore RMS was the distance-related measure used for stiffness calculations.

CHAPTER III

METHODS

The same general methods have been designed to fulfill both specific aims of the study. The external support device was created to allow expansion form the small circumference of a 3 month infant to adult trunk circumference.

Direct Measurements of Spinal Control

Postural assessment batteries were completed bimonthly for 6 months in typical infants and 2-3 times over a 3-4 month period for each subject with CP. Laboratory test sessions (90-120 minutes) were scheduled to occur at the same time of day for each session whenever possible. The child was positioned on a bench facing a computer monitor. Pelvic strapping and a rigid posterior support that circles the spine and trunk provided upright stability of the spine below the level of interest. The posterior support was adjusted to allow evaluation of 4 different spinal segments (cervical-upper thoracic (under arms), mid-thoracic (midribs), thoracic-lumbar (waist) and pelvis (hips), with segments evaluated in a pseudo-random order. The child was fitted with the Ascension system magnetic field transducers on the head, trunk and arms. Additional markers on trunk and arms provided information regarding potential sources of perturbation to the head. These data were collected in case it was necessary to rule out additional perturbation factors. The data reported in this dissertation were from the sensor on the head band. Kinematic (sampling rate = 84 Hz) and video-tape (sampling rate = 60 Hz) data were collected simultaneously for 3 minutes at each of the 4 levels of support. Hands free spinal control was assessed by encouraging infants and children to raise both arms. In infants this was done by offering toys, while children with CP were instructed to raise both arms and hold them up for three 20-second episodes evenly spaced during the 3 minutes of data collection. Children viewed a video or were visually entertained by parent or researcher during this period of data collection.

Trunk Support Device

In order to use magnetic tracking of the head, a special fiberglass support device was fabricated for use during kinematic evaluation. The posterior support was adjusted to allow evaluation of different spinal segments (cervical-upper thoracic (axillae), midthoracic (midribs), thoracic-lumbar (waist) and pelvis (hips). Figure 1 shows a child in the trunk stabilizing device used for kinematic testing. Accurate evaluation of postural control contributing to upright alignment requires that the spine be upright and stable below the level of interest (Major et al., 2001). The trunk stabilizing device allows rigid positioning of the lower spine and prevents the pelvic misalignment that is common in children with cerebral palsy.

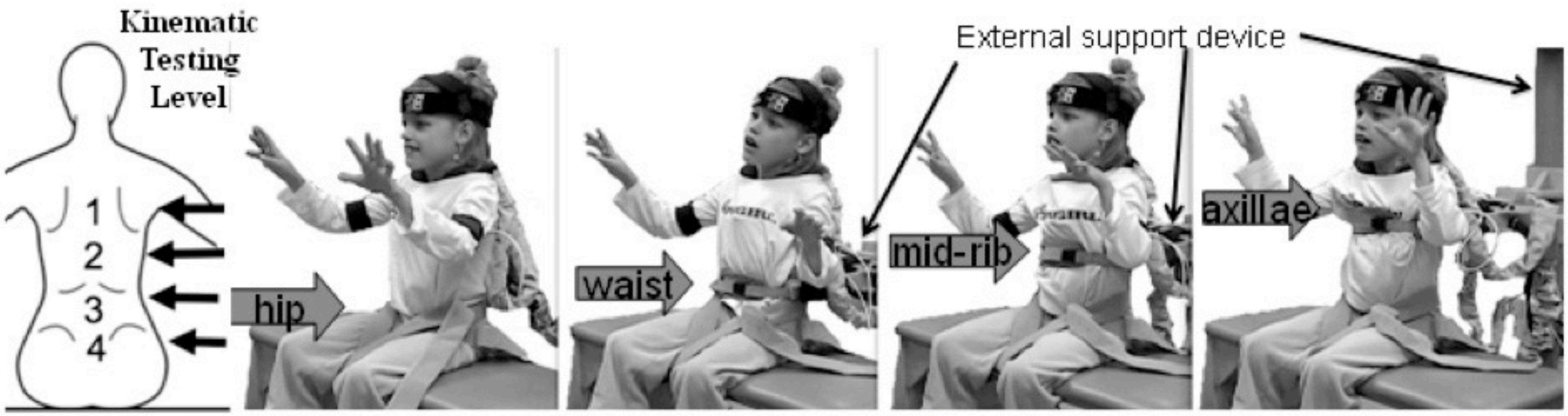

Figure 1. Trunk support device. Four levels of external support held the pelvis and lower spine in vertical alignment. Ability to align and stabilize the head in space was measured with support at 1) axillae, 2) mid-ribs, 3) waist, and 4) hip.

Kinematics

Postural sway was measured using an Ascension Flock of Birds magnetic tracking system. A magnetic field transmitter was placed to the right side of the child's head. One sensor, attached to a head-band was placed on the child's forehead, centered between and just above the eyes. The location of left and right traegus of the ear as well as the canthus of the eye were digitized in relation to the head sensor at the beginning of each assessment to allow transformation of information from the head sensor to COM of the head (Winter et al., 1993). Digitization of anterior/ posterior and lateral edges of the support device at each level of support provided height, location and area of base of support. A second sensor was attached to the back of the child's neck at the level of C7 (7^{th} cervical vertebrae, spinous process) using surgical tape. This allowed differentiation between head movement and trunk movement. Two additional sensors were attached to neoprene arm-bands to provide information regarding arm movements. Only information regarding COM of the head and location and area of the base of support are reported in this dissertation. The magnetic tracking system measures the position and orientation of the sensor with an accuracy of 1 mm and 1° (Ascension Technology Corporation, Burlington, VT). This allowed accurate measurement of the head movement with 6 degrees of freedom. Translational movements were recorded in 3 Cartesian coordinates, x, y and z, as well as angular movements in 3 orthogonal planes, roll, pitch and azimuth. This technology allowed accurate recording of complex movements while imposing only minor constraint on the participant (Peach et al., 1998). Of greatest importance to this study is that it allows accurate recording of small changes in movement without requiring line of sight to the marker. Thus, the researcher or parent could remain in close proximity to the child.

Indirect Measures of Trunk Control

Motor skills and balance abilities were evaluated in all infants and children with CP using validated clinical tests and measures including: the Gross Motor Function Measure (GMFM66) (Russell et al., 2002); the Alberta Infant Motor Scales (AIMS) (Piper et al., 2001); the Pediatric Evaluation of Disability Inventory (PEDI) (Haley et al., 1992), the Segmental Assessment of Trunk Control (SATCo) (Butler, 1998). In addition a timed sitting test was conducted during each laboratory session to determine the efficiency of upright postural control.

All behavioral assessments were scored at the time of the visit and were video taped for later review. Video scoring of GMFM66 and SATCo were completed by a second scorer and the assessment was reviewed if there was a discrepancy between scores.

Gross Motor Function Measure (GMFM 66)

The GMFM66 is a standardized assessment that was designed to measure change in gross motor function over time in children with CP (Russel et al., 1993). It is used in both clinical and research settings. There are 5 subsections of this test: Dimension A (lying and rolling, range 0 to 12), Dimension B (sitting, range 0 to 45), Dimension C (crawling and kneeling, range 0 - 30), Dimension D (standing, range 0 – 39) and Dimension E (walking, running, and jumping, range 0 – 72). Thus the highest score possible on the GMFM 66 is 198. The GMFM is an observational measure designed to score how much of an activity children can accomplish rather than how well the activity is performed. Children are scored only on the movements they demonstrate during the evaluation. We used Dimension A (lying and rolling, range 0 to 12) and Dimension B (sitting skills, range 0 to 45) for this study. A total of 57 points is possible with completion of all items in these two dimensions. Developmental motor curves show that children classified as GMFCS IV reach an average ceiling of 40 points on the total GMFM 66 (all 5 subsets) while those classified as GMFCS V reach an average ceiling of 21 points on the full assessment (Rosenbaum et al., 2002b).

Alberta Infant Motor Scales (AIMS)

The AIMS is an observational tool for measuring motor performance in typically developing infants. It is standardized and norm referenced and has been shown to be a valid, reliable and responsive measure, demonstrating change in gross motor skills in infants from birth through 18 months of age. The measure has 4 subsections in which motor function is observed, and is scored in 4 positions; prone (range 0 - 21), supine (range 0 - 9), sitting (range 0 - 12), and standing (range 0 - 16). The mean score for the AIMS total in the normative sample was 9.8 points at 3 months of age and 39.7 at 8 months of age (Piper and Darrah, 1994).

Segmental Assessment of Trunk Control (SATCo)

The SATCo is a reliable and valid clinical measure of trunk control in TD infants as well as children with neuromotor disability (Butler et al submitted). It provides a discrete assessment from head control through thoracic, lumbar, and finally full spinal control; it documents static, active and reactive control at each level tested. The range on this test is related to the anatomical level of the spine where each aspect of postural control was achieved: 1 = head control, 2 = upper thoracic control, 3 = mid-thoracic control, 4 = lower thoracic control, 5 = upper lumbar control, 6 = lower lumbar control, 7 = pelvic control, 8 = full spine control.

Health Measures and Data Management

Heterogeneity is common in children with CP. Variability within this population results from extent of injury to the maturing brain, location of damage, developmental time of damage, and life experience. While this population is difficult to study due to heterogeneity, the number of possible control strategies for the spine may be the limiting factor in finding statistical results. In order to characterize the etiology of children with CP in the study additional health measures were collected. A Health Questionnaire was completed by the parents or caregivers to obtain demographic information regarding each child (age, gender, and living situation), health status (number of prescriptions and co-morbid health problems), as well as Activities of Daily Living (ADL) status.

Each child with CP received a complete neurological and musculoskeletal evaluation after being accepted into the study. Dr. Robert Nickel, a pediatrician certified in neurodevelopmental treatment performed assessments of musculoskeletal impairments such as reduced range of motion, muscle strength, deficits in the sensory, motor, cerebellar and basal ganglia function. He provided information regarding the diagnostic category, and confirmed the gross motor function classification system level of gross motor ability (GMFCS level).

Data Management for Typically Developing Infants

Laboratory test sessions (90-120 minutes) occurred bimonthly from 3 months to 9 months of age. Kinematic measures of trunk control at 4 levels, SATCo, AIMS and timed sit data were collected on each visit to the lab. In addition to the direct and indirect measures collected in the laboratory, the parents were asked to do a postural control probe (timed sitting test) 2-3 times per week at home. For this test, parents placed the child in sitting with legs in front and timed how long they could stay upright with both hands free. The probe test allowed us to better define changes in infant sitting by tracking multiple sessions between the lab interventions. Parents were provided stop- watches and postcards to report the results of these tests on a weekly basis.

Data Management for Children with Cerebral Palsy

For children with CP, laboratory test sessions (90-120 minutes) occurred on 3-4 occasions 2-4 weeks apart, at the same time of day for each session whenever possible. Kinematic measures of postural control with 4 levels of support, the SATCo, and timed sitting (as described above) were administered at each session. Dimension A and B of the GMFM66, modified Ashworth (test of muscle spasticity) and a range of motion test were administered during one of the 3 sessions

CHAPTER IV

SEGMENTAL CONTRIBUTIONS TO TRUNK CONTROL DURING TYPICAL DEVELOPMENT

Introduction

While postural control of the trunk creates the basis for most functional movement, little is known about how stability of the spine develops. In adults and typically developing children, the sensori-motor control of the spine is so well orchestrated that it is an accepted practice to model the trunk biomechanically as a single segment. Thus postural control studies have rarely addressed the musculoskeletal complexity necessary for upright control of the spine. During development of sitting and more specifically in pathological conditions in which spinal stability is immature or compromised, lack of a more detailed analysis of trunk control may prevent accurate analysis and/or treatment of the condition.

The human spine is a mechanically unstable structure that requires constant muscle activation to assume and retain an upright position. To maintain upright spinal control, the nervous system must confront the classic “degrees of freedom” problem posed by Nikolai Bernstein (Bernstein 1967). Bernstein identified this motor control problem in which many different solutions for the performance of a task are available due to the large number of elements (degrees of freedom) that need to be controlled in the system. The coordination of muscular effort involves a combination of active muscle recruitment, active muscle stiffness and reflex responses (McGill, 1998; Panjabi et al., 1989). The recruitment patterns must continually change depending on postural alignment and task (Stokes & Gardner Morse, 2003; Hodges & Gandevia, 2000). The synchrony of balanced stiffness produced by the motor control system is absolutely critical; any one muscle with inappropriate activation amplitude or timing may produce instability. However, just as insufficient stiffness renders the spine unstable, too much stiffness and co-activation imposes excessive forces on the joints and prevents motion (Gardner-Morse & Stokes, 1998).

How are the muscles organized to orchestrate this complex task? The many degrees of freedom afforded by the joints and muscles of the spine allow multiple successful solutions to the task of remaining upright. Bernstein proposed a strategy for simplifying the control of multiple degrees of freedom by coupling, or grouping, output variables (neural commands) at the kinematic level (Bernstein, 1967). This scheme was based on experimental observations that multiple joint angles appear to be controlled together, rather than independently, during motor tasks. Indeed the COM trajectory in postural control has been shown to be more precisely controlled by the nervous system than individual joint angles (Scholz & Schoner 1999; Scholz et al., 2000). In addition, adults have been shown to couple trunk muscles into a small number of strategies which are used to maintain upright postural alignment under a variety of perturbation directions (Preuss et al., 2009). Thus research on healthy adults suggests that the sensorimotor control of the spine is so well orchestrated that it is reasonable to model the trunk as a single segment for most postural tasks.

Learning upright control of the trunk is a non-trivial problem due to the enormous biomechanical and neural complexity. The task for the young infant is to stabilize the head in space over an inherently unstable, multi-segmented column using an array of overlapping muscles. Activation of any single muscle must be carefully balanced by opposing muscle activity in order to create a stable upright position. Infants must form an internal representation of erect posture, and then they need to learn to scale their motor responses to sensory representation of movement and alignment (Massion, 1998; Hirshfield & Forssberg, 1994). How do infants accomplish this complex learning process?

Typical infants develop upright head control by 3 months of age; trunk control emerges over the next 6 months. By 9-10 months of age infants achieve stable independent sitting. Do infants acquire upright control of the trunk by globally activating all muscles across the full length of the spine, thereby coupling all joints (as in a single segment model) or do they gain control over a few individual segments at a time (multiple segment model) and gradually work their way across all segments of the spine?

Previous studies of typical infants have focused on three primary areas when assessing acquisition of upright control; 1) development of muscle synergies for reactive balance responses to external perturbations (Hedberg et al., 2005; Hadders-Algra et al., 1996; Sveistrup & Woollacott, 1996; Woollacott et al., 1987; Harbourne, 1993; Hirschfeld & Forssberg, 1994; Bertenthal et al., 1997), 2) development of muscle synergies for anticipatory balance during learning to reach (van der Fits et al., 1998, 1999, Witherington et al., 2002; Thelen & Spencer, 1998), and 3) development of ground reaction forces for stabilizing the center of mass over the base of support (Harbourne & Stergiou, 2003). All of these studies have considered the trunk to move as a single segment. They have dealt with the lack of trunk control in their subjects by using reclined seating (Woollacott et al., 1987; Bertenthal et al., 1997; van der Fits et al., 1998 and 1999a, b), propping on arms (Harbourne & Stergiou, 2003), or 3) allowing the infant's spine to collapse and /or holding them up from the chest and releasing the support (Harbourne, 1993, Harbourne & Stergiou, 2003) just prior to surface perturbation (Hedberg et al., 2004, 2005). Therefore these studies have not addressed the complexity of sensori-motor learning necessary to control the multiple segments of the spine and none of these studies have examined the contribution of trunk segments to the acquisition of vertical alignment and stability of the head.

Research on the precise mechanisms by which typical infants initiate and learn to stabilize upright control of the spine is critical to guiding clinicians in developing strategies to assist children with postural dysfunction gain this complex skill. This is of particular clinical importance considering that trunk control is the basis for all functional movement and thus impacts all aspects of daily activities and social interaction.

The goal of the current study was to examine how postural control is acquired across multiple spinal segments during typical development of sitting balance. For this purpose, kinematic data were collected longitudinally (from 3 months to 9 months) in a group of eight typically developing (TD) infants. Stability of the head in space was used as the measure of upright control. To isolate and measure postural control relative to the particular spinal segments of interest, an external support device combined with pelvic straps supported the infants in vertical alignment, blocking movement at and below the level of support while allowing full range of movement to the head and spinal segments above the support.

We predicted that control would vary across different segments with postural control progressing in a cephalo-caudal topography. This would result in greater improvement in postural parameters at higher support levels before improvements were seen at lower levels of support. Thus segments showing improvement would vary from session to session. Alternatively, if control of the trunk is learned as a single unit similar changes in kinematics will occur across all levels of support on a given session.

Methods

Participants

Eight typically developing infants (3-9 months of age) participated in the longitudinal study. Eligibility criteria for infants included: (1) born at term; (2) no prenatal, perinatal or postnatal complications; (3) no known neurological or musculoskeletal abnormalities. The study was conducted in accordance with the declaration of Helsinki guidelines and had ethical approval from the Human Subjects Committee at University of Oregon. Written consent was obtained from the infants' legal guardians prior to beginning the data collection.

Experimental Tasks

Data were collected bimonthly during the 6 month period (3-9 months of age) when TD infants gain control of the trunk for independent sitting. For each wave of assessment, data were collected for 3 minutes of quiet sitting during each of four levels of external support. Infants were securely seated on a bench facing a computer monitor. Pelvic strapping and a rigid posterior support that circled the spine and trunk provided upright stability of the spine below the level of interest. The posterior support was raised or lowered to allow evaluation of four different spinal segments (cervical-upper thoracic (under arms), mid-thoracic (midribs), thoracic-lumbar (waist) and pelvis (hips). Figure 1 shows an infant in the support device adjusted for each level of support. Infants were entertained (e.g., an infant video or visual distraction offered by parent or researcher) and encouraged to sit quietly with an erect spine and hands free of support. Variables of interest included distance and rate related measures of postural sway of the center of mass of the head (head COM) (magnetic tracking) relative to age and level of support. Adjusting the height of the support allowed for the sequential evaluation of different segments of the spine (cervical to lumbar) as they relate to head stability.

Magnetic tracking (Ascension Minibird system) was used to track alignment and movement of the head in space in relation to the support while the infants attempted to sit upright. A sensor was attached to the center of the forehead just above the eyes using a headband. Prior to data collection anterior-posterior and left-right edges of the base of support were digitized to document the location of the support in relation to the head. The

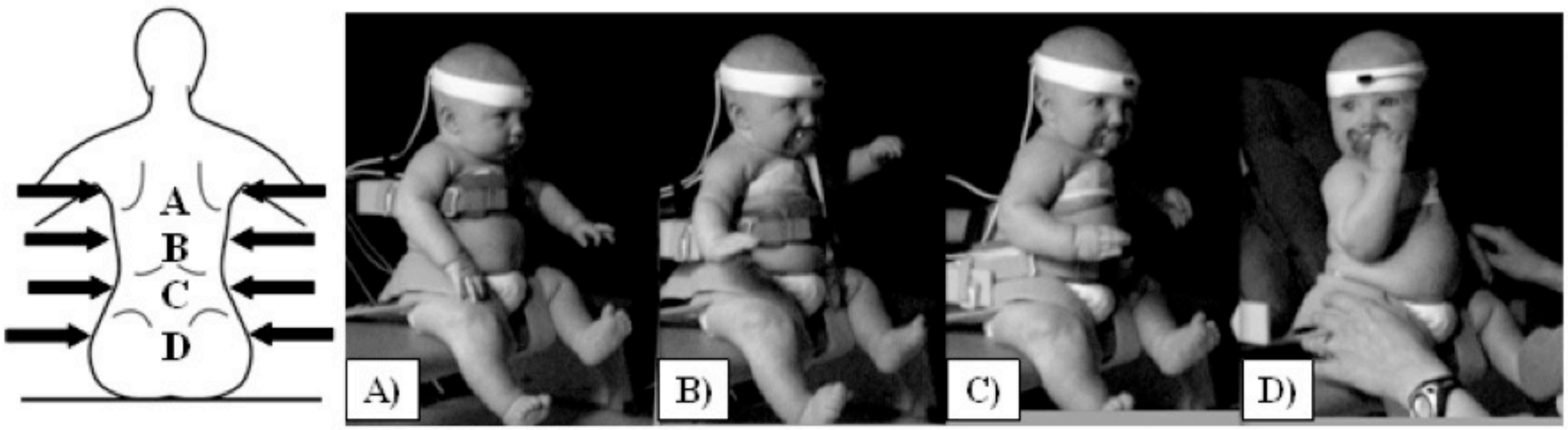

Figure 1. Trunk support device with typically developing infant. Placement of external trunk support when testing upright postural control; A) axillae, B) mid-ribs, C) waist, D) hips. Photographs show a 4 month old typically developing infant during testing with each level of support.

traegus of each ear was digitized to allow transformation from head sensor data to COM of the head. Sampling frequency was 84 Hz. The magnetic tracking system had a recording volume of 1 m^3 with a spatial accuracy of 1.8 mm.

Clinical Measures of Postural Control

During each laboratory visit 3 clinical measures were collected. The Alberta Infant Motor Scale (AIMS) is a standardized motor assessment of infants that rates motor development based on observation of motor repertoire in four different postural alignments; prone, supine, sitting and standing (Piper & Darrah, 1994). The Segmental Assessment of Trunk Control (SATCo) is a clinical test of static, active and reactive postural control of the trunk (Butler et al., submitted). This test is conducted by providing manual support to progressively lower levels of the trunk (shoulders, axillae, mid-ribs, lower ribs, waist, pelvis and finally, no manual support). The infant is scored on the ability to achieve and hold postural alignment with hands free (static), while turning or reaching (active) and during a brief nudge (reactive). The final clinical measure was a timed sit test; the infant was placed in sitting and encouraged to raise both hands. A stop watch was used to measure the amount of time they were able to remain upright with both hands free. In order to monitor the exact timeline for the emergence of sitting ability parents were given stop watches and "probe-cards" with which to report the timed sit results 2-3 days per week. Parents conducted several trials of timed sitting on at least 2 days each week. They recorded the results on the card and either mailed it or brought it to the laboratory on their next visit. Comparison of technique and times between lab and home records allowed verification of consistent procedure.

Data Reduction and Analysis

Head movement was digitized for off-line analysis using custom Matlab programs. All dependent variables were calculated from 3 minutes of data collection from each level of support (axillae, mid-ribs, waist and hips). Thus there were 4 data sets for each session and 10 to 12 data sets for each infant across time. At the earliest ages the infants were getting used to the experimental procedure. They were younger and more easily fatigued by the protocol. It was therefore not always possible to collect data at all 4 levels during these early data sessions.

Data were filtered with a zero lag fourth-order low-pass Butterworth filter (cut off frequency 5 Hz) prior to calculating dependent variables. Dependent variables were calculated along the anterior-posterior (AP) and medial-lateral (ML) axes. Two types of measurements were included (1) displacement-related measures, root mean square (RMS) and mean distance from midline (MD) and (2) rate-related measures mean velocity (MV) and (RMSV).

Statistical Analysis

Mixed within/between repeated measure ANOVAs (SPSS version 17.0) were used to evaluate the effect of support (4 levels: axillae, midribs, waist, hip) and age (month) on each of the dependent variables (above). MANOVAs were used to explore developmental patterns of change in dependent variables for each level of support. Tukey HSD post hoc tests were used to distinguish significant differences between ages. The timed sit test was used to distinguish the developmental transition to independent sitting. This allowed further exploration of factors that contribute to the emergence of independent sitting. Etta squared 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 maximum accuracy of the F-value.

G*Power (Faul et al., 2007) was used to calculate the sample size necessary for conducting the analyses with adequate power. Using effect size values from pilot data as well as the conventional alpha of .05 and a desired power of .80, the a priori power analysis based on a one-way ANOVA showed that a sample size of 8 TD infants would yield sufficient power to detect statistically significant differences in the analyses proposed for this study.

Results

Kinematic Analysis

Effect of Age and Support

Infants grow rapidly during the first year of life. To rule out the possibility that changes in height influenced the analysis, all data were normalized by the height of the free segment (distance between the top of the support and the COM of the head in the z plane). This process eliminates the chance that changes between age are related to change in body height. Normalization also neutralizes the difference in height of the free segment between levels of support. Thus changes in sway between levels are more likely to be related to changes in postural coordination between the different segments of the spine. All statistical results are given for normalized data. Plots and means tables are provided for non-normalized data to allow easy interpretability and comparison with rates and distances in other studies.

Table 1 shows the mean values for each group for all distance and rate-related measures as well as the results of the repeated measures ANOVAs including F-values, p-values and η^2 for the main effect of age, the main effect of support and the interaction between age and support. There was a significant main effect of support, and a significant interaction between age and support for all distance and rate-related variables along both axes. The main effect of age was present for distance from midline (MD) but not RMS for both axes and for both rate related variables (mean velocity (MV) and root mean squared velocity (RMSV)) along the ML axis but not the AP axis.

Overall, this shows that the effect of support varied depending on the age of the infant and that the change in height of the free segment or height of the infant was not adequate to explain the interaction. To further evaluate the interaction between age and level of support MANOVAs were completed for each level of support and post hoc Tukey HSD was used to determine significant differences between groups.

Age by Support Interaction

From the above analysis it appears that the process of gaining postural control differs from one segment of the spine to another. Since the postural parameters are

Table 1: Group means and effects of support and age.

	Means and (*standard error*) by age across all 4 levels of support						**Effect of support**			**Effect of Age**			**Age by Support Interaction**		
Variable	**3mo**	**4mo**	**5mo**	**6mo**	**7mo**	**8mo**	F (3,192)	p	etta	F (5,64)	p	etta	F (15,192)	p	etta
Sagittal Plane															
AP_MD (cm)	**6.2** *(.58)*	**4.84** *(.33)*	**4.6** *(.25)*	**4.34** *(.25)*	**3.4** *(.27)*	**3.05** *(.29)*	22.13	**<.0005**	.257	8.40	**<.0005**	.396	4.87	**<.0005**	.276
AP_RMS (cm)	**2.21** *(.41)*	**2.55** *(.24)*	**2.38** *(.18)*	**2.44** *(.18)*	**2.35** *(.19)*	**2.48** *(.20)*	52.37	**<.0005**	.45	.131	.985	.01	3.13	**.002**	.196
AP_MV (cm/s)	**1.5** *(.3)*	**2.11** *(.17)*	**1.74** *(.13)*	**1.75** *(.13)*	**1.73** *(.14)*	**1.72** *(.15)*	52.75	**<.0005**	.452	1.41	.233	.099	3.14	**.003**	.197
AP_ RMSV (cm/s)	**3.64** *(.53)*	**3.4** *(.31)*	**2.87** *(.23)*	**2.92** *(.23)*	**2.88** *(.25)*	**3.06** *(.27)*	57.13	**<.0005**	.443	1.29	.279	.092	3.53	**.001**	.216
Frontal Plane															
ML_MD (cm)	**3.69** *(.35)*	**1.92** *(.20)*	**1.71** *(.15)*	**1.66** *(.15)*	**1.36** *(.16)*	**1.59** *(.18)*	22.95	**<.0005**	.264	10.58	**<.0005**	.453	3.64	**<.0005**	.221
ML_RMS (cm)	**1.49** *(.21)*	**1.45** *(.12)*	**1.44** *(.09)*	**1.39** *(.09)*	**1.33** *(.1)*	**1.55** *(.11)*	54.56	**<.0005**	.46	.71	.618	.053	2.64	**.003**	.171
ML_MV (cm/s)	**1.15** *(.18)*	**1.55** *(.10)*	**1.29** *(.08)*	**1.19** *(.08)*	**1.22** *(.08)*	**1.21** *(.09)*	103.09	**<.0005**	.617	2.74	**.026**	.176	4.80	**<.0005**	.273
ML_ RMSV (cm/s)	**1.95** *(.25)*	**2.44** *(.15)*	**2.06** *(.11)*	**1.87** *(.11)*	**1.95** *(.12)*	**2.01** *(.13)*	60.58	**<.0005**	.486	2.96	**.018**	.188	3.99	**<.0005**	.238
Free segment height (cm)	**14.51** *(.39)*	**15.34** *(.23)*	**15.71** *(.17)*	**16.18** *(.17)*	**16.58** *(.18)*	**17.10** *(.2)*									

Infant values (by month) for distance and rate-related measures of postural sway. Values listed are the original means (bold) and standard error of the mean *(italic in parentheses)*. Data for each individual were normalized by height of the free segment at each level of support for all statistical analyses. Columns on the right show the results of the repeated measures mixed within between ANOVA, main effect of support, main effect of age and age by support interaction. Significant results ($p < .05$) are in bold print.

interrelated, a MANOVA was used to evaluate the effect of age on all dependent variables for each level of support. The results of MANOVA and univariate ANOVA were similar; thus the univariate results are given here for easier interpretability. Statistical results for Univariate ANOVAs and significant post-hoc tests, corrected for multiple comparisons are given in Table 2.

Acquisition of Upright Alignment

The first step in acquisition of upright postural control was the achievement of vertical alignment along the ML axis. This was achieved in TD infants between 3 and 5 months of age. Figure 2 shows the progression of upright alignment along the ML axis at each level of support. Notice that there is no difference between groups with support at the axillae. The 3 month olds are significantly different than all other ages with support at the mid-ribs and from all but the 4 month olds with support at the waist or hip. Thus alignment along the ML axis was achieved at the axillae by 3 months, at the mid-ribs by 4 months and at the waist and hip by 5 months (see Table 2 for post-hoc values).

Alignment along the AP axis did not differ between groups with support at the axillae or mid-ribs (Fig. 3). The younger infants (3 months, and 5 months) differed from the 8 month olds with support at the waist and there was a progressive improvement of alignment with hip support across development. The 3 month olds had greater deviation from midline than all other groups. The 4 month olds differed from 7 and 8 month olds, and the 5 and 6 month olds differed from 8 month olds. Thus there appeared to be four stages in gaining vertical alignment with support at the hip, 3 months, 4 months, 5-6

Table 2: Statistical results for each level of support.

Support Level A				Post hoc Tukey HSD significant results
Axillae	**Univariate ANOVA**			
Variable	**F (5, 71)**	**p-value**	**Etta square**	3 month (n = 7), 4 month (n = 11), 5 month (n = 16), 6 month (n = 16), 7 month (n = 15), 8 month (n = 12)
AP_MD	1.77	.129	.111	
AP_RMS	1.21	.314	.079	
AP_MV	1.22	.309	.079	
AP_RMSV	2.36	**.049***	.142	5 m vs. 8 m (**.022**)
ML_MD	.62	.684	.042	
ML_RMS	.79	.559	.053	
ML_MV	.56	.731	.038	
ML_RMSV	.74	.594	.05	
Support Level B				
Mid-rib	**Univariate ANOVA**			**Post hoc Tukey HSD significant results**
Variable	**F (5, 69)**	**p-value**	**Etta square**	3 month (n = 7), 4 month (n = 10), 5 month (n = 16), 6 month (n = 16), 7 month (n = 15), 8 month (n = 12)
AP_MD	1.11	.362	.075	
AP_RMS	1.84	.116	.118	
AP_MV	1.81	.123	.116	
AP_RMSV	2.78	**.024***	.168	5 m vs 8 m (**.006**)
ML_MD	3.68	**.005***	.211	3 m vs 4 m (**.028**), 5 m (**.002**), 6 m (**.018**), 7 m (**.01**), 8 m (**.007**)
ML_RMS	1.94	.098	.123	
ML_MV	.97	.442	.006	
ML_RMSV	1.33	.263	.088	

* indicates significance < .05 for univariate test. Right column shows the post hoc Tukey test corrected for multiple comparisons. Bold p values were significant at $p < .05$. Values for $p < .1$ are included as needed to explain univariate results and are not in bold. Number of subjects in each group for post-hoc tests is indicated in parentheses at each level of support.

Table 2, continued

				Post hoc Tukey HSD significant results
Support Level C				
Waist	**Univariate ANOVA**			**Post hoc Tukey HSD significant results**
Variable	**F (5, 68)**	**p-value**	**Etta square**	3 month (n = 6), 4 month (n = 9), 5 month (n = 16), 6 month (n = 16), 7 month (n = 15), 8 month (n = 12)
AP_MD	3.710	**.005***	.214	3 m vs 8 m (**.005**); 5 m vs. 8 m (**.046**)
AP_RMS	.46	.806	.033	
AP_MV	.98	.437	.067	
AP_RMSV	.70	.624	.049	
ML_MD	4.98	**.001***	.267	3 m vs 5 m (**.011**), 6 m (**.004**), 7 m (< **.0005**), 8 m (**.002**)
ML_RMS	1.169	.334	.079	
ML_MV	1.96	.096	.126	
ML_RMSV	2.539	**.036***	.157	3 m vs 6 m (**.04**)
Support Level D				
Hip	**Univariate ANOVA**			**Post hoc Tukey HSD significant results**
Variable	**F (5, 65)**	**p-value**	**Etta square**	3 month (n = 3), 4 month (n = 9), 5 month (n = 16), 6 month (n = 16), 7 month (n = 15), 8 month (n = 12)
AP_MD	13.49	**< .0005****	.509	3 m vs 4 m (**.002**), 5 m (**< .0005**), 6 m (**< .0005**), 7 m (< **.0005**), 8 m (**< .0005**); 4 m vs 7 m (**.007**), 8 m (**.001**) 5 m vs 8 m (**.008**) 6 m vs 8 m (**.036**)
AP_RMS	2.59	**.034***	.166	4 m vs 7 m (**.049**), 8 m (.068)
AP_MV	3.23	**.011***	.199	4 m vs 7 m (**.044**), 8 m (**.013**)
AP_RMSV	3.37	**.009***	.206	3 m vs 7 m (.062), 8 m (**.05**)
ML_MD	4.96	**.001***	.276	3 m vs 5 m (**.032**), 6 m (**.01**), 7 m (< **.0005**), 8 m (**.003**);
ML_RMS	2.38	**.048***	.155	4 m vs 7 m (.053)
ML_MV	6.81	**< .0005***	.344	4 m vs 6 m (**.008**), 7 m (**.001**), 8 m (<**.0005**) 5 m vs 7 m (**.036**), 8 m (**.004**)
ML_RMSV	6.50	**< .0005***	.333	4 m vs 6 m (**.006**), 7 m (**.001**), 8 m (<**.0005**) 5 m vs 7 m (**.037**), 8 m (**.009**)

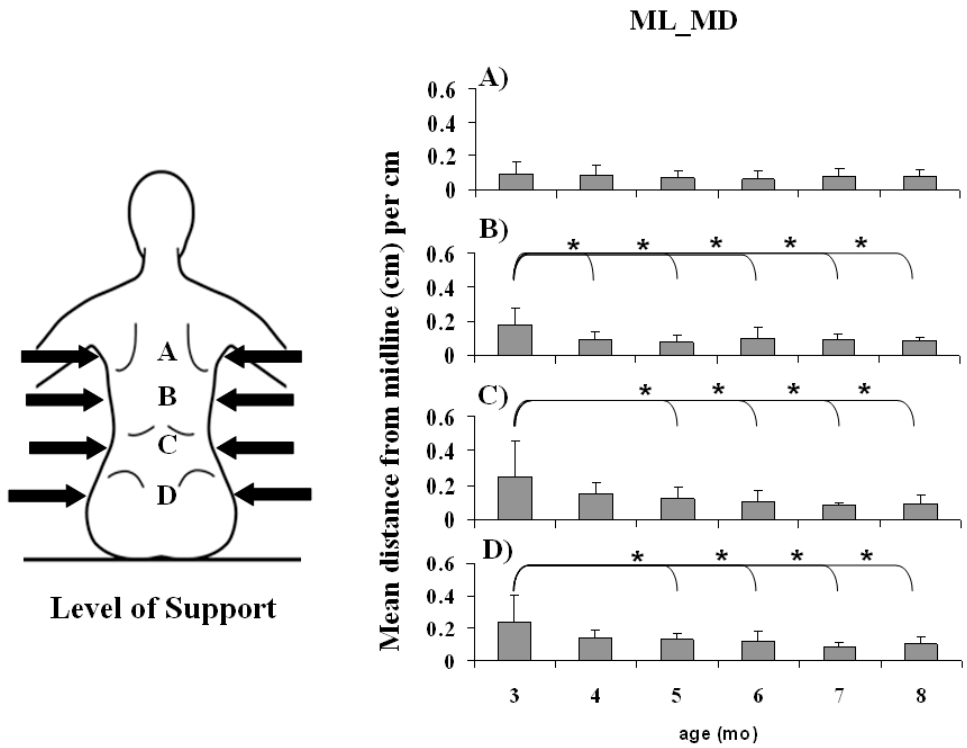

Figure 2. Vertical alignment along the medial-lateral axis. Letters indicate the level where external support was provided A) axillae, B) mid-ribs, C) waist and D) hip. Distance from midline was normalized by height of the free segments (maximum distance from level of support to center of mass of the head along z-axis). Mean value for TD infants grouped by age in months *(grey bars)*. * indicates significant difference ($p < .05$) between groups. Error bars show standard deviation for each group.

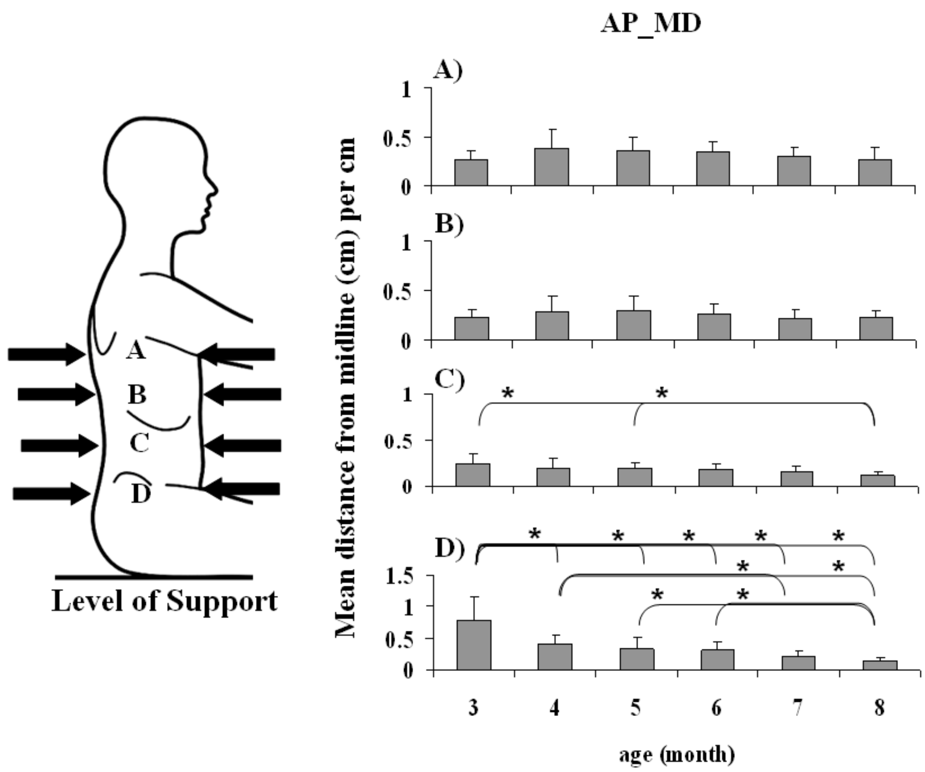

Figure 3. Vertical alignment along the anterior-posterior axis. Letters indicate the level where external support was provided A) axillae, B) mid-ribs, C) waist and D) hip. Distance from midline was normalized by height of the free segments (maximum distance from level of support to center of mass of the head along z-axis). Mean values for TD infants grouped by age in months *(grey bars)*. * indicates significant difference ($p < .05$) between groups on post-hoc tests corrected for multiple comparisons. Error bars show the standard deviation.

months and 7-8 months each marked significant changes in alignment. Figure 3 shows the progression of alignment along the AP axis and Table 2 provides statistical results.

Thus, TD infants gained alignment along the ML axis between 3 and 5 months of age. Alignment along the AP axis is gained progressively with good alignment at the upper levels of support by 3 - 4 months of age, at the waist by 6 months of age and at the hips by 7 - 8 months of age.

Stability of Sway

Stability was assessed using variability of position (RMS), variability of velocity (RMSV) and mean velocity (MV) for the both axes. The only variable that changed across development was variability of velocity along the AP axis when the support was at the axillae or mid-ribs (Fig. 4). This was due to decreased variability in the 5 month olds and increased variability at 8 months of age. When support was given at the waist variability of velocity along the ML axis was the only variable that changed across development (Fig. 5). This was the result of the 6 month olds being less variable than the 3 month olds. Changes in stability were more complex with support at the hip. All measures of stability, along both axes, showed significant changes across development at this level of support (Fig. 4 and 5, Table 2 for statistical results). For most measures the between group differences were similar (Table 2). The general pattern was increased speed and variability of sway at 4 months of age with gradual reduction in speed and variability through 8 months of age. Variability of velocity along the AP-axis is the only

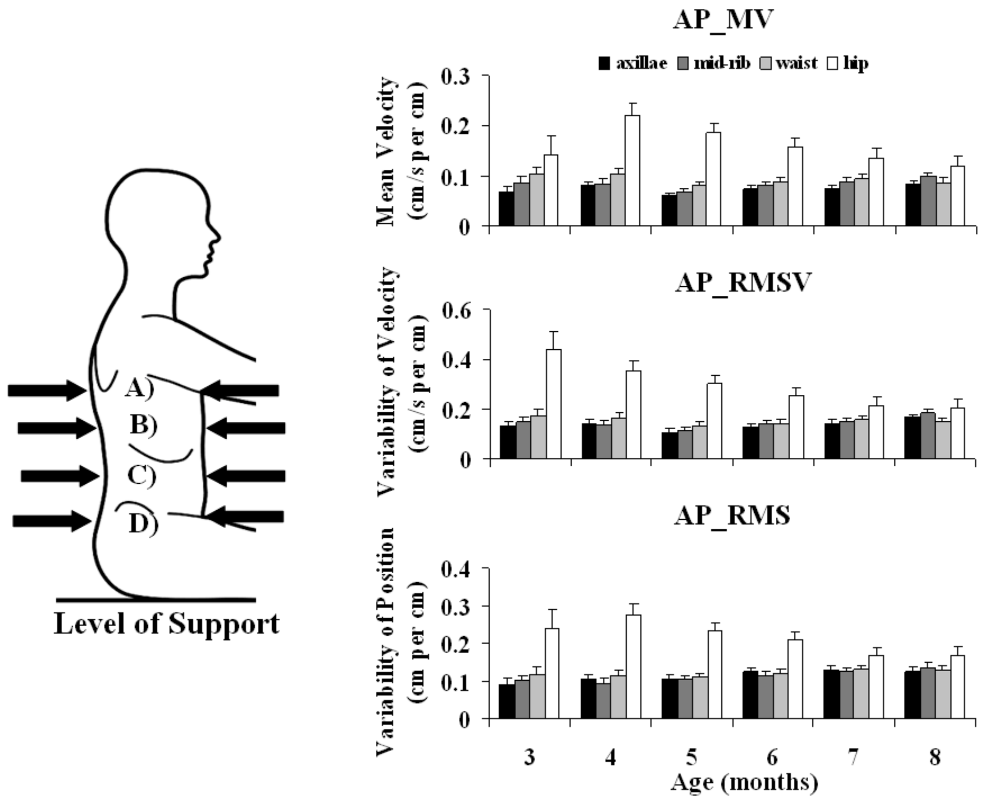

Figure 4. Stability of sway along the anterior-posterior axis. Four levels of external support: A) axillae (*black bars*), B) mid-rib (*dark gray bars*), C) waist (*light gray bars*) and D) hip (*white bars*). Bars represent mean velocity (MV), mean variability of velocity (RMSV) and mean variability of position (RMS) for TD infants grouped by age (months). Error bars represent standard error of mean. See Table 3 for post-hoc differences between groups.

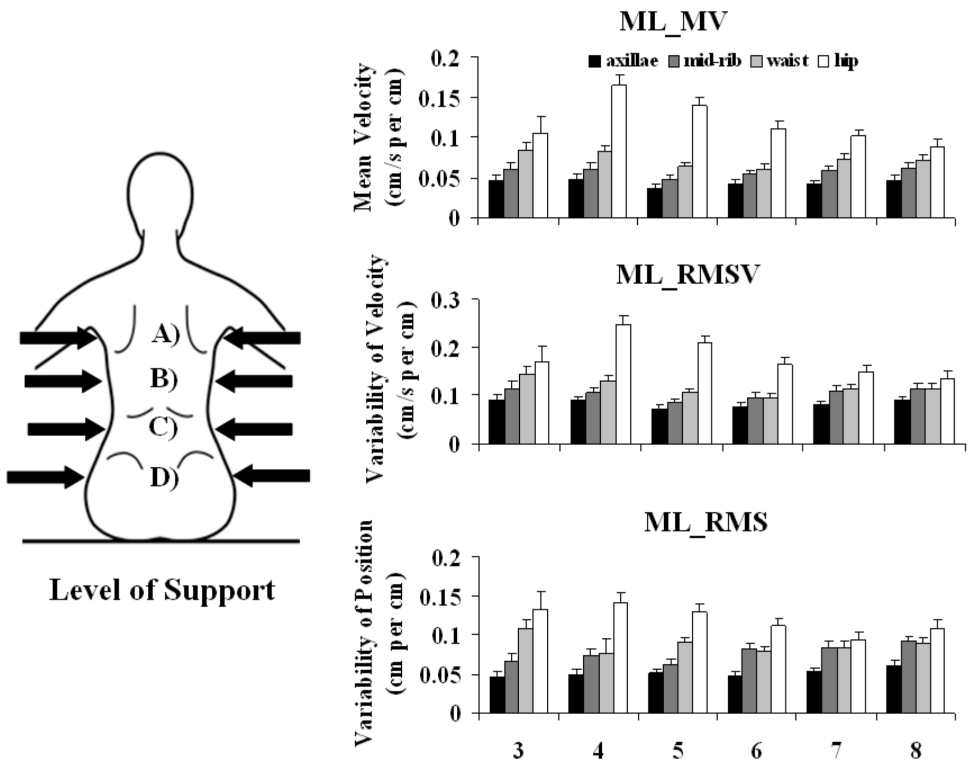

Figure 5. Stability of sway along medial-lateral axis. Four levels of external support: A) axillae (*black bars*), B) mid-rib (*dark gray bars*), C) waist (*light gray bars*) and D) hip (*white bars*). Bars represent mean velocity (MV), mean variability of velocity (RMSV) and mean variability of position (RMS) for TD infants grouped by age (months). Error bars represent standard error of mean. See Table 3 for post-hoc differences between groups.

exception. This variable had its highest value for the 3 month olds and then showed gradual progression until 8 months.

Thus, measures of stability began with slower and less variable sway in 3 month olds. Speed and variability increased to the highest levels along both axes at 4 months of age. Variability of velocity showed a decrease with development and this followed a cephalo-caudal pattern. Variability of velocity was lowest in 5 month olds with support at axillae or mid-ribs, in 6 month olds with support at waist and in 8 month olds with support at the hip (Fig. 4 and 5).

Overall, there are cephalo-caudal trends in alignment as well as stability of sway and the most diverse developmental patterns are seen with support at the hip. There appeared to be 4 behavioral stages of alignment along the AP axis and 4 stages of stability along both axes at this level of support. At 3 months of age the infants had poor alignment and had slow rate of sway with reduced variability. At 4 months of age there was an improvement in alignment and a concurrent increase in speed and variability of sway. Beyond this age there was a gradual improvement of both alignment and stability with the 5-6 month olds performing better than the 4 month olds and worse than the 7-8 month olds on most measures.

Behavioral Analysis

In addition to kinematic data we used video analysis to assist in characterization of the development of upright control. Video analysis, like kinematic analysis, showed four general behavioral patterns during the course of postural maturation. These patterns were most easily distinguished with support at the hip. Figure 6 shows the progression of one infant at each of the four kinematically different age spans and one adult. In addition to a photograph showing the behavior (Fig6 A-E), we created data plots showing postural performance over the course of the full 3 minutes. These plots are helpful in visualizing the progression of upright behavior. Center of mass (COM) plots (Fig. 6 F-J) show the 2-D path (along AP and ML axes) for the center of mass of the head in relation to the base of support. Dwell time histograms (Fig. 6 K-O) show the frequency of position along the AP axis in relation to midline during the 3 minute data collection. The adult sample represents the “gold standard” of expected head stability. Figure 7 provides visualization of changes in velocity with time series plots of change in position along the AP axis color-coded for speed. This data is from the same infant and adult shown in Figure 6. Notice the slow speed and variability of velocity at 3 months, increased speed and variability at 4 months and then gradual reduction of speed and variability of velocity at 5 months and 8 months. The adult example emphases the end goal which is not achieved until adolescence (Viel et al., 2009).

Evaluation of other infants showed similar progression through stages with support at the hip. Figure 8 and figure 9 show dwell time histograms and COM plots for each infant across 4 time points. While there is variability among infants, there is a general pattern of collapse at the earliest ages followed by a more chaotic stage when infants initiate an upright position but are unable to sustain it. The next stage is characterized by reduction of dwell time on the edges of range creating a more Gaussian distribution. This is followed by the final stage of vertical alignment with further

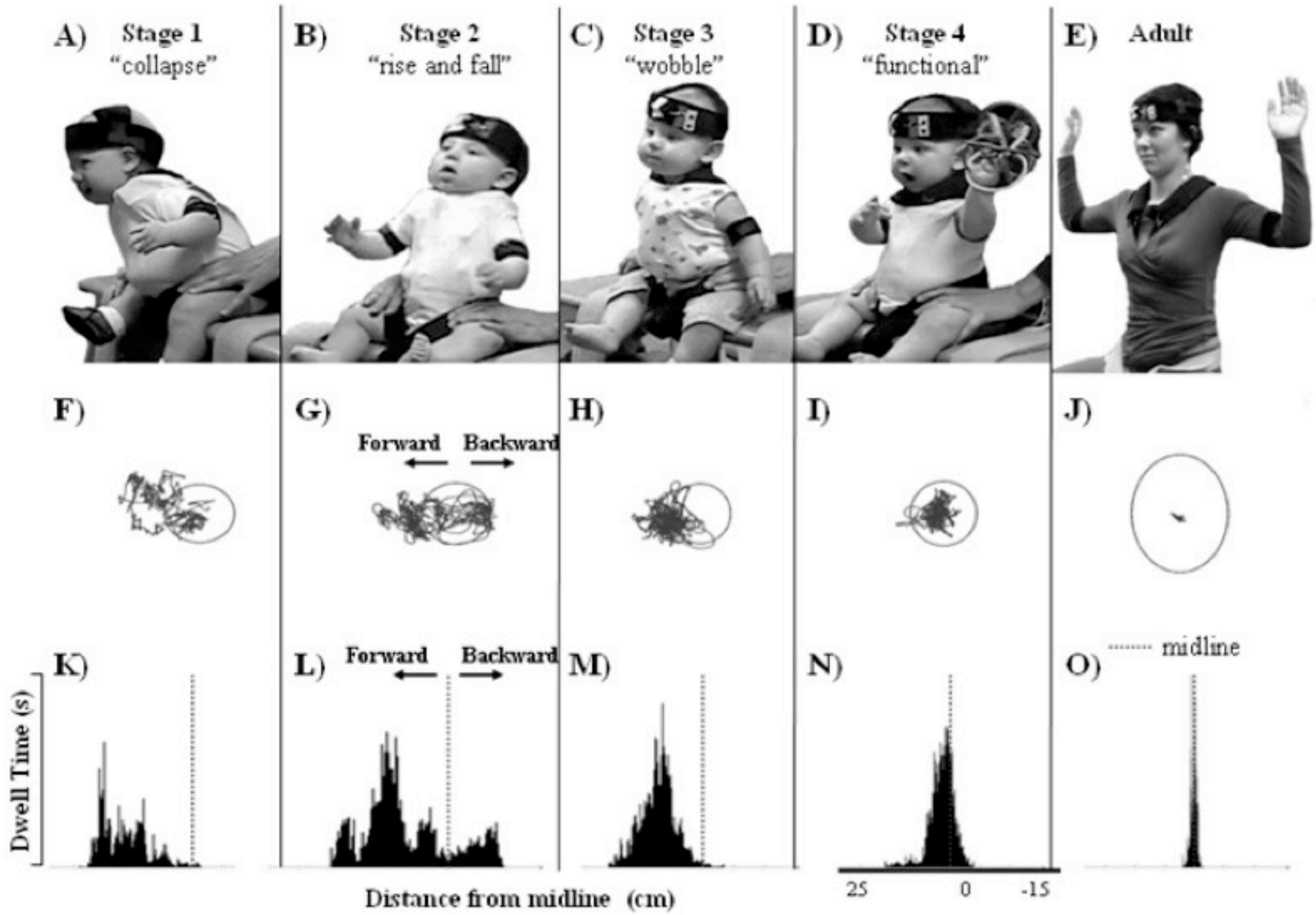

Figure 6. Stages of acquisition of upright control. Progression of upright control in one typically developing infant compared to an adult. Photographs show an example of the behavior (A-E). Center of mass (COM) plots show the path of the head COM in the transverse plane with respect to the base of support (*ellipse*) (F-J). Dwell time histograms show the frequency of head position with respect to midline (*dotted line*) along the AP axis (K-O).

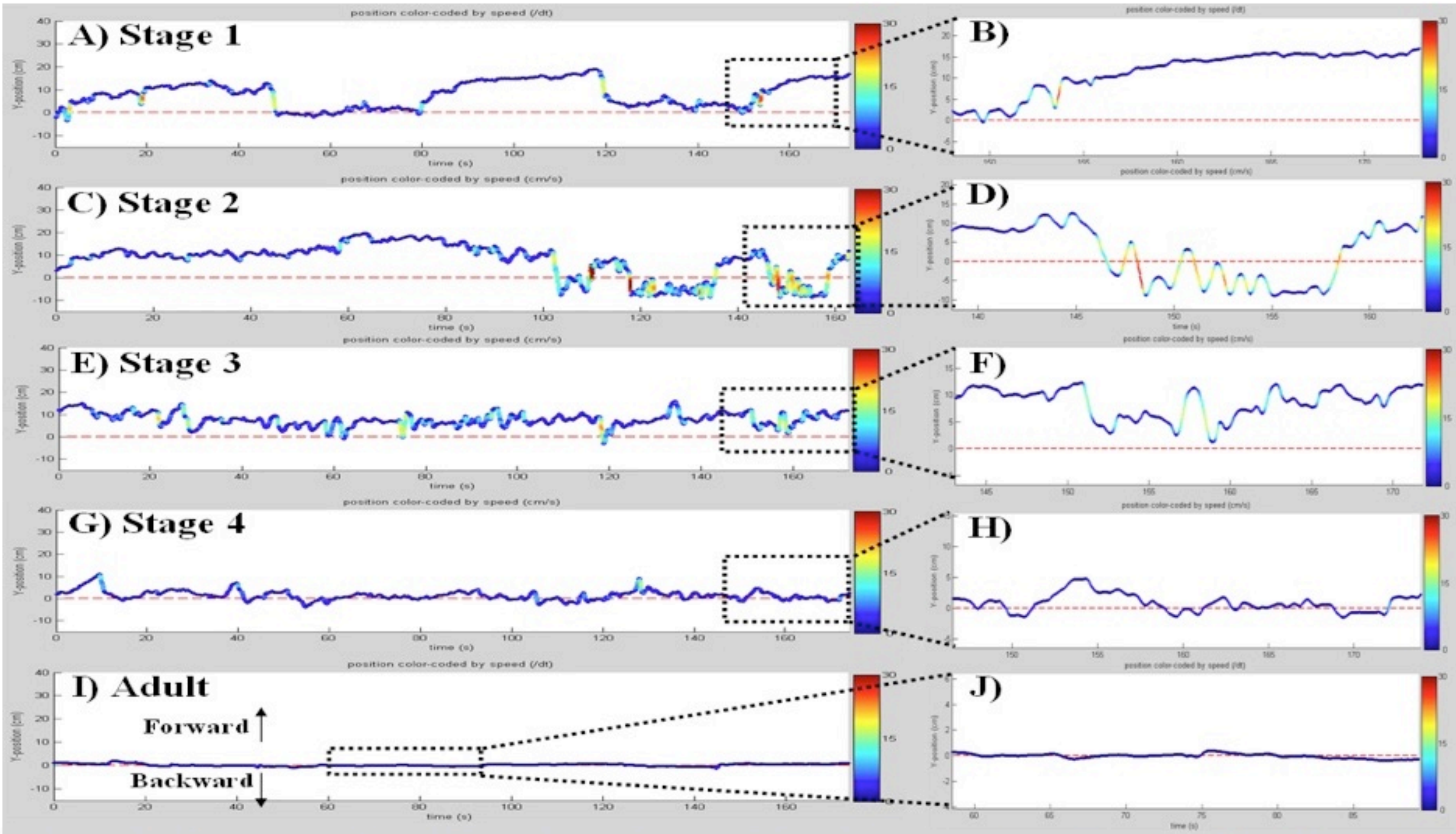

Figure 7. Position along anterior-posterior axis color-coded for speed. Panels show position of head COM (*colored line*) with relation to midline *(red dashed line*). Deviation along the AP-axis (cm) for the full 3-minute data collection (*left column*), enlarged subsection (*right column*). Color bars show color code for speed (0 to 30 cm/s). Selection of time series that is enlarged is encased in a box (*black dotted rectangle*). These data are from the same series as Fig. 6. TD infant stage 1 (A, B), assistance was required to return to midline at 45 seconds and 120 seconds. The infant was supported in midline for calming before re-release.

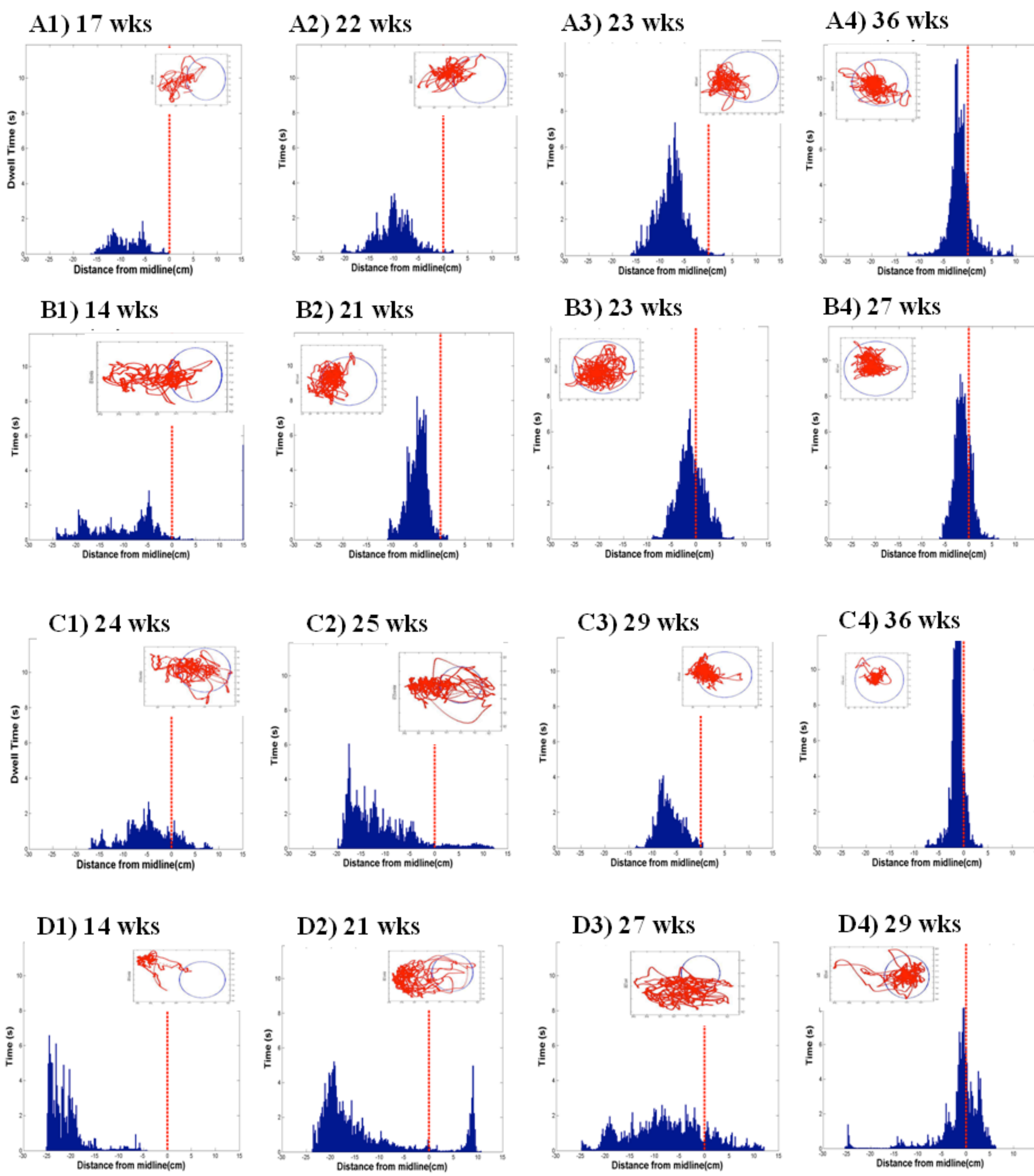

Figure. 8. Progression of upright control for individual infants (A-D). Histograms show frequency of head position along AP axis (*blue bars*) with respect to midline (*red dotted line*). Inserts show path of head COM (*red solid line*) with respect to base of support (*blue ellipse*). Subject numbers match those in Figure 11.

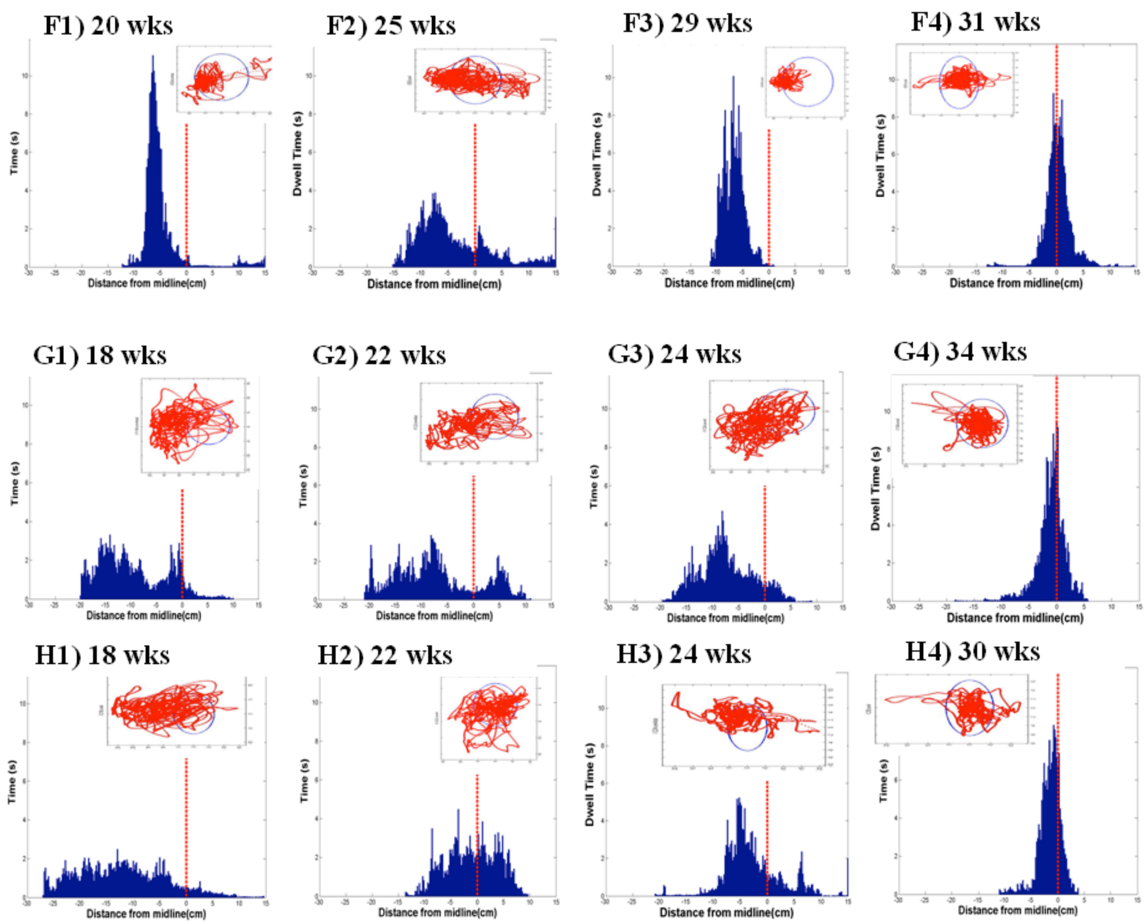

Figure 9. Progression of upright control for individual infants (F-H). Histograms show frequency of head position along AP axis (blue bars) with respect to midline (red dotted line). Inserts show path of head COM (red solid line) with respect to base of support (blue ellipse). Subject E is shown in Figure 6. Subject numbers match those in Figure 11.

reduction in sway amplitude. Technical problems resulted in lost data during some of the early trials thus there are two infants who do not have the best example of data for stage 2 (1B, 2B). Notice that the age and rate of progression varies but the general behavioral progression is consistent.

We attempted to classify the stage of control for each infant across time using information from the video analysis and distribution of position along the AP-axis. Table 3 shows the criteria used for stage identification. Table 4 shows the results across all infants for classification of stage.

Clinical Measures of Postural Control

Three clinical measures (SATCo, AIMS and timed sit) were collected during each laboratory visit. In addition parents collected data for the timed sit test 2-3 days per week between lab sessions. Thus we were able to document the behavioral emergence of sitting skills in each infant.

Standardized Test Results

Group means for SATCo and AIMS show improved trunk control and sitting behavioral across the ages included in this study (Fig. 10). Table 5 shows the Pearson correlation between behavioral and kinematic measures at each level of support. The positive correlation between variability of position and tests of sitting ability with support at the axillae and mid-ribs indicate that movement increased at the upper levels of support as posture matured. Positive correlation of AP rate related measures with support at the

Table 3: Criteria for classification of developmental stage.

Criteria for Stage Classification	Stage 1 "Collapse"	Stage 2 "Rise and fall"	Stage 3 "Wobble"	Stage 4 "Functional"
Skew of data distribution along AP axis Normal = 0	Skew < -.5	Skew ± .2 to .49	Skew .19 to -.19	Skew > .5
Kurtosis of data distribution along AP axis Gaussian = 3.0			Kurtosis 2.5 to 3.9	Kurtosis > 4.0
Distribution of head COM over BOS along AP axis	<35%	35-59%	60-89%	90% or more
Manual assistance (video analysis)	Requires manual assistance to bring head COM over BOS	> 3 episodes of active correction that brings COM over BOS	No assistance needed to remain upright	No assistance needed to remain upright

Four stages in acquisition of upright spinal control with support at the hip. If manual assistance was needed to regain vertical it is stage 1. If data met 2 out of 3 criteria for one stage it was classified in that stage. If data met criteria for 3 stages it was classified as the one in the middle.

Table 4: Stage classification for individual infants.

Subject	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
A)	17, 20*	21*	22, 23, 24,25	28, 31, 34, 36
B)	14, 18*		21, 23	25, 27, 29, 31, 33
C)	22, 24, 25	27	29, 31	34, 36, 38
D)	14,17	21, 23	25, 27	29, 31, 33, 35, 37
E)	15	18, 19,	21, 23, 25, 27	30, 32, 34, 37
F)	17,	20, 21, 23, 25	27, 29, 37	31, 33, 35
G)	18, 27	20, 22, 24, 28	33	30, 34, 36
H)	16	18, 24	20, 22, 26, 28	30

Trials with hip support for each data session. Numbers in each column represent age in weeks. Letters identify each infant and match those on plots in Figures 8, 9 and 11. * indicates technical problem with kinematic data, scoring was from video review only.

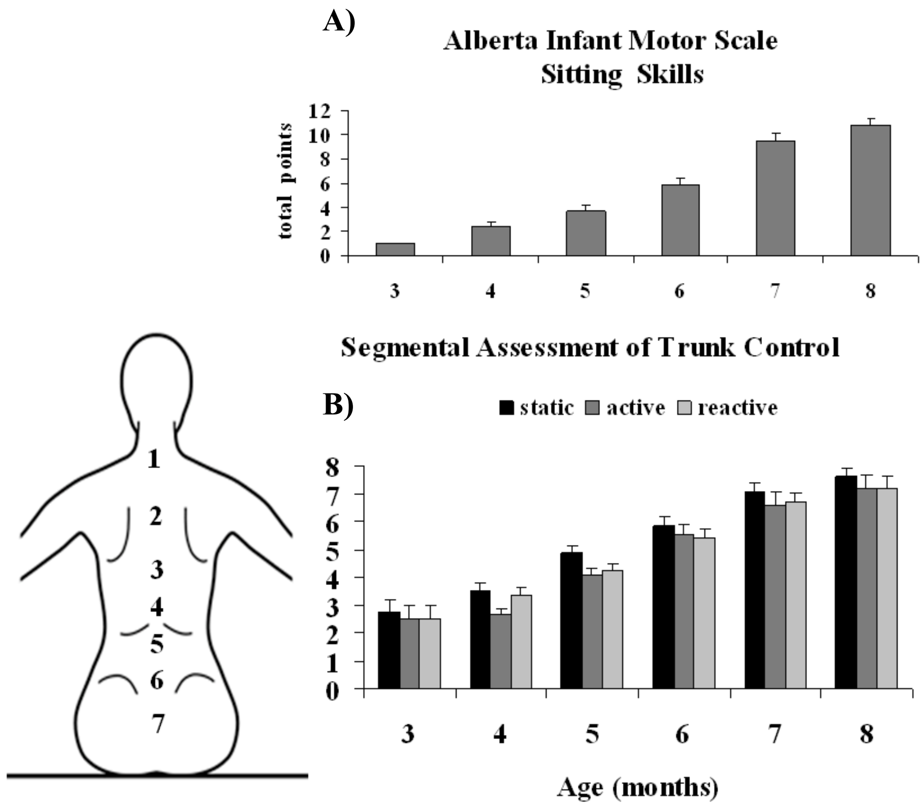

Figure 10. Results of clinical tests of trunk control. **A)** Mean performance on AIMS sit subsection for infants grouped by month of age. **B)** Mean level of trunk control demonstrated during Segmental Assessment of Trunk Control for TD infants grouped by age (months). Three aspects of control are tested **static** (the ability to align in vertical (*black bars*)), **active** (the ability to hold alignment while turning head or reaching (*dark gray bars*)) and **reactive** (the ability to hold alignment when given a brief nudge (*light gray bars*)). Control is scored 1 through 8: 1 = head control, 2 = upper thoracic control, 3 = middle thoracic control, 4 = lower thoracic control, 5 = upper lumbar control, 6 = lower lumbar control, 7 = pelvic control, 8 = full trunk control. Error bars represent standard error of the mean.

Table 5: Correlation between kinematic and behavioral measures.

Support	Distance Related Measures				Rate Related Measures			
Level A) Axillae	**AP_RMS**	**AP_MD**	**ML_RMS**	**ML_MD**	**AP_RMSV**	**AP_MV**	**ML_RMSV**	**ML_MV**
SATCo Static	.261 (.04)		.256 (.044)					
SATCo Active								
SATCo Reactive	.269 (.034)		.327 (.009)					
AIMS	.359 (.011)		.348 (.014)					
AIMS-sit	.317 (.026)		.302 (.035)					
Timed Sit	.23 (.048)				.435 (.000)			
Support	**Distance Related Measures**				**Rate Related Measures**			
Level B) Mid-Rib	**AP_RMS**	**AP_MD**	**ML_RMS**	**ML_MD**	**AP_RMSV**	**AP_MV**	**ML_RMSV**	**ML_MV**
SATCo Static	.423 (.001)		.430 (.001)		.331 (.009)	.322 (.011)		
SATCo Active	.359 (.005)		.353 (.005)		.38 (.002)	.373 (.003)		
SATCo Reactive	.357 (.005)		.387 (.002)		.273 (.033)	.266 (.038)		
AIMS	.471 (.001)		.406 (.004)					
AIMS-sit	.437 (.002)		.410 (.004)					
Timed Sit	.292 (.013)		.331 (.005)		.432 (.0005)	.418 (.0005)	.234 (.048)	.262 (.026)
Support	**Distance Related Measures**				**Rate Related Measures**			
Level C) Waist	**AP_RMS**	**AP_MD**	**ML_RMS**	**ML_MD**	**AP_RMSV**	**AP_MV**	**ML_RMSV**	**ML_MV**
SATCo Static		-.255 (.046)		-.425(.001)				
SATCo Active				-.343(.006)				
SATCo Reactive				-.401(.001)				
AIMS	-.299 (.043)	-.297 (.041)						
AIMS-sit	.287 (.048)	-.256 (.03)						
Timed Sit				-.270(.022)				

Table 5, continued

Support	Distance Related Measures			Rate Related Measures				
Level D) Hip	**AP_RMS**	**AP_MD**	**ML_RMS**	**ML_MD**	**AP_RMSV**	**AP_MV**	**ML_RMSV**	**ML_MV**
SATCo Static	-.273(.036)	-.578 (.0005)		-.419 (.001)	-.325 (.012)	-.275 (.035)	-.447 (.0005)	-.416 (.001)
SATCo Active	-.356 (.006)	-.571 (.0005)		-.377 (.003)	-.354 (.006)	-290 (.026)	-.418 (.001)	-.384 (.003)
SATCo Reactive		-.546 (.0005)		-.413 (.001)	-.357 (.005)	-.313 (.016)	-.465 (.0005)	-.436 (.001)
AIMS	-.299 (.043)	-.557 (.0005)		-.296 (.046)	-.384 (.008)	-.392 (.007)	-.478 (.001)	-.466 (.001)
AIMS-sit	-.384 (.008)	-.642 (.0005)		-.312 (.035)	-.466 (.001)	-.469 (.001)	-.544 (.0005)	-.545 (.0005)
Timed Sit	-.395 (.001)	-.521 (.0005)	-.256 (.034)	-.237 (.05)	-.359 (.002)	-.326 (.006)	-.430 (.0005)	-.405 (.0005)

Pearson correlation between kinematic measures and behavioral measures. Kinematic measures are grouped by level of support: A) Axillae, B) mid-ribs, C) waist, D) hip (on next page). Segmental Assessment of Trunk Control (SATCo), Alberta Infant Motor Scales (AIMS). p-values are in (parentheses). Only those results with $p < .05$ are shown.

mid-ribs is consistent with the finding that 8 month olds had significantly greater variability of speed at this level. The correlations at the waist are negative and indicate that distance from midline decreased as sitting skills increased. With hip support most variables were significantly correlated with measures of sitting ability. All of these correlations were negative indicating that distance from midline, speed and variability of sway with hip support all decreased as sitting behavior improved.

Transition to Independent Sit

The ability to sit with hands free emerged rapidly within a period of 2 - 3 weeks in some infants and took longer, up to 6 - 7 weeks in other infants. There was also variability in the age of independent sitting, which ranged from 6 to 8 months. We were curious to see if specific changes in behavioral or kinematic measures were related to the emergence of independent sitting. To examine this transition we grouped the infants into two time points, Fallers vs. Sitters. The data from the last visit before sitting emerged (the infant fell over in < 10 sec during hands free timed sit test) was classified as "Fallers". While the data from the first session after sitting emerged (infant sat > 1 min. with hands free) was classified as "Sitters". The mean age for the Fallers was 25 weeks and the mean age for Sitters was 29 weeks. Repeated measure ANOVAs were used to compare the kinematic and behavioral measures across the two time points. The measures of interest in these analyses are the main effects of "sitting ability" and interactions between the level of support and sitting ability. Total AIMS score, AIMS sit score and SATCo Static score were significantly different between Sitters and Fallers (AIMS: $F(1,11)=6.29$, p=.031; AIMS sit: F(1,11)=23.22, p=.001, SATCo Static: F(1,12)=10.18, p=.009). The AIMS results confirm that one group was able to sit independently while the other group was not. The relationship between SATCo Static and emergence of independent sitting is shown for each infant in Figure 11. The SATCo Static scores for Sitters ranged from 6 (lower lumbar) to 8 (full trunk control) while the scores for Fallers ranged from 4(lower thoracic) to 5(upper lumbar) control. This suggests, for typical infants, that postural control must emerge all the way through the lumbar region of the spine prior to the emergence of independent sitting.

There were no main effects of sitting ability for any of the kinematic variables; however there were four significant interactions between level of support and sit ability. These interactions are shown in Figure 12 and confirm the behavioral finding that the ability to align the spine (AP_MD: F(3, 42)= 3.155, p=.054(GG), η^2 =0.184; AP_MD level 4: F(1,15)=8.421, p=.012)) and control the rate of medial lateral sway (ML_RMS: F(3,42)= 4.13, p=.023(GG), η^2 =0.228; ML_RMSV: F(3,42)=5.185, p=.004, η^2 =0.27; ML_MV: F(3,42)= 3.355, p=.028, η^2 =0.193) at the lowest level of support distinguishes the Sitters from the Fallers. In addition these interactions show that freedom to move more freely in the upper trunk is also related to the emergence of independent sitting.

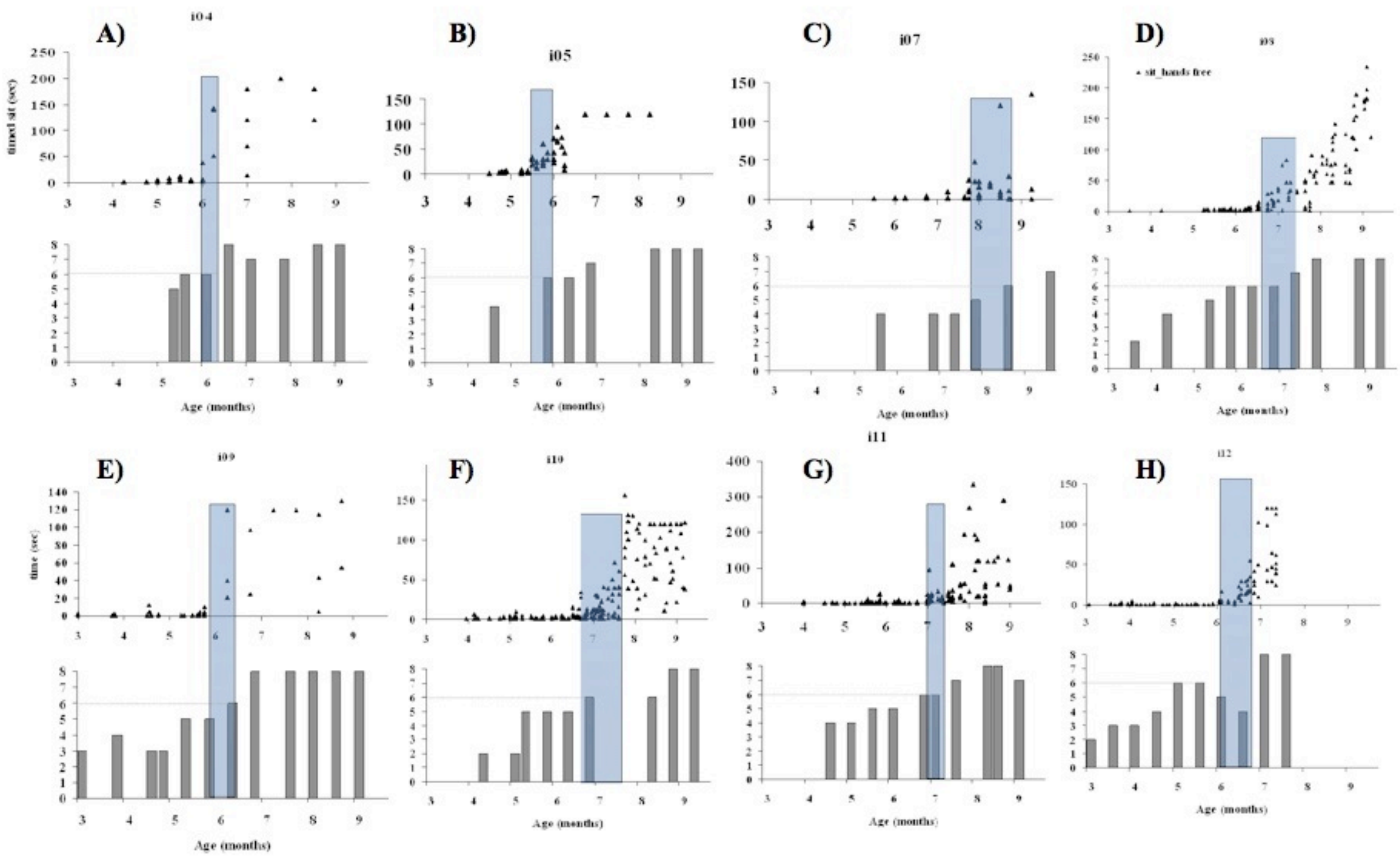

Figure 11. Timed sit compared to SATCo. Relationship of static spinal control to independent sitting transition for each infant (A-H). Infant letters match those in Fig 8A and 8B. SATCo scores (*gray bars*) represent spinal control. 1 = head control, 2 = upper thoracic, 3 = mid-thoracic, 4 = lower thoracic, 5 = upper lumbar, 6 = lower lumbar, 7= pelvic, 8= full trunk control. Timed sit with hands free (black triangles). Blue shaded bars indicate the transition from sit > 10 sec. until sit > 60 sec.

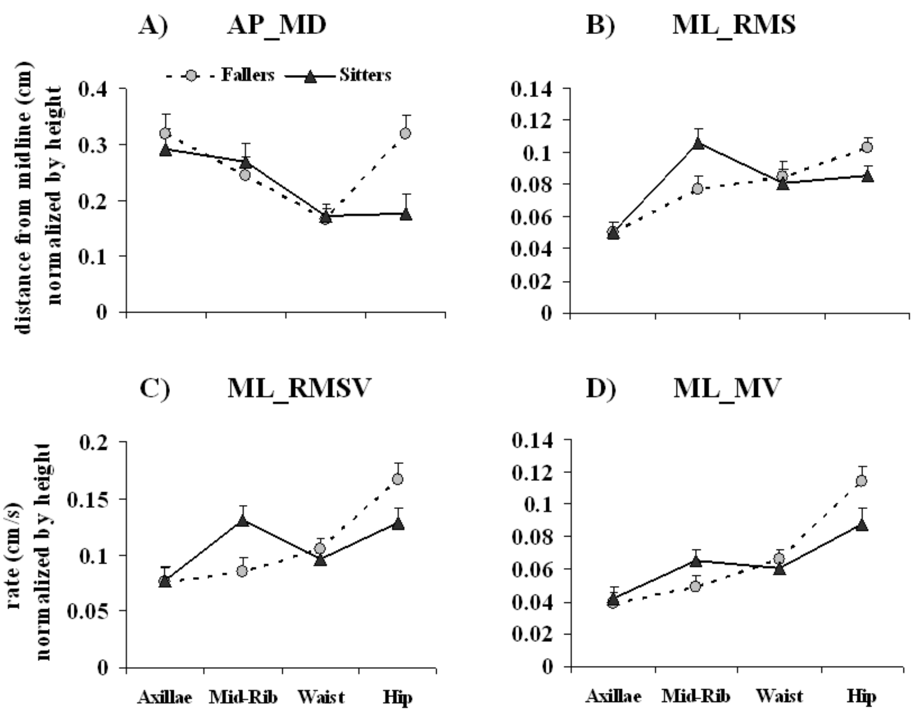

Figure 12. Sitting ability, support by group interactions. Mean value for all infants at each level of support during last visit with < 10 sec. timed sit (*fallers: light gray circles*) compared to mean value of all infants on first visit with > 60 sec. independent sit (*sitters: dark gray triangles*). The variables that had interaction between sitting ability and level of support are shown: A) mean distance from midline along AP axis, B) variability of position along ML axis, C) variability of velocity along ML axis, D) mean velocity along ML axis. Error bars show standard error.

Discussion

The goal of this study was to examine how postural control is acquired across multiple spinal segments during typical development of sitting balance. Using stability of the head in space as a measure of upright control and an external support device to align the infants vertically and isolate specific spinal segments, changes in postural control were evaluated longitudinally in a group of typically developing infants. We found that postural control is specific to the region of the spine being investigated as well as the age of the infant. Infants achieve alignment earlier along the ML axis than the AP axis and in both cases development of alignment proceeds in a cephalo-caudal manner with increasing age. Measures of stability (rate-related variables and variability of position) had non-linear changes across development. In most cases these reflected increased rate of sway when infants were 4 months of age with gradual decline to the slowest and least variable rates at 5 months (with axillae and mid-rib support), at 6 months with waist support, and at 7-8 months with support at the hips. Thus both rate and distance related measures suggest a cephalo-caudal trend in the development of upright postural control. The most diverse sway patterns were observed when support was provided at the hip. At this level infants progressed through 4 stages of upright control. The first stage consisted of slow collapse. In the second stage infants initiated vertical alignment but were unable to sustain it. During the third stage infants sustained a partially upright position but had constant wobbling type movements. The final stage was consistent upright posture that allowed functional interaction with the environment.

Nonlinearities are a common finding during the process of motor development (Gesell, 1946; Shumway-Cook & Woollacott, 1985; Saavedra et al., 2007). Thus it is not surprising to find evidence of stage-like changes in postural behavior during the acquisition of a complex motor skill like upright spinal control. In fact, there is support for each of these stages in previous research on development of sitting balance.

At 3 months infants in this study had large deviations of alignment in both planes accompanied by low mean velocity (both planes), low variability of velocity (ML plane) and low variability of position (both planes). Behaviorally, this stage consisted of slow "collapse", (laterally when given support at the midribs, in either plane with support at the waist and forward when given support at the hips). High variability of velocity occurred in the sagittal plane with support at the hips. We believe this was the result of higher velocities during "falling" followed by limited velocity when infants "rested" at the edge of their range. This stage is marked by rather passive responses to gravity; the infants did not make many recognizable attempts to right themselves and tended to collapse into the available support. This stage is consistent with reports from previous researchers who found a period of diminished postural responses to perturbation in 3 to 4 month old infants (Hedberg et al., 2005; Woollacott et al., 1987), lack of organized patterns of muscle activity to counteract gravity prior to 4 months of age (Schloon et al., 1976) and increased range and velocity of trunk collapse when trunk support was removed from infants while sitting erect (2-3 months compared to 5 months) (Harbourne, 1993).

We found more chaotic, active responses to postural alignment when infants reached 4 months of age. At this age infants appeared to recognize vertical orientation and frequently made visible attempts to rise to an upright position. During this stage infants aligned the COM closer to vertical in both the frontal and sagittal plane. This period showed the largest variability of COM position and rate of postural sway in both planes of movement. The infants were successful in coming to vertical alignment but were unable to sustain that position and constantly "fell" away from midline only to rise again. Previous research has reported an early period of higher complexity and dimensionality of postural sway at 4-5.5 months (Harbourne & Stergiou, 2003, 2009), large variation of directionally specific responses to surface perturbations during sitting in 5-6 month olds (Hadders-Algra et al., 1996, Hedberg et al., 2005), greater variability and jerkiness of response to sudden release of trunk support during sitting in 4-5 month olds (Harbourne, 1993) and higher variability of postural responses to visual perturbations in 5 month olds (Bertenthal et al., 1997). These findings are consistent with ours in showing a period of high variability during the transition before sitting postural control emerges.

Five months, the beginning of the next stage, marked the onset of upright stability. At 5 – 6 months infants in this study remained closer to midline and had significantly reduced variability in distance and rate related measures. Behaviorally, infants made frequent small postural corrections creating a "wobbling" type movement. This period of stability moved in a cephalo-caudal direction down the spine as infants matured. The greatest reduction of variability (maximum stability) in the upper trunk (axillae and mid-ribs) was in 5 month old infants; in the lower thoracic/upper lumbar levels (support at waist) the variability was minimal (maximum stability) in 6 month olds and in the lower lumbar and pelvic regions (hip support) it occurred at 8 months. This period of constrained postural sway has also been reported in previous studies as a reduction of complexity and dimensionality at 5-6.5 months (Harbourne & Stergiou 2003, 2009), increased consistency of direction-specific muscle responses to sitting perturbations at 6-7 months (Hadders-Algra et al., 1996; Hirschfield & Forssberg, 1994, Harbourne et al., 1993; Woollacott et al., 1987), and decreased positional variability during visual perturbations in 7 month old infants compared to 5 and 9 month olds (Bertenthal et al., 1997). In addition a cephalo-caudal gradient for activation of postural muscles has been demonstrated. Muscles responding to postural perturbation were more likely to be neck muscles in 5 month olds, progressing to neck and trunk muscles at 7 month olds and finally neck, trunk and leg muscles by 9-10 months (Hadders-Algra et al., 1996).

The final stage of upright control occurred at 7-8 months when infants were able to remain vertical while actively interacting with the environment. This coincided with the emergence of independent sitting. It is a period of refined alignment and reduced variability of sway at the lower regions of the spine paired with increased the variability of position at upper regions of the spine. While other studies have not isolated the changes to specific regions of the spine, they have shown results that are consistent with our findings: increased degrees of freedom and increasing variability of responses in 6 to

8 month old infants as independent sitting emerges (Harbourne & Stergiou, 2003, 2009); increased response to visual perturbation in 9 month olds following a reduction at 7 months (Bertenthal et al., 1997).

Our results differ from those of previous researchers in showing the cephalo-caudal progression of trunk alignment and postural stability (reduced variability of position and rate of sway) at progressively older ages. Previous studies have used global measures of postural control such as center of pressure, and have modeled the trunk as a single segment. Although these studies have provided information about whole body sway responses they have not provide direct information about the compensatory strategies from individual segments of the spine. By examining sway responses for specific spinal segments and measuring control from the "top down" (head COM as the measure of stability), this study expands previous results by demonstrating that postural refinement occurs in a cephalo-caudal manner with gradual progression from thoracic to lumbar and finally to hip levels of control. Furthermore this study provides evidence that spinal stability must progress into the lumbar segment prior to the emergence of independent sitting. Thus this study provides specific information to guide therapists in evaluating and treating postural dysfunction for sitting balance.

Conclusion

This study of the contribution of spinal segments to development of trunk postural control confirms that there is a cephalo-caudal progression of spinal control. Furthermore, the emergence of independent sitting does not occur until postural stability has been achieved in the lumbar spine. There is a stage-like progression in upright control when support is provided at the hip. This may be helpful in understanding where a child is along the continuum of development. However, these stages serve only as mileposts along the continuum of postural maturation and not distinct behavioral states.

This study expands previous work by demonstrating the importance of the cephalo-caudal progression of postural control in the spine to the emergence of independent sitting. This information can be used by clinicians to develop more specific treatment programs for children with postural dysfunction.

CHAPTER V

CONTRIBUTION OF SPINAL SEGMENTS TO CONTROL OF POSTURE DURING ATYPICAL DEVELOPMENT

Introduction

The act of sitting still is so stable for most people that they don't consider it a motor activity at all. Imagine not being able to hold your body steady enough to read, eat or reach for an object. This is nearly unimaginable to most of us. It is the daily experience of children with moderate to severe cerebral palsy (CP). Cerebral palsy is the most common cause of motor disability in children, with an incidence of 2 to 2.5/1000 live births (Odding et al., 2006, Cans et al., 2004). CP is an "umbrella term" covering a heterogeneous group of motor deficits that occur during the early years of life. Defined as a sensorimotor disorder, CP affects movement and posture; it is due to a "non-progressive disorder of the brain, the result of interference during its development" (Bax et al., 2005). Variability within the CP population results from extent of injury to the maturing brain, location of damage, developmental time of damage, and life experience. Several classification systems have been developed to define motor impairment and function within this population. The most broadly used classifications are based on type of motor impairment, topography of limb motor dysfunction (hemiplegia (unilateral impairment of one arm and one leg), diplegia (both legs) and quadriplegia (both arms and both legs)), and severity of motor deficit. Classification based on the severity of motor deficit using the Gross Motor Function Classification System (GMFCS) has a level of validity and reliability, which the movement disorder (spastic, ataxic, dyskinetic) and topographical (hemiplegia, diplegia, quadriplegia) classifications do not (Graham, 2001). The GMFCS provides a simple method of classifying children and youth with CP on the basis of functional ability with particular emphasis on sitting, walking, and wheeled mobility (Palisano et al., 2008). There are five levels of severity in the GMFCS ranging from mild impairment (Level I, in which children walk, run and are able to participate in most activities with typical peers) to severe impairment (Level V, in which children require assistance for all activities including mobility in a wheelchair).

Research examining the development of motor skills in children with CP has observed delayed acquisition of most functional skills (Bennett, 1987). One of the hypothesized causes for delays in mastering skills such as eating, reaching, and object manipulation is poor sitting balance control (Bleck, 1994). In fact, population studies have shown that for children with CP, development of independent sitting balance by four years of age is a key determinant of independent ambulation and future motor skill development (Wu et al., 2004). Trunk control is a necessary prerequisite for independent sitting balance. As such, development of trunk control and independent sitting balance are central to the achievement of functional skills. Studies of developmental progression in children with CP demonstrate that motor development plateaus early in children with moderate to severe motor deficits (GMFCS V at 2.8 yrs, GMFCS IV at 3.5 yrs, and

GMFCS III at 3.7 yrs) (Rosenbaum et al., 2002b) regardless of the type of movement disorder. Most children with CP at GMFCS levels IV and V (~30% of children with CP) are unable to achieve independent sitting balance. In spite of its critical importance to function, little is known about how trunk control develops in children with CP.

Previous research that explored sitting performance in children with CP included analysis of: (1) impairments in postural responses due to external perturbations (Brogren et al., 1998, 2001); (2) impairments in anticipatory postural responses during reaching (Hadders-Algra et al., 1999a & b, Van der Heide et al., 2004, 2005); and (3) changes in ground reaction forces during postural adjustments (Liao et al., 2003). Impairments such as spasticity (a velocity dependent increase in stretch reflexes), muscle weakness, excessive co-activation of agonist and antagonist muscles, decreased coordination of muscles, and decreased variability of responses have been found to constrain postural control in children with CP. While these studies have contributed important information regarding the motor control deficits in children with CP, they have considered the trunk as a single segment, and thus have not controlled for or evaluated the contributions of different spinal segments to the control of sitting balance. Moreover, selection criteria for the children included in these studies required the ability to sit independently (GMFCS I, II and III). Therefore studies have yet to address the specific constraints on sitting balance for children who are most in need of treatment for trunk control. It is likely that the segmental level of trunk control achieved by a child (e.g., control through cervical, thoracic, lumbar or pelvic regions) will strongly influence his/her level of functional skill development. Thus, it is critical to measure the development of trunk control more precisely and it is important to understand the constraints on postural control in children with moderate to severe motor disability.

The primary goal of this study was to examine the contributions of spinal segments to trunk postural control in children with moderate to severe CP. For this purpose kinematic data were collected to examine head stability and movement strategies used by children with moderate to severe motor impairment when attempting to sit in an upright position with support at different levels of the trunk (axillae, midribs, waist and hip). Results were compared to data from a longitudinal study of typically developing (TD) infants (3-9 months of age). We hypothesized that the level of trunk control would be the defining characteristic of the severity of motor deficit. Thus, we expected that children with GMFCS V (most severe deficit) would have trunk control similar to younger TD infants (3-4 months) and children with moderate disability (GMFCS IV) would be similar to older TD infants. We also hypothesized that children with severe motor deficits would have loss of control in the upper part of the spine while children with moderate disability would show better postural control when given support at the axillae or midribs and loss of control as the support level was lowered to the waist or hips.

Methods

Participants

Fourteen children with CP and moderate to severe motor impairment (GMFCS IV (n=8), GMFCS V (n=6)) who have failed to achieve independent sitting balance participated in the study. Eligibility criteria for children included: (1) A diagnosis of CP; (2) GMFCS level IV or V; (3) lack of functional, independent sitting ability; and (4) less than 18 years of age. All children had a diagnosis of quadriplegic CP; nine had spastic motor impairment and 5 had dyskinetic motor impairment. All children 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. The study was conducted in accordance 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. Data from a longitudinal study of eight TD infants were used for comparison.

Experimental Tasks

Postural assessment batteries were completed 3-4 times for each child. This allowed adequate time to build rapport and communicative understanding between the child and researcher and insured that children could produce their best effort. Laboratory test sessions (90-120 minutes) allowed time for breaks as well as extra time for explanation and demonstration. Kinematic data were collected during every

Table 1. Demographic data for children with Cerebral Palsy.

Subject	Age	Sex	Diagnosis	Mobility skill level (GMFCS)[1]	Manual skill level (MACS)[2]	Individual Data Location
1	7 yr 8 mo	M	CP Spastic quadriplegia	4	3	Fig. 10 A, E, F
2	12 yr 4 mo	F	CP Spastic quadriplegia	4	3	Fig. 11 B
3	8 yr 10 mo	F	CP Spastic quadriplegia	4	3	Fig. 11 C
4	15 yr 3 mo	M	CP Spastic triplegia	4	4	Fig. 11 D
5	8 yr 7 mo	F	CP Spastic diplegia	4	4	Fig. 11 E
6	12yr 5 mo	M	CP Spastic quadriplegia	4	4	Fig. 11 A
7	16 yr 4 mo	F	CP quadriplegia Dystonia	4	5	Fig. 11 F
8	13 yr	M	CP quadriplegia extrapyramidal	4	4	Fig. 11 G
9	11 yr 2 mo	F	CP Asymmetric quadriplegia	5	4	Fig. 11 K
10	8 yr 1 mo	M	CP Spastic quadriplegia	5	4	Fig. 8 A, E, F
11	8 yr 5 mo	M	CP Spastic quadriplegia	5	5	Fig. 11 H
12	6 yr 7 mo	F	CP quadriplegia dystonia	5	4	Fig. 9 A, E, F
13	9 yr 10 mo	M	CP quadriplegia Dystonia	5	5	Fig. 11 I
14	11 yr	M	CP quadriplegia dystonia	5	5	Fig. 11 J

M= male, F= female; [1]GMFCS = Gross Motor Functional Classification System (www.canchild.ca); [2]MACS = Manual Ability Classification System (www.macs.nu) assessment battery, while validated clinical tests of motor ability were completed one time during one of the sessions. Clinical tests included Gross Motor Function Measure (GMFM66, dimension A and B) (Russell et al., 2002), the Pediatric Evaluation of Disability Inventory (PEDI) (Haley et al., 1992), and the Segmental Assessment of Trunk Control (SATCo) (Butler, 1998).

Laboratory Test Procedure

Magnetic tracking (Ascension Minibird system) was used to collect head sway while the child attempted to sit upright. Sampling frequency was 84 Hz. The magnetic tracking system had a recording volume of 1 m^3 with a spatial accuracy of 1.8 mm. A sensor was attached to the center of the forehead just above the eyes using a headband. Children sat on a bench with foot support, facing a computer monitor. Pelvic strapping and a rigid posterior support that circled the trunk provided upright stability of the spine below the level of interest. The posterior support was raised or lowered to allow evaluation of four different spinal segments (cervical-upper thoracic (axillae), mid-thoracic (midribs), thoracic-lumbar (waist) and pelvis (hips), supporting a counterbalanced order. Figure 1 (Chapter III) shows a child during testing at each support level. Hands free spinal control was assessed by asking children to raise both arms and hold them up for three 20 second episodes evenly spaced during the 3 minutes of data collection at each level of support. Children were instructed to sit up tall and were visually entertained by a video, their parent or the researcher during the period of data collection.

Data Reduction

Head movement was digitized for off-line analysis using custom Matlab programs. Due to multiple visits and occasionally recording data from one level twice during a data session, each subject had at least three 3-minute records of postural sway for every level of support, the mean value of each variable for each level of support was used. Data were filtered with a zero lag 4th order fourth-order low-pass Butterworth filter (cut off frequency 5 Hz) prior to calculating dependent variables. We calculated dependent variables for movement along the anterior-posterior (AP) axis and along the medial-lateral (ML) axis from two types of measurement: (1) displacement-related measures, (root mean square RMS) and mean distance from midline (MD), and (2) rate-related measures (mean velocity (MV), and variability of velocity (RMSV). These variables were used by Maurer and Peterka (2005) when creating their model for interpretation of sway data.

Statistical Analysis

Mixed within/between repeated measures ANOVA (SPSS version 17.0) was used to evaluate the effect of support (4 levels: axillae, midribs, waist, hip) on children with CP grouped by functional level (GMFCS IV or V) and TD infants grouped by developmental stages of sitting balance (collapse (3 mo), rise and fall (4 mo), wobble (5-6 mo) and functional (7-8 mo)) on each of the dependent variables (above). In order to compare data between these groups all values were normalized for the height of the free segment. Univariate ANOVA exploring the effect of group at each level of support was used to explore interactions between support and group. Post hoc Tukey HSD was used to determine significant differences between groups. Etta squared 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 maximum accuracy of the F-value.

Results

The results are divided into 3 sections. The first section reports the statistical results of comparisons for kinematic measures of alignment and sway stability for groups (TD infants grouped by age, 3 months, 4 months, 5-6 months and 7-8 months and children with CP grouped by level of severity, GMFCS IV (CP4) or GMFCS V (CP5)) at four levels of external support (axillae, mid-ribs, waist and hips). This is followed by statistical results of comparisons between these groups on clinical tests of upright control (the Segmental Assessment of Trunk Control and standardized gross motor measures of sitting ability (AIMS, and GMFM66)). The final section provides a qualitative comparison of individual children with and without CP showing global views of kinematic measures (COM plots, dwell time plots and velocity coded sway path) and photographs.

Kinematic Analysis

Table 2 shows the mean values for each group for all distance and rate related measures as well as the results of repeated measure ANOVA, including F-values, p-values and η^2 for the main effects of support, group (CP4, CP5 TD: 3mo, 4 mo, 5-6 mo, 7-8 mo), and the two way interaction, group by support. The values in Table 2 are the actual measurement values, as they are easier to compare across studies and have more clinical meaning. The statistical analyses were performed only on values normalized for the height of the free segment. Main effects (support and group) and interactions (support by group) were significant for all distance and rate-related variables along both axes. Since the group by support interactions were significant for every variable, further analysis was completed using MANOVA for each level of support individually. The results for MANOVA were the same as the univariate results; therefore the univariate results are shown in Table 3 for easier interpretability. Table 3 shows the univariate ANOVA for each variable at each level of support, as well as the results of post-hoc comparisons between groups.

Acquisition of Upright Alignment

In a previous study of TD infants (Chapter IV) we showed that the first step in acquisition of upright postural control was the achievement of vertical alignment along the medial-lateral axis. This was achieved in TD infants between 3 and 4 months of age. Achieving vertical alignment along the anterior-posterior axis was achieved in TD infants in a progressive manner, with only the 7-8 month olds showing good alignment at all levels of support Alignment for children with CP varied depending on the level of support and the severity of CP.

Table 2: Group means for distance and rate-related measures of postural sway

	Means and *standard error* by group across all 4 levels of support						**Effect of support**			**Group by Support Interaction**			**Effect of Group**		
Variable	**CP 4 n=8**	**CP5 n=6**	**TD 3 mo n=3**	**TD 4 mo n=9**	**TD 5-6 m n=32**	**TD 7-8m n=26**	F (3,234)	p	etta	F (15,234)	p	etta	F (5,78)	p	etta
	Sagittal Plane						**All statistical results are for data normalized by height of free segment**								
AP_MD	**10.22**	**15.14**	**6.2**	**4.84**	**4.47**	**3.24**	16.25	**.0005**	.172	5.34	**.0005**	.255	17.83	**.0005**	.533
(cm)	*.72*	*.83*	*1.17*	*.68*	*.36*	*.40*									
AP_RMS	**4.6**	**7.42**	**2.21**	**2.55**	**2.41**	**2.41**	29.30	**.0005**	.273	5.95	**.0005**	.276	9.95	**.0005**	.389
(cm)	*.34*	*.34*	*.55*	*.32*	*.17*	*.19*									
AP_MV	**2.01**	**4.98**	**1.5**	**2.11**	**1.75**	**1.73**	32.74	**.0005**	.296	4.50	**.0005**	.224	9.38	**.0005**	.376
(cm/s)	*.28*	*.32*	*.45*	*.26*	*.14*	*.15*									
AP_RMS	**3.30**	**8.38**	**3.64**	**3.4**	**2.9**	**2.96**	36.91	**.0005**	.321	5.32	**.0005**	.254	9.36	**.0005**	.375
V (cm/s)	*.47*	*.54*	*.77*	*.44*	*.24*	*.26*									
	Frontal Plane														
ML_MD	**3.27**	**5.80**	**3.69**	**1.92**	**1.69**	**1.47**	14.74	**.0005**	.159	5.07	**.0005**	.245	12.62	**.0005**	.447
(cm)	*.33*	*.38*	*.54*	*.31*	*.17*	*.18*									
ML_RMS	**2.89**	**4.81**	**1.49**	**1.45**	**1.41**	**1.44**	40.19	**.0005**	.340	5.32	**.0005**	.254	11.81	**.0005**	.431
(cm)	*.22*	*.26*	*.36*	*.21*	*.11*	*.12*									
ML_MV	**1.54**	**3.55**	**1.15**	**1.55**	**1.24**	**1.22**	53.39	**.0005**	.406	7.80	**.0005**	.333	8.99	**.0005**	.366
(cm/s)	*.21*	*.24*	*.34*	*.20*	*.11*	*.12*									
ML_RMS	**2.55**	**5.73**	**1.95**	**2.44**	**1.97**	**1.98**	30.34	**.0005**	.280	6.90	**.0005**	.307	9.77	**.0005**	.385
V (cm/s)	*.33*	*.38*	*.53*	*.31*	*.16*	*.18*									
segment	**31.80**	**28.11**	**14.51**	**15.34**	**15.95**	**16.84**									
height (cm)	*.74*	*.85*	*1.20*	*.69*	*.37*	*.41*									

The values listed are the original means. Data for each individual were normalized by height of the free segment at each level of support for all statistical analyses. Columns on the right show the results of the Repeated Measures Mixed Within Between ANOVAs, main effect of support, group by support interaction and main effect of group.

Table 3: Support by group interaction and posthoc results.								
					Post hoc Tukey significant results			
Axillae	Univariate ANOVA				**CP4 n= 8 CP5 n=6** for all comparisons			
Measure	**F (5,91)**	**p-value**	**Etta square**		**3 mo n=7**	**4 mo n=11**	**5-6 mo n=32**	**7-8 mo n=27**
AP_MD	5.535	.0005	.246		CP5 .002	CP5 .002	CP5 .01	CP4 .056 CP5 .0005
AP_RMS	4.836	.001	.221		CP5 .001	CP5 .001	CP5 .001	CP5 .01
AP_MV	4.132	.002	.196		CP5 .024	CP5 .024	CP5 .001	CP5 .024
AP_RMSV	5.858	.0005	.256		CP5 .013	CP5 .013	CP5 .0005	CP5 .022
ML_MD	5.497	.0005	.244		CP5 .039	CP5 .039	CP5 .0005	CP4 .056 CP5 .001
ML_RMS	8.743	.0005	.340		CP5 .005	CP5 .005	CP5 .0005	CP5 .0005
ML_MV	5.22	.0005	.235		CP5 .003	CP5 .003	CP5 .0005	CP5 .0005
ML_RMSV	6.03	.0005	.262		CP5 .03	CP5 .03	CP5 .0005	CP5 .0005
Mid-Rib	Univariate ANOVA							
Measure	**F (5,89)**	**p-value**	**Etta square**		**3 mo n=7**	**4 mo n=10**	**5-6 mo n=32**	**7-8 mo n=26**
AP_MD	5.171	.0005	.238		CP5 .003	CP5 .012	CP5 .002	CP5 .0005
AP_RMS	11.04	.0005	.399		CP5 .0005	CP4 .016 CP5 .0005	CP4 .028 CP5 .0005	CP5 .0005
AP_MV	7.939	.0005	.324		CP5 .002	CP5 .0005	CP5 .0005	CP5 .0005
AP_RMSV	8.289	.0005	.333		CP5 .002	CP5 .0005	CP5 .0005	CP5 .0005
ML_MD	6.75	.0005	.289		5-6m .049	CP5 .001	3 m .049 CP5 .0005	CP5 .0005
ML_RMS	8.632	.0005	.342		CP5 .0005	CP5 .0005	CP5 .0005	CP5 .0005
ML_MV	7.101	.0005	.300		CP5 .002	CP5 .001	CP5 .001	CP5 .0005
ML_RMSV	6.573	.0005	.284		CP5 .009	CP5 .001	CP5 .001	CP5 .0005
Waist	Univariate ANOVA							
Measure	**F (5,82)**	**p-value**	**Etta square**		**3 mo n= 6**	**4 mo n= 9**	**5-6 mo n= 32**	**7-8 mo n= 27**
AP_MD	15.99	.0005	.494		CP5<.0005	CP5<.0005	CP5<.0005	CP4 .033 CP5<.0005
AP_RMS	18.38	.0005	.528		CP5<.0005	CP5<.0005	CP5<.0005	CP5<.0005
AP_MV	10.43	.0005	.389		CP5 .001	CP5<.0005	CP5<.0005	CP5<.0005
AP_RMSV	10.45	.0005	.389		CP5 .001	CP5<.0005	CP5<.0005	CP5<.0005
ML_MD	8.213	.0005	.334		5-6m .002 7-8m .0005 CP4 .004		3 m .002 CP5 .003	3 m .0005 CP5 .0005
ML_RMS	15.28 9	.0005	.482		CP5 .021	CP5 .0005	CP5 .0005	CP5 .0005
ML_MV	8.611	.0005	.344		CP5 .01	CP5 .003	CP5 .0005	CP5 .0005
ML_RMSV	9.493	.0005	.367		CP5 .0005	CP5 .001	CP5 .0005	CP5 .0005
Statistical results for Univariate ANOVA for axillae, mid-ribs and waist level of support. Right columns are Post hoc Tukey test p-values for differences between groups.								

Table 3, continued								
Hip	Univariate ANOVA							
Measure	**F (5,79)**	**p-value**	**Etta square**		**3 mo n= 3**	**4 mo n= 9**	**5-6 mo n= 32**	**7-8 mo n=27**
AP_MD	17.52	.0005	.526		4m .001 5-6m .0005 7-8m .0005 CP4 .0005	3m .001 7-8m .0005	3m .0005 7-8m .001	3m .0005 4m .0005 5-6m .001 CP5 .0005
AP_RMS	4.99	.001	.24			7-8m .017		4m .017 CP5 .045
AP_MV	6.13	.0005	.279			7-8m .009	CP4 .002	4m .009
AP_RMSV	6.36	.0005	.287		7-8m .031 CP4 .001	7-8m .039	CP4 .005	3m .031 4m .039 CP5 .0005
ML_MD	7.77	.0005	.33		5-6m .015 7-8m .001 CP4 .001		3m .015 CP5 .047	3m .001 CP5 .001
ML_RMS	5.85	.0005	.27			CP4 .034	CP5 .018	CP5 .001
ML_MV	10.7	.0005	.404			7-8m .0005 CP4 .0005	7-8m .038	4m .0005 5-6m .0005 7-8m .018 CP4 .0005
ML_RMSV	10.63	.0005	.402			7-8m .0005 CP4 .0005	7-8m .054	4m .001 5-6m .054 CP4 .019
Statistical results for Univariate ANOVA for hip level of support. Right columns are Post hoc Tukey test p-values for differences between groups.								

Evaluation of alignment along the medial-lateral axis (Fig. 1) showed that children with moderate CP did not differ from TD infants when support was provided at the axillae and midribs. They had less deviation from midline than the 3 month olds with support at the waist or hips. In contrast, children with severe CP had greater deviation than all groups of TD infants with support at the axillae, greater deviation than all but the 3 month olds with support at the midribs, and greater deviation than 5-6 or 7-8 month olds with support at the waist (see Table 3 for statistical values).

Children with moderate CP (CP4) had greater deviation from midline along the AP axis (Fig. 2) than 7-8 month olds with support at the waist, and less deviation than the 3 month olds with support at the hip. Children with severe CP deviated further from midline than all but the 4 month olds with support at the axillae, greater deviation than all TD infants with support at the mid-ribs and waist and greater than the 5-6 and 7-8 month olds with support at the hips (see Table 3 for statistical values).

Thus, the children with moderate CP aligned as well as older (5-6 or 7-8 month) typically developing infants along both axes at all levels except the AP axis with support at the waist. The children with severe CP had poor alignment along both axes at all levels of support. They did not differ from the 3 and 4 month old TD infants with support at waist and hips for the ML axis, and with support at the axillae or hips for the AP axis.

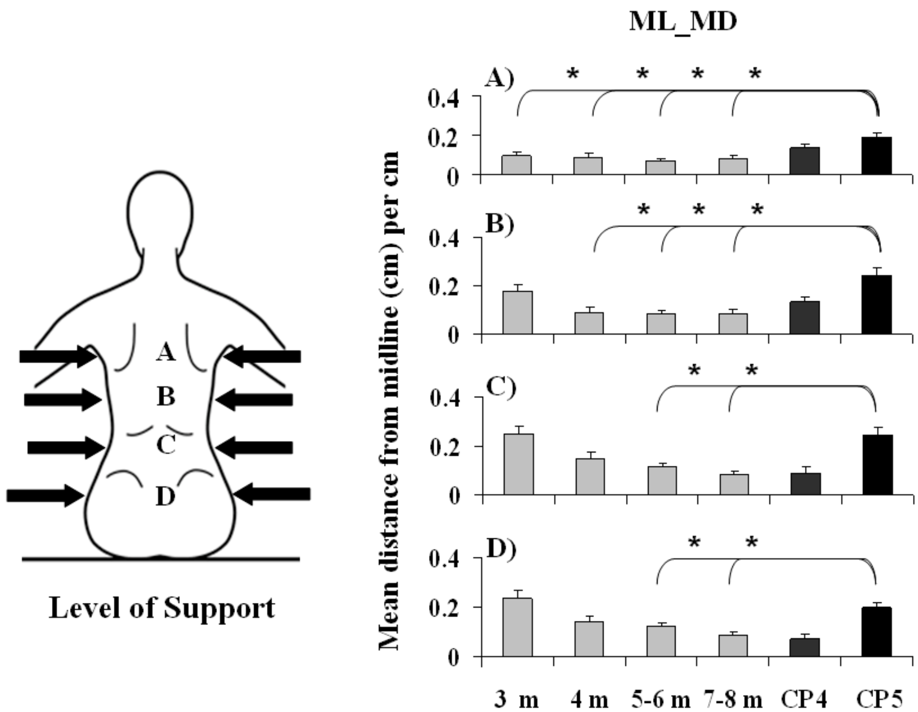

Figure 1. Vertical alignment along the medial-lateral axis. Letters indicate the level where external support was provided; A) axillae, B) mid-ribs, C) waist and D) hip. Distance from midline was normalized by height of the free segment (maximum distance from level of support to center of mass of the head along z-axis). TD infants *(grey bars)* grouped by age in months. Children with CP grouped according to severity of motor disability, GMFCS level IV and GMFCS level V (*black bars*). * indicates significant difference ($p < .05$) between groups on post-hoc tests corrected for multiple comparisons.

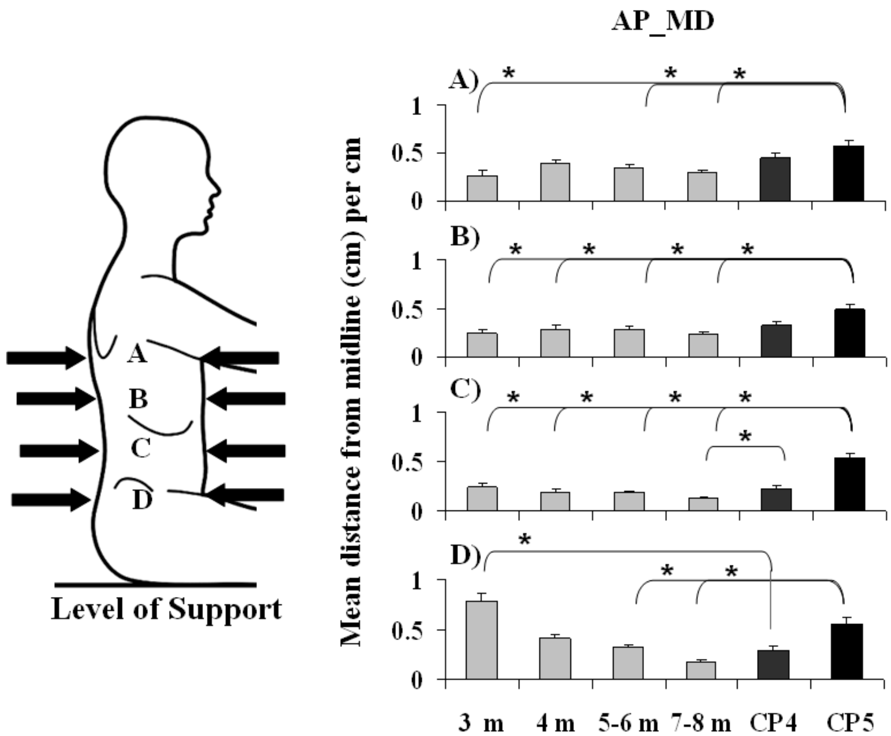

Figure 2. Vertical alignment along the anterior-posterior axis. Letters indicate the level where external support was provided: A) axillae, B) mid-ribs, C) waist and D) hip. Distance from midline was normalized by height of the free segments (maximum distance from level of support to center of mass of the head along z-axis). Bars indicate mean values for each group. TD infants *(grey bars)* grouped by age in months. Children with CP grouped according to severity of motor disability, GMFCS level IV (CP4) and GMFCS level V (CP5) (*black bars*). * indicates significant difference ($p < .05$) between groups on post-hoc tests corrected for multiple comparisons.

Stability of Sway

Stability was assessed using variability of position (RMS), variability of velocity (RMSV) and mean velocity (MV) for the ML axis (Fig 3) and the AP axis (Fig. 4). While there were distinct differences between the two CP groups and TD infants, each group showed a similar pattern of results across all three measures of stability (see Table 3 and Fig. 3 and 4).

Children with moderate CP were not different from TD infants for any of these measures when support was provided at the axillae, mid-ribs and waist, with the exception of less variability of position than 4 or 5-6 month olds along the AP axis with support at the mid-ribs. When support was lowered to the level of the hip, the CP4 group had slower mean velocity than 4 or 5-6 month olds along both axes and slower mean velocity than 7-8 month olds along the ML axis. They had less variability of position than 4 month olds along both axes and less variability of velocity than all but the 7-8 month olds along the AP axis and less than all but the 3 month olds along the ML axis.

In contrast, children with severe CP had greater values than all TD infants for all measures of stability when support was provided at the axillae, mid-ribs and waist, with the exception of mean velocity, which was not different than 4 month olds along either axis with support at the axillae. When support was lowered to the level of the hip, the CP5 group had greater variability of position (RMS) than 7-8 month olds along both axes, and 5-6 month olds along the ML axis. At this level mean velocity (MV) was not different than any TD infant group and variability of velocity did not differ from TD

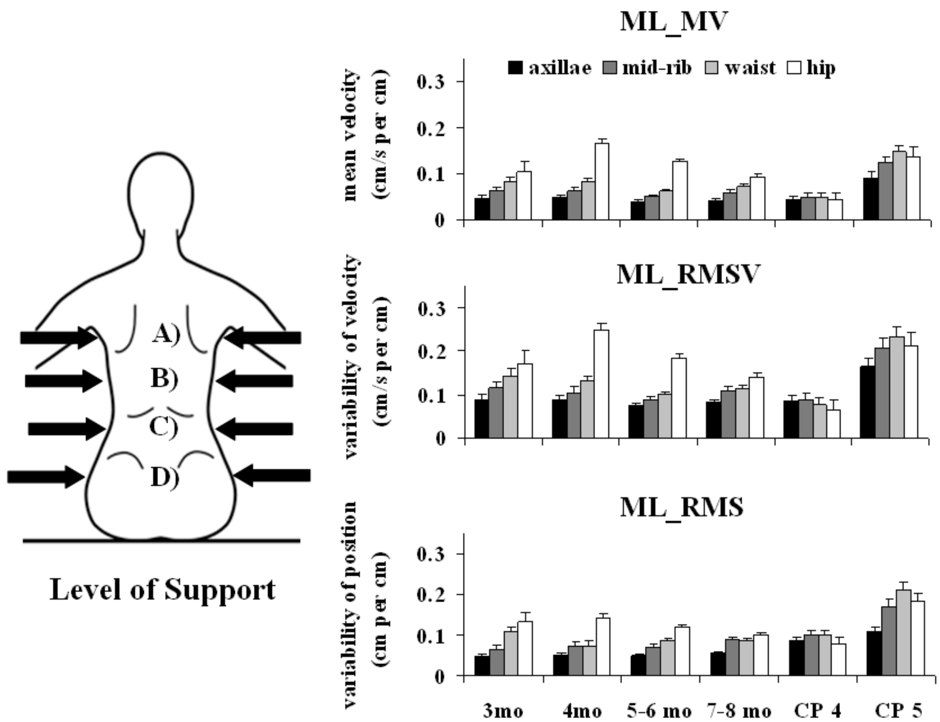

Figure 3. Stability of sway along medial-lateral axis. Four levels of external support: A) axillae (*black bars*), B) mid-rib (*dark gray bars*), C) waist (*light gray bars*) and D) hip (*white bars*). Bars represent mean velocity (MV), mean variability of velocity (RMSV) and mean variability of position (RMS) for TD infants grouped by age and children with CP grouped by level of severity, GMFCS level IV (CP4) and GMFCS level V (CP5). Error bars represent standard error of mean. See Table 3 for post-hoc differences between groups.

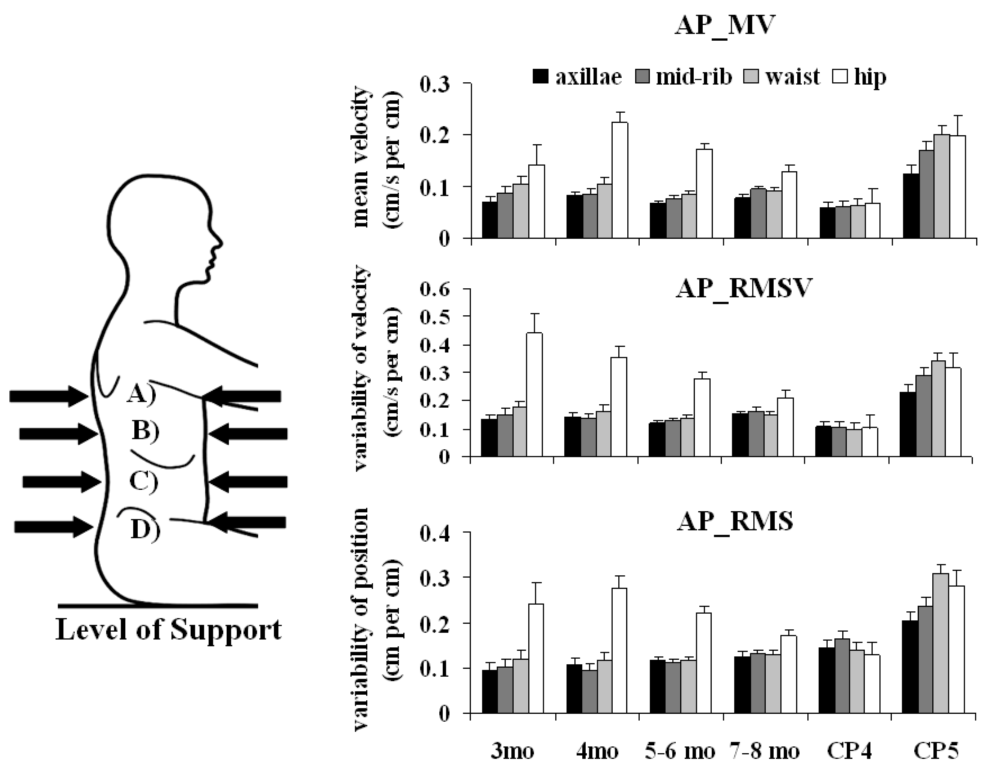

Figure 4. Stability of sway along anterior-posterior axis. Four levels of external support: A) axillae (*black bars*), B) mid-rib (*dark gray bars*), C) waist (*light gray bars*) and D) hip (*white bars*). Bars represent mean velocity (MV), mean variability of velocity (RMSV) and mean variability of position (RMS) for TD infants grouped by age and children with CP grouped by level of severity, GMFCS level IV (CP4) and GMFCS level V (CP5). Error bars represent standard error of mean. See Table 3 for post-hoc differences between groups.

infants along the AP axis but was greater than 5-6 month and 7-8 month TD infants along the ML axis.

Thus, children with moderate CP were able to stabilize their postural sway similarly to TD infants with support at the axillae, mid-ribs or waist and had greater stability than most TD infant groups with support at the hip. Review of mean values (Fig. 4 and 5) shows that the children with moderate CP, unlike TD infants, did not have changes in measures of sway stability across levels of support. In contrast, children with severe CP had stability similar to TD infants with support at the hip, and larger amplitude, velocity and variability of sway than TD infants with support at axillae, mid-ribs or waist. Although providing support did reduce the means for this group the effect of support was not as strong as the reduction seen in TD infants.

Behavioral Analysis

Segmental Assessment of Trunk Control (SATCo)

Figure 5 shows the results of the average SATCo test results for children with CP and for TD infants categorized by age in months. This test indicates that children with severe CP lost postural control in the cervical or upper thoracic spine while those with moderate CP lost control in the upper to mid thoracic spine. TD infants gained control in a cephalo-caudal manner, with control progressing from the upper thoracic area at 3-4 months through the lower thoracic spine at 5 and 6 months, to lumbar and full spine control by 8 months of age. ANOVA showed significant differences between groups for

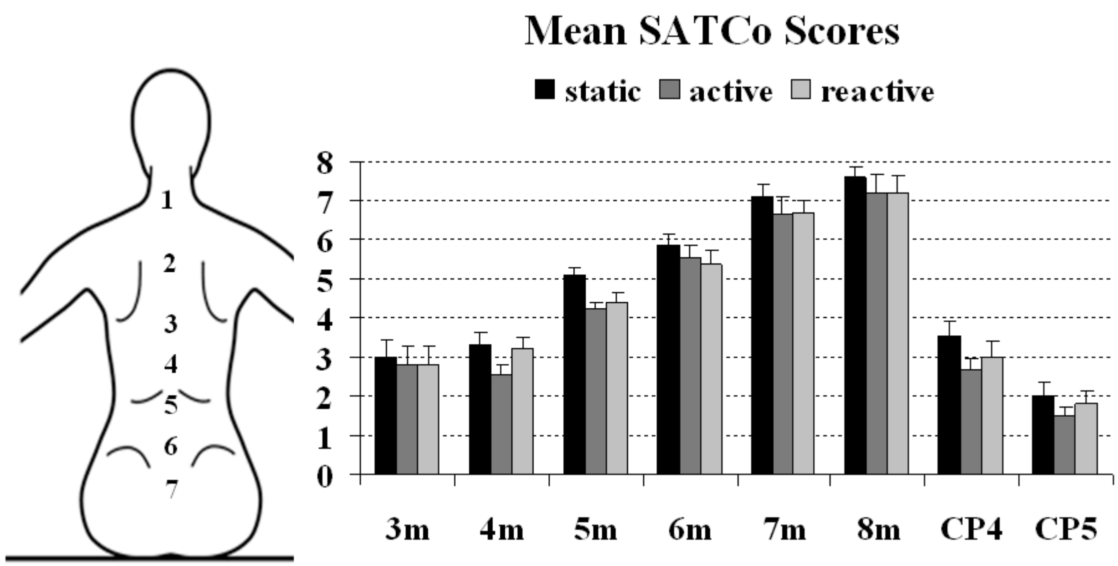

Figure 5. Segmental Assessment of Trunk Control. Mean level of postural control for children in each group (TD infants by age (month) and children with CP by level of severity, GMFCS level IV (CP4) and GMFCS level V (CP5). Three aspects of control are tested static, the ability to align in vertical (*black bars*), active, the ability to hold alignment while turning head or reaching (*dark gray bars*) and reactive, the ability to hold alignment when given a brief nudge (*light gray bars*). Control is scored 1 through 8, 1 = head control, 2 = upper thoracic control, 3 = middle thoracic control, 4 = lower thoracic control, 5 = upper lumbar control, 6 = lower lumbar control, 7 = pelvic control, 8 = full trunk control. Error bars represent standard error of the mean.

static ($F(5,70)=48.79$, $p<.0005$), active ($F(5,70)=35.89$, $p<.0005$), and reactive ($F(5,70)=36.09$, $p<.0005$) tests on the SATCo. Post hoc tests show that TD 5-6 mo, and 7- 8 mo old infants had postural control at significantly lower levels of the spine than all groups with CP ($p \leq .001$ for all comparisons). Thus the SATCo results are consistent with the comparisons seen in kinematic data for the children with severe CP and suggest loss of control at higher levels of the spine than indicated by kinematic data for children with moderate CP.

Functional Sitting Assessments

We tested all children with CP using the Gross Motor Function Measure_66 dimension B (sitting skills) and all infants with the Alberta Infant Motor Scale which also has a subsection for sitting skills. These two tests have been shown to be valid and reliable measures of change in motor function for their respective populations. There is direct overlap in many of the items tested between the two measures; however scoring and exact method of administration varies. In order to compare functional sitting ability between the two groups we calculated the percent success from the total possible for each infant and child on their respective tests. Figure 6 shows the average functional sit score for each group. ANOVA demonstrated a main effect of group on these test scores ($F(5,57)= 32.25$, $p<.0005$). Children with moderate CP, like TD 5-6 month olds, performed better than TD 3 and 4 month olds, while performing worse than the 7-8 month olds ($p<.01$ for all comparisons). Children with severe CP performed significantly worse than TD 7-8 month olds ($p <.0005$).

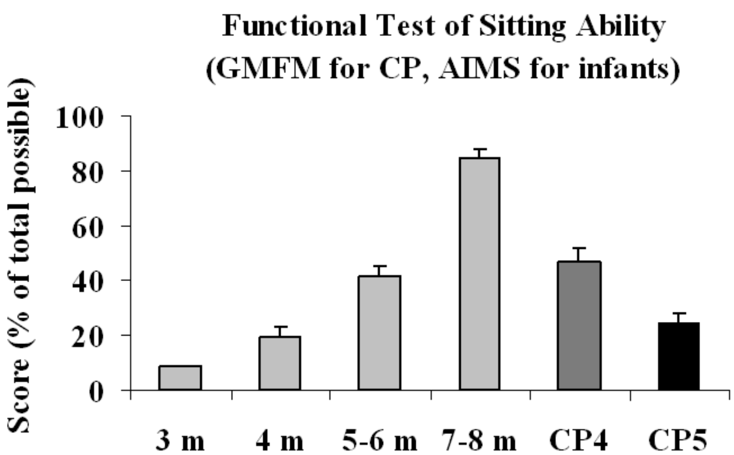

Figure 6. Percent success on standardized tests of sitting skills. Alberta Infant Motor Scales (AIMS) for TD infants (*light gray bars*) and Gross Motor Function Measure (GMFM 66) dimension B for children with CP (GMFCS IV (dark gray bar), GMFCS V (black bar).

Qualitative Comparison of Postural Control

In order to better demonstrate the similarities and differences in the kinematic and behavioral results this section shows results from qualitative analysis of postural sway. Dwell time plots show the distribution of head position in the along the AP axis over the full 3 minutes of data collection. These histograms provide a qualitative view of distance-related variables (RMS, MD) along the AP axis. They are the best plot for demonstrating changes in RMS. The center of mass (COM) plots show the path of the COM of the head in relation to the base of support, as if looking down from above the child. Thus these plots provide a good view of the relationship between distance-related measures along both (AP and ML) axes and the base of support. The final plots show change of position along the AP axis across time, with position color coded for velocity. These plots allow a more specific evaluation of the sway pattern of the child over time and offer a qualitative view of rate-related as well as distance-related measures for movement along the AP axis.

Based on results from kinematic as well as behavioral data, we chose to examine individual children with support at the hip level. This level provides the greatest variability between groups across all measures. We chose to compare the qualitative plots of a single TD infant across development at 3 months, 4 months and 5 months of age with those of individual children with CP.

The first comparison (Fig.7) shows data from the TD infant at 15 weeks of age and an 8 year old with severe CP. Notice that both children demonstrate slow collapse. Both children required assistance after the slow collapse and were returned to vertical by the researcher during the data collection (8C and 8E at ~45 seconds and again at ~120

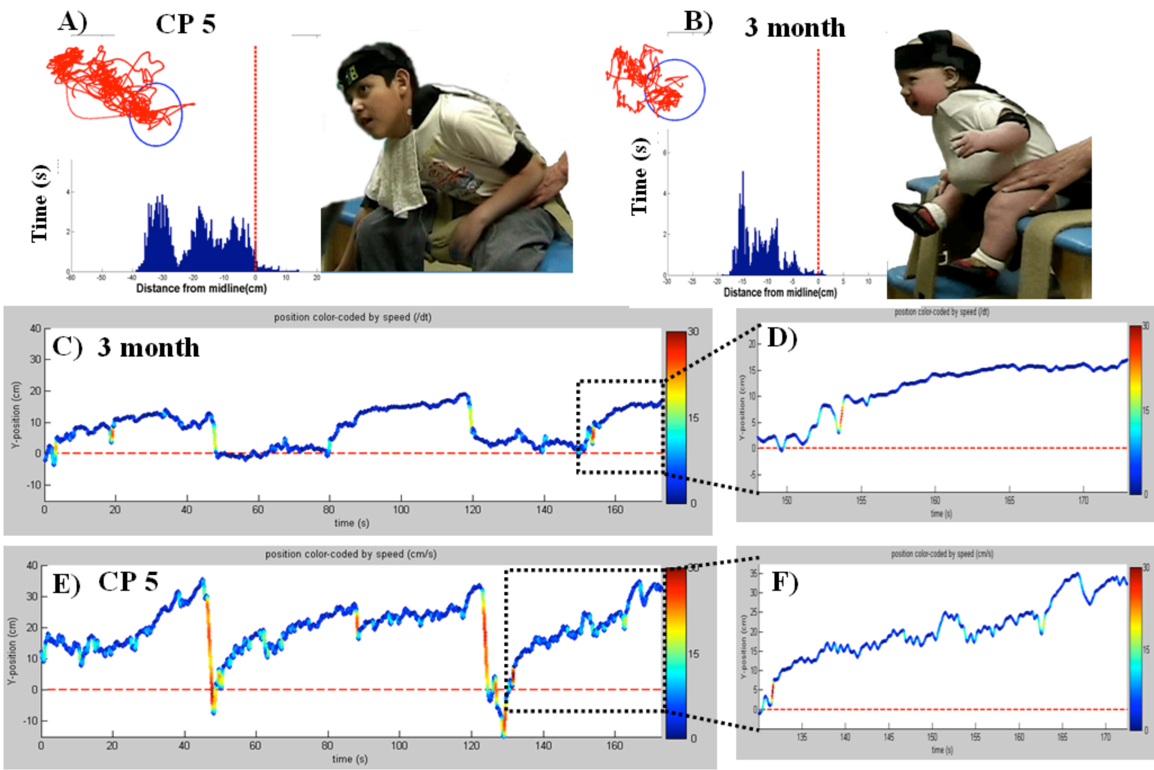

Figure 7. Qualitative comparison I. Eight year old with severe CP (panels A, E, F) and a TD infant at 3 months of age (panels B, C, D). COM plots show circumference of base of support (*blue ellipse)* with path of the head COM (*red line*) over the 3-minute data collection (A, B). Histograms show the position of the COM of the head (*blue columns*) in relation to midline (*red dotted line*) along the AP axis (A, B). The position of the head COM along the AP axis across time is color coded for speed (0 to 30 cm/s) (C-F). Selection of time series that is enlarged is encased in a box (*black dotted lines*). Both children required assistance to return to midline at ~ 45 seconds and ~ 120 seconds. The TD infant was supported in midline for calming before re-release.

seconds. The TD infant required a longer period of support to be in a calm state before re-release. All three plots show qualitatively similar movement patterns between these two children.

Figure 8 shows sway data from a 6 year old in the CP5 group, placed adjacent to the TD at 18 weeks of age. Both of these children were able to initiate movement to the upright position. The TD infant spent most of the data collection in a forward collapsed position but made several attempts to align vertically towards the end of the session, while the child with CP made frequent attempts to align vertically throughout the data collection. Notice both plots show increased speed and variability of movement and look more chaotic than the plots in Figure 7, as children initiate vertical and then fall away. The child with CP clearly had greater difficulty constraining movement along the ML axis than the TD infant. Other than this difference, all 3 types of plots show qualitatively similar patterns of movement.

Figure 9 shows data from an 8 year old in the CP4 group adjacent to data from the TD infant at 21 weeks of age. Both children show refined edges to the sway plot as they correct their position each time they move away from their self-defined center of control. Notice that both children sustain a slight forward lean, suspending their center of mass near the front edge of their base of support. They rarely come all the way to vertical. Again, all three plots demonstrate qualitatively similar patterns of sway.

Dwell time histograms and COM plots for each remaining child in the GMFCS IV group (Fig. 10, A-G) and GMFCS V group (Fig. 10,H-K) indicate that, at the hip level

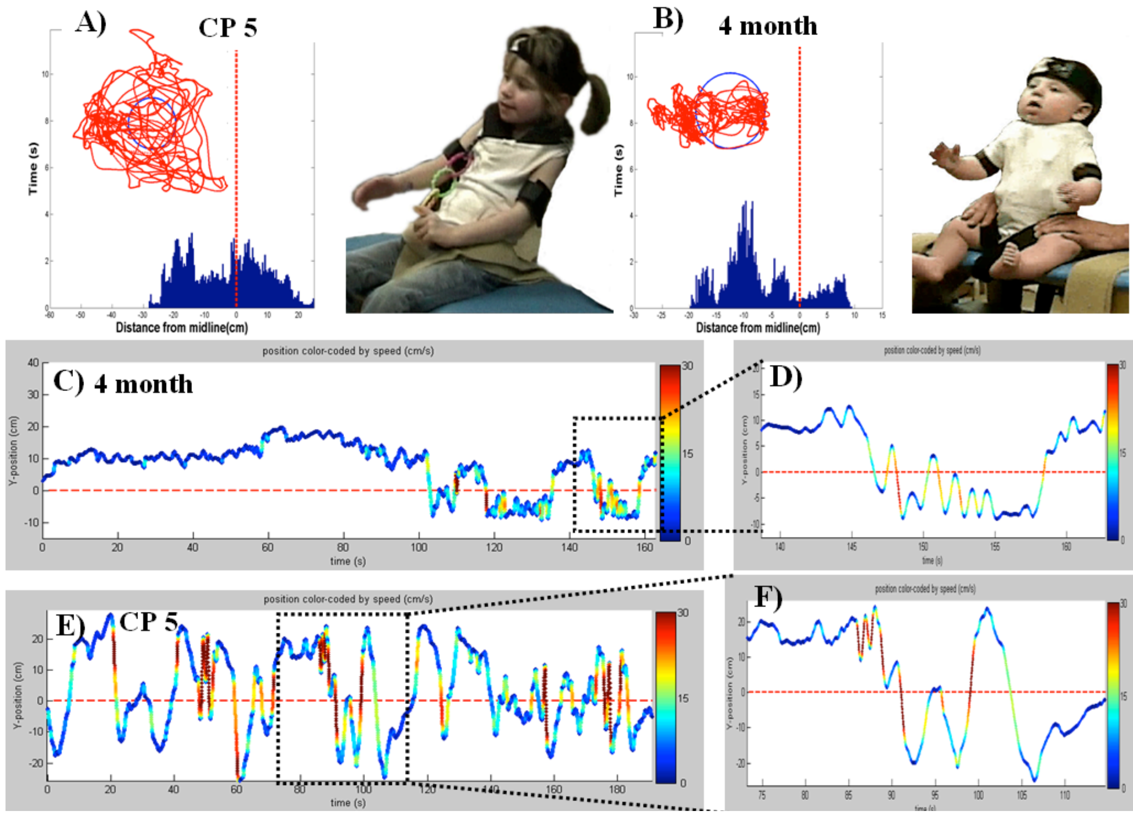

Figure 8. Qualitative comparison II. Six year old with severe CP (panels A, E, F) and a TD infant at 4 months of age (panels B, C, D). COM plots show circumference of base of support (*blue ellipse)* with path of the head COM (*red line*) over the 3-minute data collection (A, B). Histograms show the position of the COM of the head (*blue columns*) in relation to midline (*red dotted line*) along the AP axis (A, B). The position of the head COM along the AP axis across time is color coded for speed (0 to 30 cm/s) (C-F). Selection of time series that is enlarged is encased in a box (*black dotted lines*).

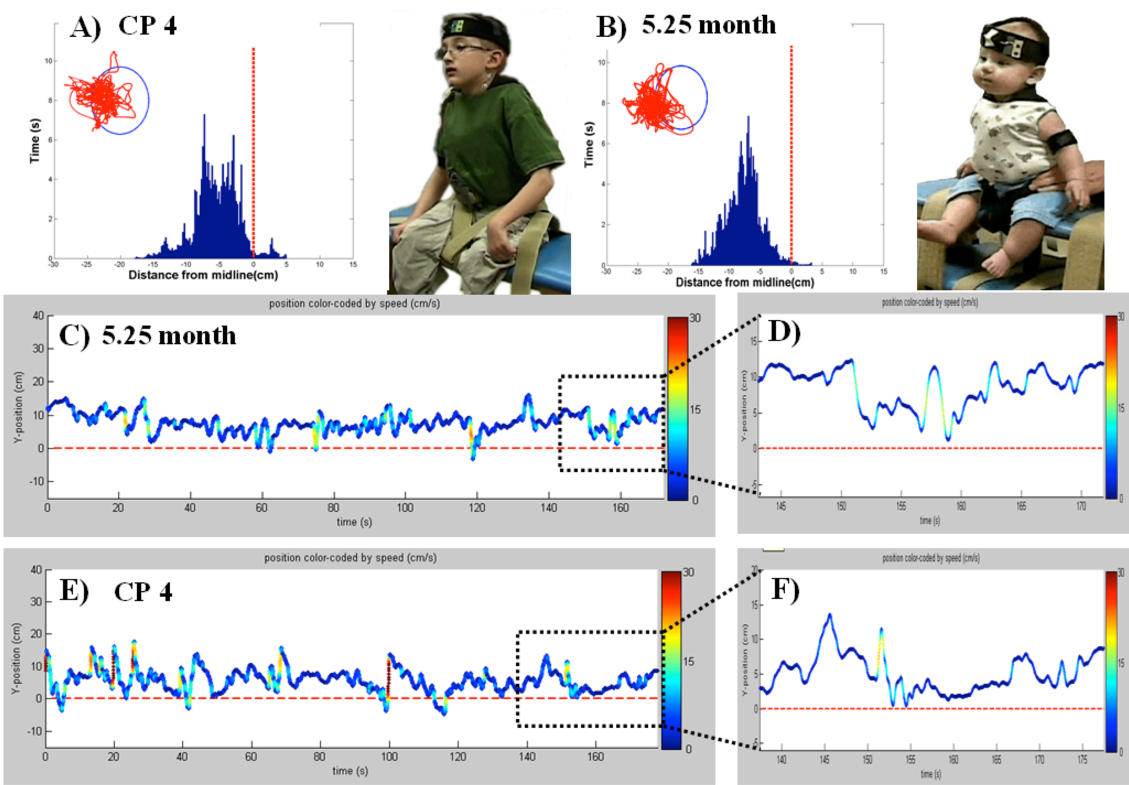

Figure 9. Qualitative comparison III. Eight year old with moderate CP (panels A, E, F) and a TD infant at 5 months of age (panels B, C, D). COM plots show circumference of base of support (*blue ellipse)* with path of the head COM (*red line*) over the 3-minute data collection (A, B). Histograms show the position of the COM of the head (*blue columns*) in relation to midline (*red dotted line*) along the AP axis (A, B). The position of the head COM along the AP axis across time is color coded for speed (0 to 30 cm/s) (C-F). Selection of time series that is enlarged is encased in a box (*black dotted lines*).

of support four of the children in the CP5 group resembled TD 3 month olds (Fig. 10 H, I, J and Fig. 7) in that they collapsed forward and were unable to return to midline independently. Two children in this group resembled 4 month olds (Fig. 10 K and Fig 8), in that they initiated an upright position, but were unable to sustain that position. Five children in the GMFCS IV group (Fig. 10 A-D and Fig. 9) resembled the TD 5-6 month olds. They sustained a forward lean position without completely collapsing but also without rising all the way to vertical; an additional three children in the GMFCS IV group (Fig. 10 E-G) resembled the TD 4 month olds, showing greater variability of position and a collapse and rise pattern of movement.

Active Stiffness Analysis

Thus far, none of the results have explained the fact that children with moderate CP appeared to have improved stability at lower levels of trunk support. Children with mild CP have been shown to use co-contraction and stiffness, which interferes with flexibility in responding to postural perturbations. Therefore we hypothesized that children with more severe CP might also use active stiffness as a postural control strategy. Maurer and Peterka (2005) showed that active stiffness changes postural sway parameters in a unique way; distance related measures decreased, while rate related measures increased. We examined the relationship between these sway measures across the different levels of support to look for evidence of active stiffness as a postural control strategy. Each panel in Figure 11 shows mean variability of position (RMS) compared to mean velocity (MV) along the AP axis at each level of support for each group (TD

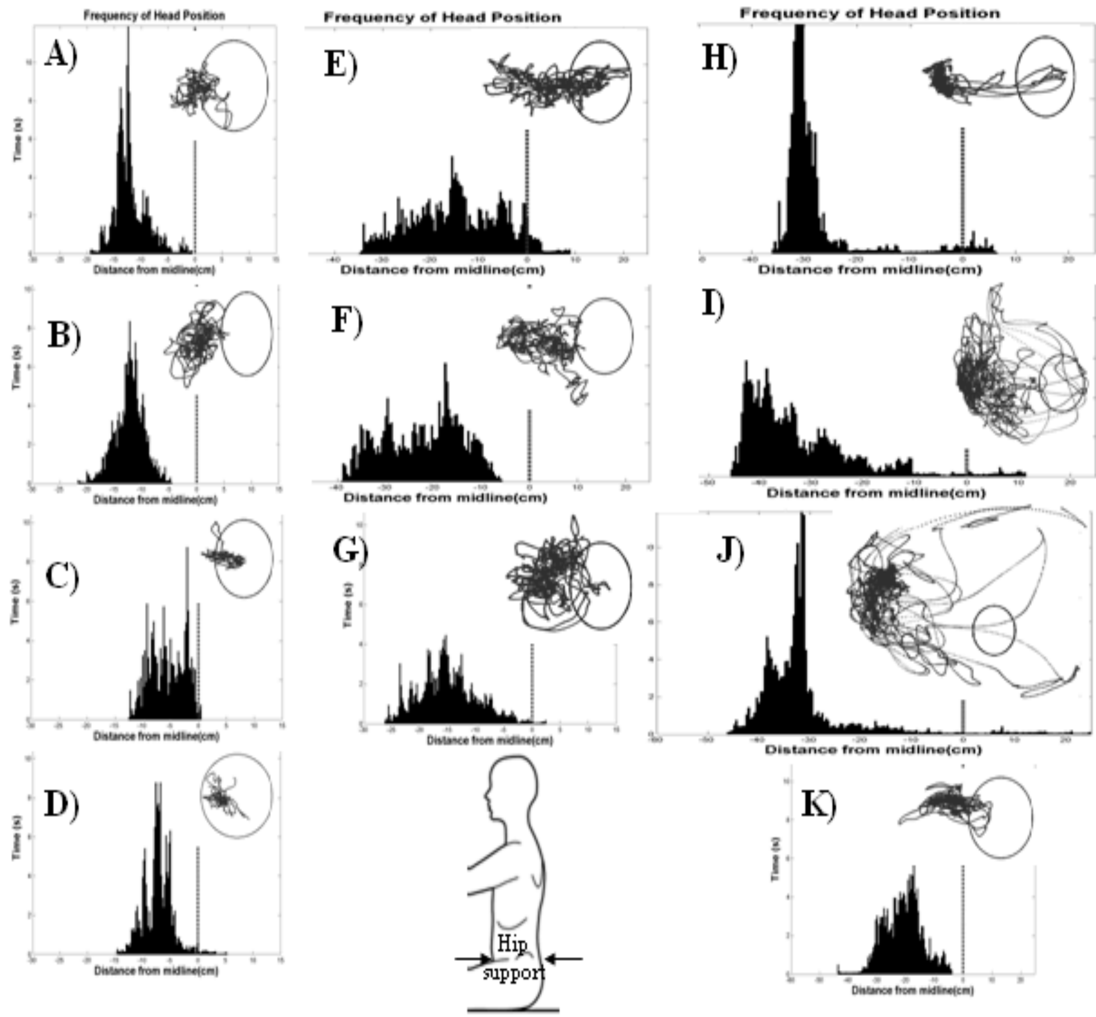

Figure 10. Individual histogram and COM plots. Support at the hip. Data are for children with CP not shown in previous figures. GMFCS IV group (panels A-G) and GMFCS V group (panels H-K). Figure and panel numbers are indicated in the last column of Table 1 to allow these plots to be compared with demographic information for each child.

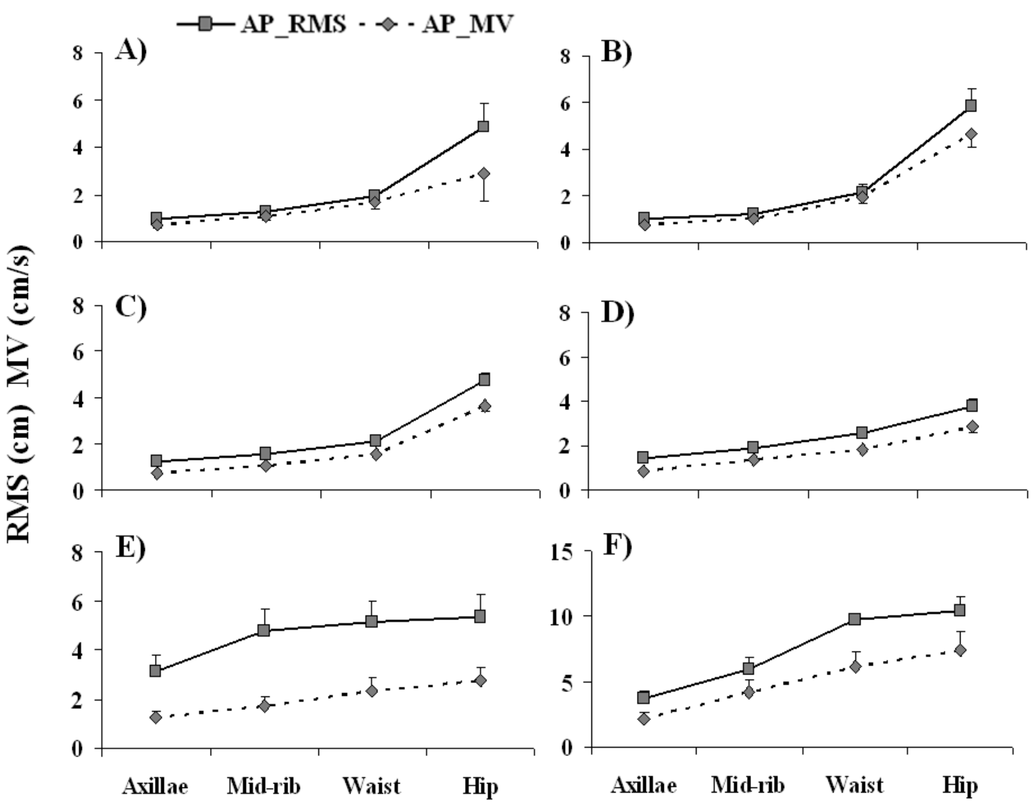

Figure 11. Active stiffness evaluation along anterior-posterior axis. Decrease in distance related measures (RMS, *gray squares, solid line*) with concurrent increase in rate related measures (MV, *gray triangles, dotted line*) indicates use of active stiffness. Each panel shows changes in data from one group across all 4 levels of support. A) TD 3 mo, B) TD 4 mo, C) TD 5-6 mo, D) TD 7-8 mo, E) CP4, F) CP5.

infants = panels A-D, children with CP = panels E-F). Notice that typical infants (A-D) had a progressive increase in RMS as the support was lowered. Mean velocity increased in parallel with RMS or slightly more slowly. In contrast increases in RMS leveled off sharply between mid-ribs and waist/hip support in the CP4 group and between waist and hip support in the CP5 group. In both cases velocity continued to gradually increase. Thus, the changes in postural parameters suggest the use of active stiffness with support at the waist and hip for the CP4 group, and with support at the hip for the CP5 group.

Discussion

The goal of this study was to examine the contribution of spinal segments to trunk postural control in children with moderate to severe CP and to compare those results to the developmental progression of spinal control seen in TD infants (3-9 months of age). Using stability of the head in space as a measure of upright control and an external support device to align the children vertically and isolate specific spinal segments, changes in postural control were evaluated in a group of 14 children with quadriplegic CP who had moderate (n=8) or severe (n=6) motor disability based on GMFCS (level IV and V). Results indicated that deficits occur at different levels of the spine in children with moderate and severe CP. Children in both groups were situated along the developmental continuum of upright control seen in TD infants of 3-6 months of age. Sway patterns with support at the hip show strong similarities between children with CP and TD infants.

Children with severe CP (GMFCS V) performed similarly to TD 3 or 4 month olds and children with moderate CP (GMFCS IV) performed similarly to 5-6 month olds at this level of support.

We hypothesized that the level of trunk control would be the defining characteristic of the severity of motor deficit. Thus, we expected that children with severe CP (GMFCS V) would have trunk control similar to younger TD infants (3-4 month olds) and that they would have deficits in postural control in the upper segments of the spine. Our results support these hypotheses. Kinematic measures for the CP5 group were not significantly different from 3 and 4 month olds when support was provided at the hip. Qualitative comparisons of sway parameters at this level of support showed strong similarities in postural performance between the children with CP and TD 3 or 4 month olds.

These groups also showed comparable levels of achievement on standardized assessments of functional sitting skills (% of total points achieved on the AIMS sit subsection for TD infants and GMFM 66 dimension B for children with CP). In the upper levels of the spine (support at axillae, mid-ribs or waist), children with severe CP had greater difficulty achieving vertical alignment along both the AP and ML axes and had faster sway, with greater variability of position and velocity than all TD infants. This result was partially due to instability in the children with CP and partially due to the fact that support in the upper trunk had a more stabilizing effect on TD infants than on children with CP.

Results of the SATCo test provided additional support for the idea that children with severe CP have deficits in the upper spine. This test indicated that children with severe CP had deficits in the upper spine that were worse than those seen in TD 3 or 4 month olds. SATCo results showed that children with severe CP lost upright control in the cervical or upper thoracic spine, while TD 3 and 4 month olds showed control in the cervical and upper thoracic spine, but lost control in the mid-thoracic spine.

We also hypothesized that children with moderate motor deficits would perform similarly to older TD infants and would show better postural control when given support at the axillae or midribs and loss of control as the support level was lowered to the waist or hips. As hypothesized, we found evidence of better development of spinal control in the children with moderate CP than those with severe CP. The GMFCS IV group most closely resembled the 5-6 month olds in sway characteristics when support was provided at the hip and during functional sitting skills. Their alignment differed significantly from older TD infants (4 month, 5-6 month, 7-8 month) only when support was provided at the waist. At this level they had significantly greater deviation from midline along the AP axis than TD 7-8 month olds. The only stability measure in which they performed worse than TD infants was variability of position; they had greater variability of position (RMS) than the 4 month and 5-6 month olds along the AP axis when support was provided at the mid-ribs.

It is a bit surprising that these children have poor sitting balance. Their kinematic measures indicate that they were able to achieve reasonable alignment and stability at all levels of support. In contrast to the kinematic findings, the SATCo scores for this group showed deficits in spinal control with support at the mid-thoracic spine, similar to TD 3 and 4 month olds. Observation of these children showed that they had a tendency to have exaggerated thoracic kyphosis, which allowed their head to remain closer to midline at lower levels of support. When support was provided at the mid-ribs, this compensatory measure was blocked and their head position extended further from midline along the AP axis. When they raised their hands they also straightened their spines and thus had greater variability of position than the TD infants who remained reasonably upright with hands up or down.

This group also varied from TD infants when their data were examined for evidence of active stiffness. The children with CP demonstrated reduction in distance-related variables as support was lowered, while TD infants had a simultaneous increase in distance and rate-related variables as support was lowered. Based on the pattern of changes in mean velocity and variability of position, we suggest that the children with CP used an active stiffness strategy in order to control the increasing degrees of freedom of the spine as the support was lowered to the waist and hips. Co-activation of antagonistic muscles and stiffening of joints have been previously shown when children with spastic CP (GMFCS I, II, II) were exposed to postural perturbations in standing (Nashner et al., 1983, Burtner et al., 1998) and sitting (Brogren et al., 1998). It appears that the children in the GMFCS IV group used a strategy of active stiffness when support was provided at the waist and at the hip. This is consistent with the SATCo findings of poor postural control in these regions of the spine.

By examining the control of the spine segmentally we were able to demonstrate that active stiffness was used during quiet sitting as children became challenged to control the full length of the spine. One of the primary deficits noted in postural control in children with CP is the inability to adapt their responses to changing environmental conditions (Roncesvalles et al., 2002, Brogren et al., 1998). We suggest that active stiffness may interfere with the flexibility of response needed to adjust to environmental conditions and thus, may contribute to the failure of these children to gain functional sitting skills.

Implications for Treatment

Although postural deficits are a hallmark of children with CP (Bax et al., 2005) and postural control creates the basis for all functional movement there is a paucity of published studies examining the effect of training on postural control in TD infants or children with CP. Two studies have demonstrated improved adaptability of postural responses in TD infants when given intensive practice near the edges of control in sitting (Hadders-Algra et al., 1996) or on a moving platform when in the process of learning to stand (Sveistrup & Woollacott., 1997). When similar types of standing perturbation training were given to a group of school age children (7-12 years) with cerebral palsy, the children were able to improve their balance recovery skills. Reduced antagonist co-activation accompanied improvements in balance in four of these children (Shumway-Cook et al., 2003). Thus, we know it is possible to change postural control developmentally and it is also possible to change postural control in older children with mild CP. There is preliminary evidence from a case series of 6 children with moderate CP (5 quadriplegic and 1 diplegic) that demonstrated improved independent sitting balance when posture control was trained with a device that allowed targeting of specific segments of the spine (Butler, 1998). The results of the current study demonstrate deficits of postural control in the neck and upper thoracic spine in children with severe CP (GMFCS V) and in the mid or lower thoracic spine in children with moderate CP (GMFCS IV) classification. Previous research and clinical treatment focus has been based on a single segment model of trunk control. This has led to global treatment focused on strengthening the entire trunk or training postural control at the level of independent sitting, without assisting children to develop the necessary progression of segmental spinal control seen in TD infants. The current study supports the concept of training postural control segmentally as recommended by Butler (1998).

Of primary importance is the evidence that segmental deficits of postural control occur in the trunk in children with CP and that these deficits are comparable to those seen in early stages of the normal development of trunk control for independent sitting. Awareness is the first and most important step to creating change. Once clinicians become aware of the possibility of segmental deficits in the spine, and that these deficits are related to GMFCS level, they will be motivated to refine their clinical evaluations to include more precise evaluation of trunk control. Specificity of evaluation has the potential to promote specificity of treatment in many ways.

Even without training devices, the child’s current support devices could be adapted to promote more optimal levels of support. This would include improved support to areas that need it as well as creating freedom to move above the level of support so that training of postural control could be enhanced throughout the day as children use their positioning device. The knowledge that the support level should be re-evaluated and adjusted as children gain control is new. Currently support devices are adjusted for growth, but not for promotion of skill advancement. Increased awareness of variations in segmental control of the spine in this population would also promote changes in handling techniques provided by therapists and family members. Adjustment of manual support to the appropriate level of the spine during therapy sessions and home programs could help the child be more successful. Thus all activities in the day of a child with moderate to severe disability could potentially be adjusted to promote not only improved function but also to promote continued development.

Conclusion

This study of segmental contributions to the development of trunk control makes important contributions to the scientific and clinical literature, as well as the rehabilitation of children with moderate to severe CP. This information will provide a foundation for the innovation of new methods to assess and treat postural dysfunction and its associated constraints on other functional skills. This study establishes a paradigm for continued research regarding posture treatment techniques for children with CP. Since the concept of considering the trunk as a single unit currently exists within all of neurological rehabilitation, the concept of studying the segmental contributions to trunk control, once proven for this population, may improve treatment for children with other neuromuscular and orthopedic deficits that constrain postural development as well as adults following neurologic lesion.

CHAPTER VI

CLINICAL IMPLICATIONS FOR TREATMENT

Studies have shown that for children with cerebral palsy, timely development of independent sitting balance is a key determinant of independent ambulation and future motor skill development (Wu et al., 2004). Trunk control is a necessary prerequisite to development of independent sitting balance. A serious health care issue is that most children with CP at GMFCS levels IV and V (30% of children with CP) do not have adequate trunk control to achieve functional independent sitting balance; thus they have severely impaired motor skills including reaching, walking, and dressing (Kennes et al., 2002). This dissertation examined principles underlying the development of segmental trunk control in typically developing infants, and compared segmental contributions in typically developing infants to those in children with CP. Thus results of this study provide new insights into the specific improvements in postural control at various spinal segments during typical development and how this varies in atypical development. These insights can be used to critique and improve current approaches to training trunk postural control for this vulnerable population.

Current Approaches to the Care of Children Lacking Trunk Control

Guidelines for treating the child with moderate to severe CP are limited. Traditional approaches to treatment for this group of children have focused on the use of positioning devices to assist mobility, promote weight bearing, prevent muscle contractures, and reduce stereotyped muscle reflex responses. Much of the focus of treatment is on improving ease of care giving, comfort and prevention of secondary deformity rather than changing function. Recent population studies have demonstrated that motor skill development plateaus much faster for children in GMFCS categories IV and V. Indeed these children reach 90% of their motor potential as early as 2.7 years of age for children in GMFCS V (Rosenbaum et al., 2002b). These children remain dependent on caregivers for all mobility. Transfers require complete physical assistance of one and eventually two adults or a mechanical lift. Special equipment is needed for positioning in sitting, standing and often for head control (Palisano et al., 2008).

The conclusions of a recent research summit from the Pediatric Section of the American Physical Therapy Association (Fowler et al., 2007) focused only on protocols for strength and fitness training in ambulatory children with CP (GMFCS I, II, and III). The only comment regarding children with more severe deficits was that "more research is needed to identify appropriate training strategies and outcome measures for children with other movement disorders, such as athetosis, dystonia and ataxia, and a wider spectrum of functional impairments (e.g., GMFCS IV and V)". The call for more innovation and more research has been echoed by a number of studies regarding postural control in CP (Butler & Major, 2003, Westcott & Burtner, 2004, Mahoney et al., 2004, Harris & Roxborough, 2005, deGraaf-Peters et al., 2007).

Underlying Assumptions to Guide Therapy Practice

The single segment model of the trunk is pervasive in clinical practice as well as research on postural control. Assessments of trunk control in children with CP evaluate the global ability to sit and document children's ability to raise their head, sit in a propped position with one or two hands used for support as well as the ability to get in and out of a sitting position (Russel et al., 2002). The underlying assumption is that these functional level assessments demonstrate the amount of postural control available in the spine. Butler and Major (2003) have challenged these assumptions by pointing out that these tests evaluate overall function but fail to produce specific details of spinal control to guide therapy. It is their approach we have used in these studies. Although they hypothesized gradual development of spinal control in typical infants and created a treatment paradigm for targeting spinal segments based on this assumption, until now there was no empirical evidence to support their claims. The studies in this dissertation challenge clinicians and researchers to reconsider the use of the single segment model of trunk control during development, especially in children with neuromotor deficits that interfere with maturation of postural control.

The evidence contributed by this dissertation suggests that the segmental level of spinal control may be a key factor in determining severity of motor function and thus contributing to motor development and prognosis in children with CP. Indeed, the guidelines for scoring the GMFCS include the following statements: GMFCS III, “when seated, children may require a seat belt for pelvic alignment and balance,” GMFCS IV, “children require adaptive seating for trunk and pelvic control,” and GMFCS V, “children are limited in their ability to maintain antigravity head and trunk postures” Palisano et al., 2008). Notice the progressive nature of the trunk control issues alluded to in these guidelines. This dissertation provides more specific information regarding the level of spinal control at each of the levels of classification. We show evidence that children at GMFCS level V have deficits in postural control in the cervical and upper thoracic spine, and that children at GMFCS level IV have deficits in postural control in the mid and lower thoracic spine. Pilot data collected during the course of the dissertation provide additional evidence that children at GMFCS level III have deficits in postural control of the lumbar spine.

Implications for Therapeutic Intervention

This research has the potential to impact therapy for children with CP in three primary areas. 1) Increased awareness of the contribution of spinal segments to control of posture will promote more specific clinical evaluations of postural control and therefore will promote more specific treatment. 2) Adaptive equipment design will be challenged to incorporate the goal of advancing postural skills instead of primarily positioning for comfort and immediate function. 3) Research paradigms regarding the nature of postural deficits and the effectiveness of treatment protocols for postural deficits will be expanded to include this vulnerable group of children.

Of primary importance is the evidence that segmental deficits of postural control occur in the trunk in children with CP and that these deficits are comparable to the normal developmental process of gaining trunk control for independent sitting. Awareness is the first and most important step to creating change. Once clinicians become aware of the possibility of segmental deficits in the spine, and that these deficits are related to GMFCS level, they will refine their clinical evaluations to include more precise evaluation of trunk control. Specificity of evaluation will inevitably lead to new innovative ideas concerning how to impact postural control in the clinic as well as at home.

Current positioning equipment is designed for promotion of upper extremity function, feeding and care giving ease and for comfort of the child.

It is interesting from an orthopedic point of view to consider the effect of support at various levels of the spine. Across all groups (TD and CP) there was a tendency to lean forward when external support was provided at the axillae or the hips and to lean sideways when external support was provided at the mid-ribs or waist. These quadratic trends for lateral deviation along the ML axis with support at midribs and waist were most prevalent in those children with deficits in the upper spine (TD 3 and 4 month olds and children at GMFCS V (Chapter V, figure 1)). These same tendencies have been seen in children with CP in response to wheelchair trunk supports and may contribute to formation and progression of scoliosis. Evaluation of the specific level of spinal deficit could guide seating adaptations. Creation of positioning devices to allow vertical alignment with adjustable support would offer the opportunity for optimal function and also allow for gradual progression in postural control.

Even without specific training devices, the child's current support devices could be adapted to promote more optimal levels of support. This would include improved support to areas that need it as well as creating freedom to move above the level of support. The knowledge that the support level should be re-evaluated and adjusted as children gain control is new. Currently support devices are primarily adjusted for growth, or comfort.

Future Directions for Research

This research has demonstrated that different levels of spinal postural control can be differentiated in children prior to the development of independent sitting. This paradigm offers the foundation for future exploration both in the realm of typical development as well as exploration of postural control in children with CP.

Of primary importance for clinical purposes would be a training study to evaluate the effectiveness of training postural control at specific spinal segments. Butler (1998) has presented preliminary evidence of the effectiveness of improved sitting balance using this approach. Her results need to be replicated and expanded to examine kinematic changes across different spinal segments following segmental training of postural control. We now know from typical infants that increases and decreases in variability are part of the normal course of development. It would be helpful to know if training postural control at the mid-ribs or waist would allow children with moderate CP (GMFCS IV) to release active stiffness and explore more freedom of motor control. Many interesting questions of clinical importance could be explored. Can postural control be improved in older children with moderate to severe CP? Can postural control be achieved progressively down the spine? If so, can it be improved in one segment, in 3 segments, or down the full spine? If control is achieved down the full length of the spine will functional gains spontaneously emerge or will it be necessary to train functional skills once the foundation of control is achieved? Could sensory stimulation (e.g. visual or proprioceptive enhancement) improve sensori-motor gain and thus help children refine their upright control?

In addition, EMG studies need to be conducted to explore the underlying neural mechanisms of postural control in TD infants as well as children with CP. Are the neuromuscular responses of the TD infants and children with CP comparable when they appear to be at similar stages in the development of spinal control?

The major contribution of this research has been to open the doorway for a new direction in research regarding the development of trunk control that specifically addresses the needs of the most vulnerable children. This offers the potential for innovations that may eventually lead to better function and better prognosis for children with severe motor deficits.

BIBLIOGRAPHY

Bax M, Goldstein M, Rosenbaum P, Leviton A, Paneth N, Dan B, Jacobsson B, Damiano D.(2005). 'Proposed definition and classification of cerebral palsy', *Developmental Medicine and Child Neurology,* vol. 47, pp. 571-576.

Bennett CF. 1987, 'The effectiveness of early intervention for infants at increased risk'. in *The Effectiveness of Early Intervention for At-risk and Handicapped Children*, eds Guralnick MT, Bennett FC, Orlando, FL, Academic Press, pp. 79-112.

Bernstein N. 1967, *The coordination and regulation of movement*, London, Pergamon.

Bertenthal B, Von Hofsten C. 1998, 'Eye, head and trunk control: the foundation for manual development', *Neuroscience and Biobehavioral Rev*iew vol. 22, pp. 515–520.

Bertenthal BI, Rose JL, Bai DL. 1997, 'Perception-action coupling in the development of visual control of posture', *Journal of Experimental Psychology Human Perception and Performance,* vol. 23, no. 6, pp.1631-1643.

Bleck EE. 1994, Editorial: 'The sense of balance', *Developmental Medicine and Child Neurology,* vol. 36, pp. 377-378.

Brogren E, Forssberg H, Hadders-Algra M. 2001, 'Influence of two different sitting positions on postural adjustments in children with spastic diplegia', *Developmental Medicine and Child Neurology,* vol. 43, pp. 534-546.

Brogren E, Hadders-Algra M, Forssberg H. 1998, 'Postural control in sitting children with cerebral palsy', *Neuroscience and Biobehavioral Rev*iew, vol. 22, pp. 591-596.

Burtner PA, Qualls C, Woollacott MH. 1998, 'Muscle activation characteristics of stance balance control in children with spastic cerebral palsy', *Gait and Posture,* vol. 8, pp. 163-174.

Burtner PA, Woollacott MH, Qualls C. 1999, 'Stance balance control with orthoses in a group of children with spastic cerebral palsy', *Developmental Medicine and Child Neurology*, vol. 41, no. 11, pp. 748-757.

Burtner PA, Woollacott MH, Craft GL, Roncesvalles MN. 2007, 'The capacity to adapt to changing balance threats: a comparison of children with cerebral palsy and typically developing children', *Developmental Neurorehabilitation,* vol. 10, no. 3, pp. 249-260.

Butler PB. 1998, 'A preliminary report on the effectiveness of trunk targeting in achieving independent sitting balance in children with cerebral palsy', *Clinical Rehabilitation,* vol. 12, pp. 281-289.

Butler PB, Major R. 2003, 'The missing link? Therapy issues of open and closed chains', *Physiotherapy,* vol. 89, no. 8, pp. 465-470.

Butler, PB, Saavedra S, Sofranac M, Jarvis S, Woollacott M. 2009, 'Development and reliability of the Segmental Assessment of Trunk Control (SATCo)', In press *Pediatric Physical Therapy,* February 2010.

Cans C, McManus V, Crowley M, Guillem P, Platt MJ, Johnson A, Arnaud C; Surveillance of Cerebral Palsy in Europe Collaborative Group. 2004, 'Cerebral palsy of post-neonatal origin: characteristics and risk factors', *Paediatric Perinatology and Epidemiology,* vol.18, no. 3, pp. 214-220.

Cheney PD. 1997, 'Pathophysiology of the corticospinal system and basal ganglia in cerebral palsy', *Mental Retardation and Developmental Disabilities Research Reviews,* vol. 3, pp. 153-167.

deGraaf-Peters VB, Blauw-Hospers CH, Dirks T, Bakker H, Bos AF, Hadders-Algra M. 2007, 'Development of postural control in typically developing children and children with cerebral palsy: possibilities for intervention?', *Neuroscience and Biobehavioral Reviews,* vol. 31, no. 8, pp. 1191-1200.

Faul F, Erdfelder E, Lang AG, Buchner A. 2007, 'G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences', *Behavioral Research Methods,* vol.39, no. 2, pp. 175-191.

Filloux, FM. 1996, 'Neuropathophysiology of movement disorders in cerebral palsy', *Journal of Child Neurology* vol. 11, no. S1, pp. S5-S12.

Fowler EG, Kolobe TH, Damiano DL, Thorpe DE, Morgan DW, Brunstrom JE, Coster WJ, Henderson RC, Pitetti KH, Rimmer JH, Rose J, Stevenson RD; Section on Pediatrics Research Summit Participants; Section on Pediatrics Research Committee Task Force. 2007, 'Promotion of physical fitness and prevention of secondary conditions for children with cerebral palsy: section on pediatrics research summit proceedings'. *Physical Therapy*, vol.87, no. 11, pp. 1495-1510.

Gardner-Morse MG, Stokes IAF. 1998, 'The effects of abdominal muscle coactivation on lumbar spine stability', *Spine,* vol. 23, pp. 86-91.

Gesell A. 1946, 'The ontogenesis of infant behavior' In: Carmichael L (ed). *Manual of child psychology*, New York, Wiley, pp 295–331.

Graham K. 2007, 'Classification of cerebral palsy: the surgeon's perspective', *Developmental Medicine and Child Neurology,* vol. 49, no. S109, pp. 21-23.

Hadders-Algra M, Brogren E, Forssberg H. 1996, 'Ontogeny of postural adjustments during sitting in infancy: variation, selection and modulation', *Journal of Physiology,* vol. 493, pp. 273-288.

Hadders-Algra M, van der Fits IB, Stremmelaar EF, Touwen BC. 1999, 'Development of postural adjustments during reaching in infants with CP', *Developmental Medicine and Child Neurology*, vol. 41, pp. 766-776.

Hadders-Algra M, Brogren E, Katz-Salamon M, Forssberg H. 1999, 'Periventricular leucomalacia and preterm birth have different detrimental effects on postural adjustments', *Brain,* vol.122, pp. 727-740.

Haley SM, Coster WJ, Ludlow LH, Haltiwanger JT, Andrellos PJ. 1992, *Pediatric Evaluation of Disability Inventory: development, standardization, and administration manual, version 1.0.* Boston, New England Medical Center Hospitals.

Harbourne RT. 1993, 'A kinematic and electromyographical analysis of the development of sitting posture in infants', *Developmental Psychobiology,* vol. 26, pp. 51-64.

Harbourne RT, Stergiou N. 2003, 'Nonlinear analysis of the development of sitting postural control', *Developmental Psychobiology,* vol. 42, pp. 368-377.

Harbourne RT, Stergiou N. 2009, 'Movement variability and the use of nonlinear tools: principles to guide physical therapist practice', *Physical Therapy,* vol. 89, no. 3, pp. 267-282.

Harris SR, Roxborough L. 2005, 'Efficacy and effectiveness of physical therapy in enhancing postural control in children with cerebral palsy', *Neural Plasticity* vol. 12, no. 2-3, pp. 229-243.

Hedberg, A, Forssberg H, Hadders-Algra M. 2004, 'Postural adjustments due to external perturbations during sitting in 1-month-old infants: evidence for the innate origin of direction specificity', *Experimental Brain Research*, vol. 157, pp. 10-17.

Hedberg A, Carlberg-Brogren E, Forssberg H, Hadders-Algra M. 2005, 'Development of postural adjustments in sitting position during the first half year of life', *Developmental Medicine and Child Neurology,* vol. 47, pp. 312-320.

Hirschfeld H, Forssberg H. 1994, 'Epigenetic Development of Postural Responses for Sitting during Infancy', *Experimental Brain Research*, vol. 97, pp. 528-540.

Hodges PW, Gandevia SC. 2000, 'Changes in intra-abdominal pressure during postural and respiratory activation of the human diaphragm' *Journal of Applied Physiology*, vol. 89, pp. 967-976.

Iscoe, S. 1998, 'Control of abdominal muscles'*, Progress in Neurobiology,* vol. 56, pp. 433-506.

Kennes J, Rosenbaum P, Hanna SE, Walter S, Russell D, Raina P, Bartlett D, Galuppi B. 2002, 'Health status of school-aged children with cerebral palsy: information from a population-based sample', *Developmental Medicine and Child Neurology*, vol. 44, no. 4, pp. 240-247.

Keshner E, Cromwell RL, Peterson BW. 1995, 'Mechanisms controlling human head stabilization. 2. head-neck characteristics during random rotations in the vertical plane',
Journal of Neurophysiology vol. 73, no. 6, pp. 2302-2312.

Lee DN, Lishman JR. 1977, 'Vision-most efficient source of proprioceptive-information for balance control', *Aggressologie* vol. 18, no. SA, pp. 83-94.

Liao SF, Yang TF, Hsu TC, Chan RC, Wei TS. 2003, 'Differences in seated postural control in children with spastic cerebral palsy and children who are typically developing'*, American Journal of Physical Medicine and Rehabilitation,* vol. 82, pp. 622-626.

Mahoney , Robinson C, Perales F. 2004, 'Early motor intervention-the need for new treatment paradigms', *Infant and Young Child,* vol. 17, no. 4, pp. 291-300.

Major RE, Johnson GR, Butler PB. 2001, 'Learning motor control in the upright position: a mechanical engineering approach', *Proceedings of the Institution of Mechanical Engineers Part H-Journal of Engineering in Medicine*, vol. 215, pp. 315-323.

Massion J. 1998, 'Postural control systems in developmental perspective', *Neuroscience and Biobehavioral Reviews,* vol. 22, no. 4, pp. 465–472.

Maurer C, Peterka RJ. 2005, 'A new interpretation of spontaneous sway measures based on a simple model of human postural control', *Journal of Neurophysiology* vol. 93, pp. 189–200.

Maurer C, Mergner T, Peterka RJ. 2006, 'Multisensory control of human upright stance', *Experimental Brain Research,* vol. 171, no. 2, pp. 231-250.

McGill SM, Grenier S, Kavcic N, Cholewicki J. 2003, 'Coordination of muscle activity to assure stability of the lumbar spine'. *Journal of Electromyography and Kinesiology,* vol. 13, pp. 353-359.

McGill SM. 1998, 'Importance of the intersegmental trunk muscles for the stability of the lumbar spine - A biomechanical study in vitro - Point of view', *Spine*, vol. 23, pp. 1945.

Nashner LM, Shumway-Cook A, Marin O. 1983, 'Stance posture control in select groups of children with cerebral palsy: deficits in sensory organization and muscular coordination', *Experimental Brain Research,* vol. 49, pp. 393-409.

Nashner LM, Mccollum G. 1985, 'The organization of human postural movements-a formal basis and experimental synthesis', *Behavioral Brain Science,* vol. 8, no. 1, pp. 135-150.

Odding E, Roebroeck ME, Stam HJ. 2006, 'The epidemiology of cerebral palsy: Incidence, impairments and risk factors', *Disability Rehabilitation,* vol. 28, pp. 183-191.

Palisano R, Rosenbaum P, Walter S, Russell D, Wood E, Galuppi B. 1997, 'Development and reliability of a system to classify gross motor function in children with cerebral palsy', *Developmental Medicine and Child Neurology,* vol. 39, pp. 214-223.

Palisano RJ, Rosenbaum P, Bartlett D, Livingston MH. 2008, 'Construct validity of the expanded and revised Gross Motor Function Classification System', *Developmental Medicine and Child Neurology,* vol. 50, pp. 744–750.

Panjabi M, Yamamoto I, Oxland T, Crisco J. 1989, 'Spinal Stability and Intersegmental Muscle Forces - a Biomechanical Model', *Spine,* vol. 14, pp.194-200.

Peach JP, Sutarno CG, McGill SM. 1998, 'Three-dimensional kinematics and trunk muscle myoelectric activity in the young lumbar spine: A database', *Archives of Physical Medicine and Rehabilitation,* vol. 79, pp. 663-669.

Peterka RJ. 2003, 'Simplifying the complexities of maintaining balance'. *IEEE Engineering and Medical Biology,* vol. 22, no. 2, pp. 63-68.

Piper MC, Darrah J. 1994, *Motor Assessment of the Developing Infant (AIMS),* Philadelphia, WB Saunders Company.

Pozzo,T, Berthoz A, Lefort L. 1990, 'Head Stabilization during various locomotor tasks in humans.1. normal subjects', *Experimental Brain Research,* vol. 82, pp. 97-106.

Preuss R, Popovic MR. 2009, 'Three dimensional spine kinematics during multidirectional, target-directed trunk movement in sitting', *Journal of Electromyography and Kinesiology,* DOI 10.1016/j.jelekin.2009.07.005

Prince F, Winter DA, Stergiou P, Walt SE. 1994, 'Anticipatory control of upper body balance during human locomotion', *Gait and Posture,* vol. 2, pp. 19-25.

Roncesvalles N, Woollacott MW, Burtner PA. 2002, 'Neural factors underlying reduced postural adaptability in children with cerebral palsy', *Neuroreport,* vol. 13, no. 18, pp. 2407-2410.

Rosenbaum PL, Walter SD, Hanna SE, Palisano RJ, Russell DJ, Raina P, Wood E, Bartlett DJ, Galuppi BE. 2002, 'Prognosis for gross motor function in cerebral palsy: creation of motor development curves', *Journal of the American Medical Association,* vol. 288, no. 11, pp. 1357–1363.

Rosenbaum PL. 2002, 'Cerebral palsy: what parents and doctors want to know', *British Medical Journal,* vol. 326, pp. 970-974.

Russell DJ, Rosenbaum PL, Avery LM, Lane M. 2002, *Gross Motor Function Measure (GMFM-66 & GMFM-88) User's Manual,* Clinics in Developmental Medicine No. 159, London, Mac Keith Press.

Saavedra S, Woollacott M, van Donkelaar P. 2007, 'Effects of postural support on eye-hand interactions across development', *Experimental Brain Research,* vol. 180, pp. 557-567.

Schloon H, Obrien JM, Scholten CA, Prechtl HFR. 1976, 'Muscle-activity and postural behavior in newborn infants-polymyographic study', *Neuropadiatrie,* vol. 7, no. 4, pp. 384-415.

Scholz JP, Schoner G. 1999, 'The uncontrolled manifold concept: identifying control variables for a functional task', *Experimental Brain Research,* vol. 126, no. 3, pp. 289-306.

Scholz JP, Schoner G, Latash ML. 2000, 'Identifying the control structure of the multijoint coordination during pistol shooting', *Experimental Brain Research,* vol. 135, no. 3, pp. 382-404.

Shumway-Cook A, Woollacott MH. 1985, 'The growth of stability: postural control from a developmental perspective', *Journal of Motor Behavior,* vol. 17, no. 2, pp. 131-147

Shumway-Cook A, Hutchinson S, Kartin D, Price R, Woollacott M. 2003, 'Effect of balance training on recovery of stability in children with cerebral palsy', *Developmental Medicine and Child Neurology,* vol. 45, pp. 591-602.

Snyder, Batista AP, Andersen RA. 2000, 'Saccade-related activity in the parietal reach region', *Journal of Neurophysiology,* vol. 83, no. 2, pp. 1099-1102.

Stoffregen TA, Smart LJ, Bardy BG, Pagulayan RJ. 1999, 'Postural stabilization of looking', *Journal of Experimental Psychology, Human Perception and Performance,* vol. 25, pp. 1641–1658.

Stokes IAF, Gardner-Morse M. 2003, 'Spinal stiffness increases with axial load: another stabilizing, consequence of muscle action', *Journal of Electromyography and Kinesiology,* vol. 13, pp. 397-402.

Sveistrup H, Woollacott M. 1996, 'Longitudinal development of the automatic postural response in infants', *Journal of Motor Behavior,* vol. 28, pp. 58-70.

Thelen E, Spencer JP. 1998, 'Postural control during reaching in young infants: a dynamic systems approach', *Neuroscience and Biobehavioral Reviews,* vol. 22, pp. 507-514.

Ting LH, McKay JL. 2007, 'Neuromechanics of muscle synergies for posture and Movement', *Current Opinion Neurobiology,* vol. 17, no. 6, pp. 622-628.

van Der Fits IB, Hadders-Algra M. 1998, 'The development of postural response patterns during reaching in healthy infants', *Neuroscience and Biobehavioral Reviews,* vol. 22, pp. 521-526.

van der Fits IB, Otten E, Klip AW, Van Eykern LA, Hadders-Algra M. 1999, 'The development of postural adjustments during reaching in 6- to 18-month-old infants. Evidence for two transitions', *Experimental Brain Research,* vol. 126, pp. 517-28.

van der Fits IBM, Klip AW, van Eykern LA, Hadders-Algra M. 1999, 'Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life', *Behavioral Brain Research,* vol. 106, pp. 75-90.

van der Heide JC, Begeer C, Fock JM, Otten B, Stremmelaar E, van Eykern LA, Hadders-Algra M. 2004, 'Postural control during reaching in preterm children with cerebral palsy', *Developmental Medicine and Child Neurology,* vol. 46, pp. 253-266.

van der Heide JC, Fock JM, Otten B, Stremmelaar E, Hadders-Algra M. 2005, 'Kinematic characteristics of reaching movements in preterm children with cerebral palsy', *Pediatric Research,* vol. 57, pp. 883-889.

Westcott SA, Burtner P. 2004, 'Postural control in children: implications for pediatric practice', *Physical and Occupational Therapy in Pediatrics,* vol. 24, pp. 5-55.

Winter DA, MacKinnon CD, Ruder GK, Wieman C. 1993, 'An Integrated EMG/Biomechanical Model of Upper-Body Balance and Posture during Human Gait', *Progress in Brain Research,* vol. 97, pp. 359-367.

Winter DA 1995, *A.B.C. (Anatomy, biomechanics and control) of balance during standing and walking,* Waterloo Biomechanics, bound at Graphic Services, University of Waterloo.

Witherington DC, vonHofsten C, Rosander K, Robinette A, Woollacott MH, Bertenthal BI. 2002, 'The development of anticipatory adjustments in infancy', *Infancy,* vol. 3, pp. 495-517.

Woollacott M, Debu B, Mowatt M. 1987, 'Neuromuscular control of posture in the infant and child-is vision dominant?', *Journal of Motor Behavior,* vol. 19, pp. 167-186.

Woollacott MH, Burtner P, Jensen J, Jasiewicz, Roncesvalles N, Sveistrup H. 1998, 'Development of postural responses during standing in healthy children and children with spastic diplegia', *Neuroscience and Biobehavioral Reviews,* vol. 22, pp. 583-589.

Wu YW, Day SM, Strauss DJ, Shavell RM. 2004, 'Prognosis for ambulation in cerebral palsy: A population-based study', *Pediatrics*, vol. 114, pp. 1264-1271.

Zedka M, Kumar S, Narayan Y. 1998, 'Electromyographic response of the trunk muscles to postural perturbation in sitting subjects', *Journal of Electromyography and Kinesiology,* vol. 8, pp. 3-10.