CONTRIBUTIONS OF DISTINCT TRUNK SEGMENTS TO CONTROL OF POSTURE AND REACHING DURING TYPICAL DEVELOPMENT

by

JAYA RACHWANI PARSHOTAM

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

December 2014

DISSERTATION APPROVAL PAGE

Student: Jaya Rachwani Parshotam

Title: Contributions of Distinct Trunk Segments to Control of Posture and Reaching During Typical 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:

Dr. Andrew Karduna	Chairperson
Dr. Marjorie Woollacott	Core Member
Dr. Anita Christie	Core Member
Dr. Dare Baldwin	Institutional Representative

and

J. Andrew Berglund	Dean of the Graduate School

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

Degree awarded December 2014.

DISSERTATION ABSTRACT

Jaya Rachwani Parshotam

Doctor of Philosophy

Department of Human Physiology

December 2014

Title: Contributions of Distinct Trunk Segments to Control of Posture and Reaching During Typical Development

The relationship between the development of sitting postural control and of reaching during infancy has not been addressed in detail. It has recently been shown that trunk control develops starting with the head, then the upper trunk and subsequently the lower/pelvic regions. However, previous studies on infant reaching evaluated infants during supported supine or reclined sitting positions, failing to address the contributions of distinct regions of the trunk to reaching.

This dissertation explores the relationship between the progression of trunk control and reaching performance in healthy infants. The effects of stabilizing the upper and lower regions of the trunk were assessed by providing vertical trunk fixation at two levels of support (thoracic and pelvic). Documentation of postural and reaching performance reflected how control of the free regions of the trunk modulated both behaviors. First, kinematic data were collected in infants aged 4-6 months who were grouped according to their sitting ability and extent of trunk control. Second, a longitudinal study was implemented in which kinematic and electromyographic recordings were collected bi-monthly from 2.5-8 months.

Results from the cross-sectional study showed that postural stability and reaching kinematics of the two groups were similar when they received support at the thoracic level but differed when the support was limited to the pelvic level. Infants who were able to sit independently outperformed the infants who were unable to sit without help. These data were further expanded with the results obtained from the longitudinal study, showing that during the months prior to independent sitting, infant reaches were impoverished and were associated with a lack of postural stability when provided with pelvic, in comparison to thoracic, support. In addition, infants displayed inefficient muscle patterns in response to the instability. Differences between levels of support were not observed once infants acquired independent sitting.

Taken together, these results offer detailed measures of the progression of trunk control and its relation to reaching. This raises important questions regarding whether this more specific approach may create the foundation for evaluating and improving trunk control in atypically developing populations.

This dissertation includes previously published and unpublished co-authored material.

CURRICULUM VITAE

NAME OF AUTHOR: Jaya Rachwani Parshotam

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene (US)
University of Salamanca, Salamanca (Spain)
Catholic University of San Antonio, Murcia (Spain)
International University of Catalunya, Barcelona (Spain)
University of Malaga, Malaga (Spain)

DEGREES AWARDED:

Doctor of Philosophy, Human Physiology, 2014, University of Oregon
Master of Neuroscience, 2010, University of Salamanca
Master of Neuro-Rehabilitation, 2009, Catholic University San Antonio Murcia
Postgraduate Specialization in Pediatric Physical Therapy, 2008, International University of Catalunya
Bachelor Degree in Physical Therapy, 2007, University of Malaga

AREAS OF SPECIAL INTEREST:

Typical and Atypical Motor Control
Development of Postural Control
Pediatric Neuro-Rehabilitation
Neuroscience
Movement Science

PROFESSIONAL EXPERIENCE:

Graduate Research Fellow, Department of Human Physiology, University of Oregon, September 2011 – June 2014

Graduate Teaching Fellow, Department of Human Physiology, University of Oregon, January 2012 – March 2014

Pediatric and Neurologic Physical Therapy, Spain, 2008 - 2011

Physical Therapy in Traumatology/Orthopedics, Spain, 2007 - 2008

English to Spanish Translator in Official Courses, Spain, 2009 – 2011

Delegate of Spanish Society of Pediatric Physical Therapy (SEFIP) of Andalucia, Spain (2007-2011).

GRANTS, AWARDS, AND HONORS:

Eugene & Clarissa Evonuk Memorial Graduate Fellowship in Environmental Physiology, College of Arts and Sciences, June 2014

Betty Foster McCue Scholarship, University of Oregon, Graduate School, June 2014.

Accesit Award of Investigation, Ilustrious Professional College of Physical Therapists of Andalucia, December 2010

PUBLICATIONS:

Rachwani, J., Santamaria, V., Saavedra, S., & Woollacott, M. (under review). The development of trunk control and its relation to reaching in infancy: a longitudinal study.

Santamaria, V., Rachwani, J., Saavedra, S., & Woollacott, M. (under review). The impact of segmental trunk support on posture and reaching in children with moderate and severe cerebral palsy: an electromyographic study.

Santamaria, V., Rachwani, J., Saavedra, S., & Woollacott, M. (under review). The impact of segmental trunk support on posture and reaching in children with moderate and severe cerebral palsy: a kinematic study.

Santamaria, V., Rachwani, J., Manselle, W., Saavedra, S., & Woollacott, M. (under review).The impact of segmental trunk support on a reaching task while sitting.

Santamaria, V., & Rachwani, J. (2014). Literature review: XL scientific document. Development of reach-to-grasp & related sensorimotor systems in typical developing infants. Spanish Society of Pediatric Physical Therapy. [Barcelona].

Rachwani, J., Santamaria, V., Saavedra, SL., Wood, S., Porter, F., & Woollacott, M. (2013). Segmental trunk control acquisition and reaching in typically developing infants. *Experimental Brain Research, 228*(1), 131-139.

Santamaria, V., & Rachwani, J. (2010). Physiotherapy in haemophilic artropathy of the knee. *Cuestiones Fisioterapia, 39*(1), 68-77.

Rachwani Parshotam, J., Santamaria Gonzalez, V.F, & De Ru, E. (2009). Functional effects of strengthening programmes in spastic diplegia. *Developmental Medicine & Child Neurology, 51*(*Suppl*. 5), 23.

ACKNOWLEDGMENTS

"Tell me and I forget, teach me and I may remember, involve me and I learn" --Franklin

Although I recognize and acknowledge the support of many people for completing this dissertation, my sincerest gratitude and appreciation is extended to my advisor, Dr. Marjorie Woollacott. She not only guided me throughout my years as a graduate student, but she also involved me actively in every aspect of the research. Without her mentorship, enthusiasm and dedication I would not be where I am today.

I must thank all my committee members with whom I have worked over the last two years and who have been integral to my dissertation, each one of them in their own unique way. Dr. Andy Karduna has always supported me with his valuable advices and continuous guidance. I thank Dr. Anita Christie for modeling great teaching and for furthering my thinking about motor control. My gratitude is also addressed to Dr. Dare Baldwin for her contributions and suggestions during the analysis of this project.

The conceptual framework of this project came from the work of Dr. Sandra Saavedra. I thank her for her willingness to collaborate and offer her expertise in this topic. I also owe an enormous *thank you* to Wayne Manselle who was instrumental in helping me resolve technical and programming issues.

The journey would have not been possible without the support of my family. To my parents, thank you for your inspiration to follow my dreams and to never give up. I always knew you believed in me and would support me in every stage of my life. I am blessed to have parents like you.

To pursue a doctoral degree, it takes tremendous courage and motivation. This motivation came from the endless love and faith of my colleague, friend and husband, Victor Santamaria. He is the person with the ability to make me smile and enlighten my darkest moments during my years as a doctoral student.

Above all, I thank God most sincerely for everything He has done for me and for giving me the strength that I need for facing life’s challenges.

The studies presented in this dissertation were supported by the National Institutes of Health Grant 1R01HD062745-01, Marjorie Woollacott, principal investigator. In addition, I received support from the Betty Foster McCue Fellowship and from the Eugene Evonuk Memorial Graduate Fellowship.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

Motor development during infancy is clearly impressive. Developmental changes in the form and display of infants' movements are vast in scope. At birth, newborns can hardly lift their head in space, but within a year or so, infants are able to sit, stand, walk, reach, manipulate and even feed themselves. This is a period of substantial change in the infant's ability to move and learn. Infants experience dramatic changes that are obvious in character, involving the transition of babies' uncoordinated head/gaze, arm/hand, trunk/leg movements to adult-like looking, reaching, sitting and walking movements (Adolph & Berger, 2006).

It is no surprise, therefore, that the study of infant motor development is of interest to researchers in many disciplines. Over the past three decades, research in this area has progressively laid a foundation for our understanding of both normal and abnormal infant motor development. Scientists, just like parents, have a long tradition of using infants' physical and motor development as a criterion for testing their health status. The development of normal motor control can be assessed throughout infancy and research based on these observations has indeed influenced the way in which practitioners and therapists approach interventions. While the infant grows, the abilities to roll, keep the head stable against gravity, sit, stand and walk, among others, are major indications of proper neural development. Moreover, motor development is reciprocally conjoined with perception and is implicated in the development of cognition and emotion (Adolph & Berger, 2006).

One of the basic functional components of motor development is postural control (Reed, 1989). In order for an infant to acquire the many motor skills that are accomplished during the first year of life, a critical prerequisite is adequate postural control. The infant's ability to move in refined ways derives from their having learned and mastered the underlying postural skills early in life. For example, it is known that when children perform a simple voluntary task, such as reaching for a toy, they activate postural muscles to support the body against the destabilizing effect of the movement (Woollacott, Assaiante, & Amblard, 1996). Similarly, abnormalities in postural development could constrain the child's ability to perform such tasks.

Therefore, understanding normal motor development is mandatory in order to understand the processes that are disrupted in abnormal motor development. In working with children with abnormal motor development, it is essential to not only assess gross or fine motor performance but also the basic postural skills, which are the foundation of these movements. This has become a key issue in research over recent years and is the focus of the current dissertation. The main goal of the current set of studies is to understand the basic mechanisms of the development of trunk control and its relation to reaching movements. The results will then be used in the clinical setting as normative data for comparison with the trunk and reaching abilities of children who suffer from developmental delays or neurological deficits.

MOTOR CONTROL THEORIES

In the middle of the 20th century, motor development was generally described as the emergence of predetermined patterns of behavior, or motor milestones, which follow an orderly sequence. Gesell and Amatruda (1947) noted that the general direction of motor development follows a cranial-caudal (downward from head to feet) and proximal-to-distal (outward from trunk to the hands and feet) sequence. Since then, several theories of motor development have been formulated that try to relate neural structure and behavior in developing infants. The classic theory, also known as the reflex-hierarchical theory, places great importance on a reflex substrate for the emergence of mature human behavior patterns. This means that in the normal child, the emergence of posture and movement control is dependent on the appearance and subsequent integration of reflexes. The appearance and inhibition of these reflexes reflect the increasing maturity of cortical structures that inhibit and integrate reflexes controlled at lower levels within the central nervous system into more functional postural and voluntary motor responses (Shumway-Cook & Woollacott, 2012a). However, when researchers tried to examine the development of reflexes and their association with motor development in infants, they found that results were inconclusive and that other systems beyond the reflex circuits contribute to the development of motor control. These conclusions then led to new theories and concepts in motor control.

Neuronal Group Selection Theory

A widely known approach to motor development is the Neuronal Group Selection Theory (NGST). This theory focuses on the fact that normal development is characterized by variation. Motor development is defined as having specific phases of variability across time. Sporns and Edelman (1993) were the pioneers of this theory and they explain that the cortical and subcortical systems are dynamically organized into variable networks, whose structure and function are selected by development and behavior. The NGST states that development starts with a primary neuronal repertoire, which is determined by evolution. Then, as a result of sensorimotor information elicited by behavior and experience, development proceeds with the creation and establishment of neuronal connections. This is known as the selection process, also known as the phase of primary variability. When the selection process is achieved, variability of behavior is reduced. In the secondary variability phase, variation increases as a result of continuing motor and sensorial experiences, and continues until neuronal connectivity becomes more refined. Thus, this theory clearly proposes that development is the result of a complex interaction between the genetic information encoded in infants and their interaction with the environment (Hadders-Algra, 2008).

Dynamic Systems Theory

A broader, current approach to motor development is the Dynamic Systems Theory. This theory is based on the proposition posed by Nikolai Bernstein (Bernstein, 1967). He noted that many different solutions to a task are available due to the large number of degrees of freedom that need to be controlled in the system. Therefore, to simplify control, movements are activated by muscle synergies, which are functional links of muscles that are activated as a pattern to accomplish a functional task. Dynamic Systems Theory also states that the final outcome of a behavior is a result of (1) the multiple neural and musculoskeletal subsystems or component parts that contribute to it, such as muscle strength, body weight, postural support, the infant's mood, and brain development, and (2) the effect of environmental conditions and task requirements, that influence the specific patterns of motor output. Thus, motor development is considered as a self-organizing process where the environment plays an essential role in the maturation of the motor system (Shumway-Cook & Woollacott, 2012b).

MOTOR DEVELOPMENT IN INFANCY – THE CONQUEST OVER GRAVITY

Infants acquire the main developmental motor milestones at specific points in time (Table 1.1); however, the emergence of these motor abilities is characterized by variation across infants, with contributions from the cultural context and conditions in which they are raised (Adolph & Robinson, 2008; Piper & Darrah, 1994).

Table 1.1. Motor Milestones across the First Year of Life

Motor milestone	Temporal window
Head control	3-4 months
Independent sitting	7-8 months
Pull-to-stand	9-10 months
Independent stance	10-14 months
Locomotion	12-15 months

Note: Obtained from Shumway-Cook & Woollacott, 2012a.

In addition, developmental phases may overlap as one is being refined while a new stage emerges. For instance, infants learn to stand independently, and though this skill continues to be refined, they move on to learn to walk, refining gait parameters as well through further sensori-motor development and practice (Sutherland, Olshen, Cooper, & Woo, 1980).

Though the acquisition of each motor milestone during the developmental continuum has its own contribution to overall motor acquisition, among them, independent sitting is critical. This milestone is acquired early in life and it allows functional independence, the practice of psychosocial activities (e.g. play, work, education and personal interactions) and the ability to perform manual skills that could not be efficiently achieved in the lying position. Sitting posture requires the control of the head and the trunk to offer a stable and relatively large base of support that can serve as a secure basis when performing daily activities, such as reaching.

Head Control

Newborns have insufficient strength in the muscles of the neck to allow them to resist gravity and hold the head upright. For instance, when they are lying in prone position, they are able to quickly turn their heads from side to side to facilitate breathing but cannot lift their head off the floor for a sustained period of time. But by 1-2 months of age, they can then lift the head in prone position and by 3 months they have sufficient control to maintain their head in midline while they use their arms for propping themselves up. However, trunk balance is still weak, since infants at this age cannot shift their weight from one arm to the other using their hands (Adolph & Berger, 2005).

Trunk Control

Being able to sit on a chair, unsupported and move the hands freely marks the end of the progression toward independent sitting. Yet, infants take months to accomplish this milestone. Due to their lack of muscle strength in the trunk and hips, infants continue to fall forward while sitting with extended legs. There is a top-down order of progression toward independent sitting which is clearly evident even to an untrained eye. As Adolph & Berger (2005) mention:

> The cephalocaudal progression seems especially striking in the development of sitting, as if infants gain control of the sitting posture one vertebra at a time. At first, infants' heads flop when they are supported at the shoulders. Then, after babies can balance their heads between their shoulders, their backs crumple when they are supported at the hips. After babies can keep a straight back, they still topple, chest to knees, without hip support. To sit alone, infants must have muscular control over the entire trunk. (p. 238)

Infants at 5 months of age are able to prop sit, and are able to balance their body only when they are supporting themselves on their arms. By 6 months, they are able to independently sit with arms free but still cannot rotate their trunk. It is not until 7 months of age that infants acquire sufficient lower trunk and hip control to turn while reaching and also to transition from kneeling or crawling to sitting without falling between postures (Adolph & Berger, 2005).

Reaching

The development of reaching depends on neurophysiological, biomechanical and perceptual components. Infants need to lift their arm against gravity and have sufficient strength in the trunk to maintain balance while reaching. However, they also need to locate the object relative to the position of the hand for goal-directed reaching, which is not required in spontaneous arm movements observed in newborns and very young infants.

Goal-oriented reaching begins around the age of 3-5 months, before infants are able to independently sit, but only if infants are placed in positions in which balance is not a major constraint. In supported seated conditions, either with semi-reclined chairs or with the support of a parent, infants are able to successfully reach for and contact a toy. These reaches are less controlled, being more devious, and composed of several arm movements, termed movement units (MUs) (von Hofsten, 1979). Each MU is composed of an acceleration followed by a deceleration, usually accompanied by a change of direction. Early reaches are characterized as having 4-5 MUs in contrast to 1 MU seen in adult reaching. With practice and experience, infant reaches become straighter and smoother, and have only 2 MUs. The first MU brings the hand close to the target, whereas the second one prepares the hand to grasp the object (von Hofsten & Rönnqvist, 1993).

However, insufficient strength to stabilize the body is a major impediment to the development of reaching (Konczak, Borutta, & Dichgans, 1997; Out, Van Soest, Savelsbergh, & Hopkins, 1998). Reaching movements cause the body's center of mass to shift forward, and infants must compensate for such disequilibrium. Thus, goal-directed reaching requires "whole body engagement" (Rochat & Goubet, 1995) and will have different developmental arm trajectories depending on the initial position of the body during the reach. For instance, infants at 4 months of age are able to successfully reach toward a toy when in a supine or semi-reclined seated position but in prone position, they cannot use their arms for reaching (Adolph & Berger, 2005).

Once infants achieve propped sitting, postural requirements compete with action goals. For example, new sitters reach with only one hand and avoid leaning forward because they need the supporting arm in order to not disrupt their fragile postural equilibrium that keeps them from falling (Rochat & Goubet, 1995). Infants progress from reaching with one hand while the other arm is used for balance support, to being able to reach in all directions with both hands at 7 months of age. Thus, maintaining stability in the sitting position is integral to the development of reaching. Studies have tested reaching trajectories while experimentally mimicking the type of support infants will eventually generate for themselves. With the extra trunk stabilization and hip support, non-sitters' reaching movements were as coordinated as those of sitting infants (Hopkins & Rönnqvist, 2002; Rochat & Goubet, 1995). Therefore, additional postural control enhances reaching performance, regardless of whether postural balance is acquired naturally or with the use of an external device (Adolph & Berger, 2005).

POSTURAL CONTROL

Within models of motor control, actions are often subdivided, with certain specific actions considered to be nested within other more global actions. For example, visual tracking with the eyes is nested within visual tracking with the head, or grasping with the hands is nested within reaching with the arms. All other motor actions - just like looking and grasping - are embedded, in turn, within the most basic action of all: posture (Bernstein, 1967; Gibson & Pick, 2000; Reed, 1989). Therefore, to understand the emergence of any motor action in infancy, such as reaching while sitting upright, it is crucial to understand the postural substrate for these skills (Shumway-Cook & Woollacott, 2012a).

What Is Posture and How Is It Controlled?

Postural control is essentially defined as the ability to control the body's position in space for both stability (maintaining the projected center of mass within the limits of base of support) and orientation (relative position of the body segments with respect to one another and the environment or the task being performed); thus, postural control emerges from the interaction of the individual, with the task and the environment. This requires a complex interaction of musculoskeletal and neural systems (Shumway-Cook & Woollacott, 2012c). At the level of the individual, postural control involves three different types of tasks: 1) steady state balance, which is defined as the ability to maintain the position of the center of mass within the base of support, 2) reactive balance, which is defined as the ability to recover from a stable position of the center of mass following a perturbation, and 3) proactive or anticipatory balance, which is defined as the ability to activate the postural system in advance of a potentially destabilizing movement, to minimize instability.

Most tasks include all three aspects of balance control, for example, reaching while sitting. Upright sitting requires steady state, then anticipatory balance before reaching, then reactive balance for fine balance adjustments at the end of the reach, and then steady state balance again to maintain the limb against gravity (Shumway-Cook & Woollacott, 2012c).

Traditionally, the primary contributors to the control of posture were considered to be spinal reflexes and muscle tone (Peiper, 1963); however, over the last forty years, this notion has been replaced by the understanding that postural control is an active process involving a variety of different neural subsystems, including not only spinal reflexes, but also brainstem, basal ganglia, and cerebellar pathways, as well as higher level cortical systems and attentional resources. It is also well recognized that sensory information from the visual, somatosensory and vestibular systems plays a critical role in the maintenance of posture (Shumway-Cook & Woollacott, 2012c).

The Spinal Cord. Studies with humans who have spinal cord injuries have shown that these patients have increased amounts of antigravity muscle tone but lack automatic postural muscle responses below the level of the injured region. These results suggest that spinal cord circuits are sufficient for maintaining antigravity support but not balance. Balance control is thus a more complex process that requires the involvement of supraspinal circuits (Macpherson & Fung, 1999).

The Brain Stem, Vestibular System and Cerebellum. Muscle synergies which are necessary for automatic postural responses are organized in the brain stem, specifically in the reticular formation. However, adaptation of postural synergies to changes in the environment or task also requires the influence of the vestibular system and cerebellum. The two major regions of the cerebellum that regulate orientation and balance are the vestibulocerebellum (visual and vestibular inputs) and the spinocerebellum (proprioceptive inputs from the body). Lesions in the brainstem and vestibulocerebellum produce a variety of deficits in head and trunk control. Damage in the spinocerebellum produces excessive postural sway, ataxia during walking and hypermetric postural responses, suggesting its main role in balance reactions (Horak & Diener, 1994).

The Spinocerebellum and Basal Ganglia. Patients with spinocerebellar disorders or basal ganglia deficits, like Parkinson disease, experience difficulties in adapting postural responses to changing conditions. The spinocerebellum is responsible of adjusting the magnitude of postural responses over the course of repeated trials but is also able to rapidly adapt postural responses immediately after a change in condition. For example when a healthy person balances on a platform whose movement velocity increases with each trial, they have no problem adjusting to the changing velocities, and remaining well balanced. However, a patient with a spinocerebellar disorder will not be able to adapt to the perturbation velocity changes and shows muscle contractions that are hypermetric for all velocities. On the contrary, a patient with Parkinson disease has difficulty in changing postural responses when task conditions change; for instance, when changing from standing upright to sitting on a stool. Postural responses to perturbations in different conditions are inflexible and will be the same for either condition in a patient with Parkinson disease (Horak, Nutt, & Nashner, 1992).

The Cerebral Cortex. Areas of the cerebral cortex are known to influence both postural orientation and stability, including both anticipatory and automatic postural reactions. The supplementary motor area is involved in anticipatory postural adjustments that accompany voluntary movements. The temporoparietal cortex integrates sensory information for perceiving body verticality. It is also known that the control of posture, just like the control of any voluntary movement, requires attentional resources. In this regard, the pre-frontal cortex is involved in the processing of visuospatial attention (Mihara, Miyai, Hatakenaka, Kubota, & Sakoda, 2008). Research has demonstrated that when subjects perform a cognitive task while actively maintaining posture, the performance of either or both can degrade (Macpherson & Horak, 2013).

Sensory Information. Multiple sources of sensory information must be integrated for an adequate response to changes in orientation and motion of the body. It is known that somatosensory inputs are critical for maintaining balance during quiet stance. Individuals with peripheral neuropathy in the legs accordingly experience ataxia and difficulties with balance. The vestibular organs inform the nervous system about the changes in body tilt with respect to gravity as well as body sway in all directions. In addition, subjects with eyes closed have a substantial increase in body sway, indicating that vision actively contributes to postural orientation (Brandt, Paulus, & Straube, 1986).

However, even though each sensory modality alone provides information about postural orientation and body motion, their influence can change according to the task requirements. For example, subjects on a firm, stable surface tend to rely primarily on somatosensory information for postural orientation, but when the support is unstable, subjects depend more on vestibular and visual information. Nevertheless, even when the support surface is not stable, a light touch with a fingertip on a stable object is more effective than using vision in maintaining balance. Thus, the postural control system is able to change the relative weighting of different sensory modalities to accommodate changes in the environment and goal of the task (Macpherson & Horak, 2013).

Development of Postural Control for Independent Sitting

The development of postural control has traditionally been associated with a predictable sequence of motor skills, including crawling, sitting, creeping, pull-to-stand, independent stance, and walking. However, for infants to develop trunk control, and thus independently sit, they must learn to master the control of spontaneous background sway of both the head and the trunk and to respond to perturbations of balance. This requires the coordination of motor and sensory information relating the two body segments (head and trunk) together in the control of posture. As noticed in the sections below, research suggests that there are innate components of postural control, already available in the newborn, and also emergent aspects of control, resulting from the infant interacting in a dynamic way with the environment (Shumway-Cook & Woollacott, 2012a).

Motor Contributions to the Development of Independent Sitting

Research performed in the past on the development of sitting postural control has focused on investigating the hypothesis that postural responses are innate, and follow two phases of variability. In the first phase, directionally appropriate muscle responses are noted at the age of 1 month and continue to increase until 6 months, prior to the achievement of independent sitting. After 6 months, occurs the second phase, in which amplitude and temporal ordering of muscle responses start to be refined and can be attributed to the modification of neural circuitry by continuing sensory input (Hadders-Algra, 2000). Under this theoretical viewpoint, corresponding to the neuronal group selection theory, postural control is interpreted as being an aspect of behavior, governed by genetic and environmental factors, which then progresses toward adult-like levels as the nervous system matures.

Another viewpoint of the development of postural control is the one associated with the dynamic systems theory. In this perspective, postural control derives from self-organizing systems, and emerges as the organism interacts with the environment. Critical features that are examined are called the “non-linear properties” of the system, in which a behavior transforms into a new configuration when a single parameter of that behavior is gradually altered and reaches a critical value. For example, as an animal walks faster, there is a point at which it shifts from the walk to a trot (Shumway-Cook & Woollacott, 2012b). In the following section, sitting development will be discussed from both perspectives.

Development of Sitting – Neuronal Group Selection Theory Perspective. Hirschfeld and Forrsberg (Forssberg & Hirschfeld, 1994; Hirschfeld & Forssberg, 1994) formulated a functional model describing the development of postural adjustments – based on the concept that a central pattern generator (CPG) generates the basic pattern of postural adjustments, which are then shaped by multisensory interactions from all activated sensory systems. In general terms, CPGs involve neural networks that coordinate the activity of the muscles, for the coordination of a variety of activities including locomotion and respiration. These networks are controlled by reticulospinal neurons, but segmental afferent inputs modulate and optimize the pattern (Hadders-Algra, 2005).

Therefore, similar to the concept of the two-level organization in the CPG-model for motor activity (pattern generator plus sensory modulation), postural adjustments are considered according to this model to have a first and second level or organization. The first level involves the generation of direction-specific activity – this means the activation of the muscles opposite to the direction of the body sway (for example, a perturbation inducing a backward sway evokes responses in the ventral muscle). The second level involves the fine-tuning of the postural response, which mainly relies on the multi-sensorial afferent input from the visual, somatosensory and vestibular systems. Such modulation can be accomplished in various ways, for example, by altering the degree of activation, or by changing the recruitment order.

Research done in typically developing infants has shown that postural adjustments are characterized by two phases of variability, primary and secondary, related to the first and second level respectively, of postural organization described above (Hadders-Algra, 2000; Touwen, 1993). During the primary phase of variability, motor behavior is not geared to external conditions, whereas in the phase of secondary variability, motor performance is adapted to specific external situations. There are four periods of transition that can be distinguished in the development of postural adjustments, occurring at the ages of 3, 6, 9-10 and 13-14 months. Six months of age is probably the most important of all, which is when infants shift from a primary to secondary phase of variability and which coincides with the onset of independent sitting ability.

The research studies performed by Hedberg, Forssberg, and Hadders-Algra (2004), and Hedberg, Carlberg, Forssberg, and Hadders-Algra (2005) were the first to study postural adjustments in 1 month old infants. They used a paradigm in which movement perturbations were generated while infants were seated on a platform. The perturbation provoked a pelvic rotation. They found that 1 month old infants are able to generate direction-specific postural adjustments to seated perturbations and therefore they concluded that postural adjustments have an innate origin. These were highly variable, especially in the number of postural muscles that were activated. The data indicated that sensory information from the rotation of the pelvis was insufficient to trigger direction-specific postural activity, since infants during forward perturbations often showed direction specific postural activity in the absence of a pelvic tilt or body sway in the opposite direction. Vestibular information did not serve as the primary trigger since head swayed in all directions. Thus, the authors concluded that sensory information from multiple sources of the pelvic region, such as proprioceptive and tactile information, cooperate in producing postural activity. Authors found that the number of direction-specific muscles that participated in these adjustments decreased with age, reaching its lowest at 3 months, after which the number increased again. This observation suggests that at 3 months of age, there is a period of developmental transition in postural control, corresponding to the age at which goal-directed arm motility emerges.

From 3 to 6 months, infants continue to show a variable repertoire of direction-specific adjustments and are not able to adapt postural responses to the specifics of the situation – for example, to the degree of the perturbation or to changes in the position of the infant (supine versus sitting) (van der Fits, Klip, van Eykern, & Hadders-Algra, 1999a). Then, once infants reach 6 months of age, directional specificity matures, and the ability to adapt postural activity emerges. First, they develop the capacity to select a complete pattern, in which all direction-specific muscles are activated (Hadders-Algra, Brogren, & Forssberg, 1996; van der Fits, Otten, Klip, van Eykern, & Hadders-Algra, 1999b). Second, infants develop the capacity to adapt the selection of the complete pattern to the degree of balance perturbation. For example, the complete pattern is more frequently selected during sudden and vigorous perturbations of balance than by small perturbations. Therefore, it is suggested that infants shift from the primary phase of variability, in which postural muscles are activated without precise adaptation to the environmental constraints, to the phase of secondary variability in which they learn to adapt to the specifics of the situation. Six months is thus considered to be a significant transition phase in development, which is also the age when infants generally learn to sit independently (Piper & Darrah, 1994). This would suggest that the process of learning to sit independently is not dependent on the precise ability to adapt postural muscle activity to the specifics of the situation, as this does not begin to emerge until 6 months of age, when sitting is already achieved. From a postural adjustment view point, the only requirement for the development of independent sitting would be the ability to generate direction-specific postural adjustments.

From 6 to 9-10 months of age infants continue to increase the ability to activate the complete pattern for postural adjustments in response to perturbations of balance, which as mentioned earlier, is especially used when the risk of losing balance is high. This explains why the selection of the complete pattern is dominant during external perturbations in a sitting position till the age of 30 months (van der Heide, Otten, van Eykern, & Hadders-Algra, 2003) and during walking until 3 years (Assaiante, 1998). From 9-10 months onwards, infants also learn to adapt postural adjustments in a more refined way by means of 1) adapting the degree of contraction to changes in velocity of the moving seat surface and 2) to adapt postural activity to changes in body configuration. The emergence of the ability to fine tune postural activity to the specifics of the situation suggest that the age of 9-10 months is regarded as the third transition period, which also is the stage of preparation for the development of standing and walking (Hadders-Algra, 2005).

Lastly, during the age of 13-14 months, anticipatory postural control in a sitting position matures to adult timing characteristics (van der Fits et al., 1999b), and it is known to be related to the development of independent walking, suggesting another period of transition during which feed-forward mechanisms becomes embedded in the control of posture (Hadders-Algra, 2005). However, examination of the emergence of anticipatory postural adjustments in sitting position while reaching has yielded discrepant results. For instance, using a broader time window for infant anticipatory adjustments, von Hofsten and Woollacott (1989) found evidence that 9-month old infants show activation of postural muscles in advance of most reaching movements. This might suggest that anticipatory postural adjustments, though less refined in younger infants, are fundamental to balance control well before independent walking has been established.

Development of Sitting – Dynamic Systems Theory Perspective. Another theoretical perspective on the development of sitting postural control is the dynamic systems perspective (Bernstein, 1967; Shumway-Cook & Woollacott, 2012b). Using this perspective, researchers have noted a nonlinear progression in the development of skills. Transitions to new levels of a skill are explained by an initial limiting of the degrees of freedom of the segments to be controlled, to create stability in the behavior, followed by freeing of the degrees of freedom, as the infant begins to master the skill, increasing the adaptability of the behavior. Thus, as a skill progresses toward maturity, the degrees of freedom are released to allow a more flexible and adaptable coordination of the body segments within the environment. Studies have examined this non-linear progression in the dynamic process of developing postural control by applying techniques to evaluate the stability, dimensionality, and complexity of the center of pressure (COP) time series during the development of sitting. These techniques are based on examining the structural characteristics of the COP time series in a determined space where 1) the term stability refers to the natural fluctuations that occur, or postural sway; 2) dimensionality refers to the actual area that the COP time series occupies in the state space; and 3) complexity quantifies the regularity of the COP time series (Harbourne & Stergiou, 2003). In a study performed by Harbourne and Stergiou (2003), infants were tested during three developmental stages: Stage 1, when infants could hold up their head and upper trunk, but could not sit independently; Stage 2, when infants began to sit independently briefly; and Stage 3, when infants could sit independently. While stability and regularity increased over the three stages, the dimensionality followed a non-linear progression. Information regarding the number of degrees of freedom, determined by the dimensionality of COP time series, showed high values at Stage 1 with a significant decrease at Stage 2, indicating a reduction in the degrees of freedom as is often seen when attempting to learn a new skill (Woollacott et al., 1998). The significant increase from Stage 2 to Stage 3 indicates an increment in the degrees of freedom, which provides the infant with an increased adaptability or flexibility in controlling posture over the base of support while sitting. With these results, it is suggested that the development of sitting skills is softly assembled, with an initial strategy of freezing the degrees of freedom. Infants first discover a solution to the problem of controlling the body segments while upright sitting by stiffening the joints and reducing the degrees of freedom; then they release the degrees of freedom to adaptively interact with the environment in a coordinated way (Harbourne & Stergiou, 2003).

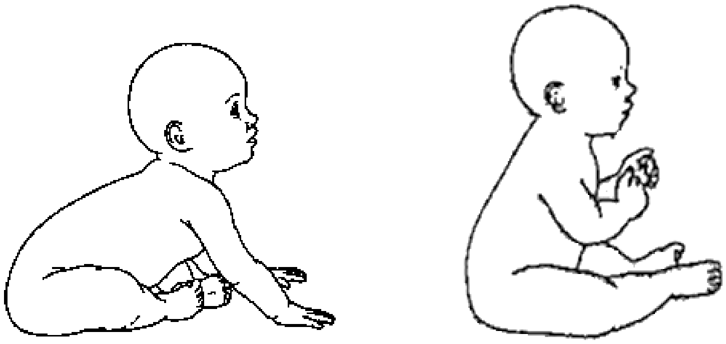
Thus, considering both perspectives, it is now evident that many factors, both internal and external, guide the developmental process of independent sitting, in which postural control is an essential requirement. Research has identified several variables that influence the control of posture. One of those variables is the development of sensory systems, in particular, the somatosensory, vestibular, and visual systems. Other variables that have been investigated include neuromuscular development, muscle strength, body mass, and the changing center of gravity through changes in body morphology (Piek, 2006).

Sensory Contributions to the Development of Independent Sitting

Research investigating the role of sensory systems during the development of seated postural control has shown that infants appear to have a map of the relationship between sensory inputs and muscle activity of the neck, trunk, and leg for sitting control. Butterworth and Hicks (1977) investigated the role of vision in infants at different stages of the development of independent sitting. Infants were given the illusion of a postural perturbation (a moving-room paradigm, where the walls and ceiling moved, but the floor did not). Infants with less sitting experience showed loss of balance in response to visual stimulation, whereas infants with increased experience did not. This implies that infants rely heavily on visual inputs for controlling sway when they are first learning to sit independently, and this dependence decreases with age and sitting experience, as infants rely more on somatosensory inputs. Woollacott, Debu and Mowatt (1987) used a different protocol to study the impact of sensory inputs during the development of sitting. They studied muscle patterns in the neck and trunk in response to platform perturbations in seated infants with and without vision. They saw that the presence of visual stimuli did not affect the muscle activation patterns in response to perturbations, concluding that somatosensory and vestibular systems are capable of eliciting postural actions in isolation of vision in infants first learning how to sit. To further study the extent to which vestibular and visual inputs are necessary for sitting postural control, Hirschfeld and Forrsberg (1994) performed experiments in which head orientation varied in seated infants undergoing perturbations. They saw that coordinated muscle activity did not change regardless of how the head was oriented, suggesting that postural responses to perturbations are largely controlled by somatosensory inputs rather than vestibular or visual stimulation.

RESEARCH JUSTIFICATION: RATIONALE

Regardless of the specific theory proposed to explain the development of postural control in sitting, from a behavioral aspect, it is indisputable that infants gain control of an increasing number of body segments as they develop the ability to independently sit. Infants take approximately 3-4 months to transition from using their arm for support in sitting (prop sitting) to independent sitting (Figure 1.1).



a) *3 months* b) *6 months*

Figure 1.1. Example of Infant Sitting. Example of infant performing a) prop sitting at 3 months and b) independent sitting at 6 months (Obtained from Piper, Pinnell, Darrah, Maguire, & Byrne, 1992).

This evidence suggests that infants first acquire control of the upper trunk region (allowing prop sitting), followed by the lower trunk region (allowing independent sitting), implying that there could be a segmental progression of control, as infants gradually achieve full trunk control and consequently, are able to independently sit. This is further supported by the fact that the human spine is a multi-segmented structure that requires control of the superficial and deep multifascicular trunk muscles to maintain upright stability (Park, Tsao, Cresswella, & Hodges, 2014).

One of the main functions of the spine is to provide structural support and balance to maintain an upright posture. The spine is a multi-segmented column with anatomically distinct regions, cervical, thoracic, lumbar and sacral, each of which varies in structure, movement and function. For instance, the vertebrae of the thoracic region have longer spinous processes, which make the thoracic spine more stable than the cervical or lumbar regions. On the other hand, the vertebrae of the lumbar region become bigger in size and shape from L1 to L5, a design which allows them to carry most of the body's weight (Kapandji, 2008). Additionally, there is a transitional change in the morphology of the spinal curvatures during development. Newborns present a complete physiological kyphosis that evolves to a lordosis at the approximate age of 10 years. In this regard, research has shown that the alignment of certain spinal segments, like the lumbar segment for instance, with respect to the longitudinal axis of the vertebral column can modulate the neuromuscular control of the spinal region (Park et al., 2014). Because of all these variations in the segments that compose the vertebral column, assessments of trunk function and stability should include the spinal segment to be targeted.

Panjabi (1992) was one of the first researchers to hypothesize mechanisms to explain spinal stability. One of the basic biomechanical functions of the spine is to allow movements between body parts. For this to happen, mechanical stability of the spine is necessary. Panjabi proposed that the stabilizing system of the spine consists of three subsystems: 1) the passive musculoskeletal subsystem, including vertebrae, facets, articulations, intervertebral discs, spinal ligaments, joint capsules, as well as passive components of the musculature; 2) the active musculoskeletal subsystem, consisting of muscles and tendons surrounding the spine; and 3) the neural subsystem, including the various forces and motion transducers, located in ligaments, tendons, muscles and neural control centers (Panjabi, 1992). Though these three subsystems are theoretically different, they are interdependent in function.

During normal function of the spine, the stabilizing systems work together to control the instantaneously varying stability demands that are caused by changes in spinal postural alignment. When there is a dysfunction of any of these three subsystems, the neural subsystem responds to this, and consequently compensates by initiating appropriate changes in the active subsystem. The neural subsystem has the complex task of continuously monitoring and adjusting the forces surrounding the spinal column when there are changes in posture, especially when this happens dynamically, since additional considerations related to masses, inertias, and accelerations are involved (Panjabi, 1992).

Taking this into account, the coordination and balance control of the trunk produced by the stabilizing system of the spine is absolutely crucial for upright human tasks. While these biomechanical mechanisms for trunk postural control are evident in healthy adults, they are not present at birth and are gradually mastered during the development of sitting postural control.

It is proposed that the stabilizing system of the spine during development follows a cranial-caudal progression, in accordance with the anatomically distinct regions of the spine (cervical, thoracic, lumbar, and sacral regions). As infants master the ability to stabilize the spine during static and dynamic changes in posture and across every region of the spine, they achieve complete spinal postural control. This is the substrate for complete trunk control and subsequent independent sitting in development.

GAPS IN THE LITERATURE

Though considerable research has been performed independently on both the development of sitting postural control and the development of reaching, the relationship between the maturational transition of reaching performance across early development and its interrelation with the progressive development of postural control of the trunk has not been thoroughly investigated.

As described earlier, postural control development appears to improve reaching kinematics because reaching is associated with self-produced complex and internal postural perturbations which change according to the infant's position and level of stability (de Graaf-Peters, Bakker, Van Eykern, Otten, & Hadders-Algra, 2007; Hopkins & Rönnqvist, 2002; Thelen & Spencer, 1998). These self-produced perturbations caused by the reach must be compensated by preparatory postural adjustments to allow an accurate reach to occur. Trunk control, which is the foundation of posture, is a critical element for early reaching. Studies have demonstrated this by enabling the emergence of reaching movements in new-born infants when given appropriate support of the entire trunk (Amiel-Tison & Grenier, 1983; von Hofsten, 1982). This fact suggests that arm muscular strength or control of the arm's biomechanics may be a less significant factor in relationship to reaching efficiently once the trunk is supported (Konczak et al., 1997; Out et al., 1998).

Recently, Saavedra, van Donkelaar and Woollacott (2012) examined the segmental differences in trunk stability during the development of upright sitting and saw that developmental changes in postural sway were unique to the region of the trunk that was being tested. These results further refine the hypothesis regarding the progressive development of segmental control during the development of the trunk for upright sitting.

However, it is surprising, considering that the development of reaching skills is crucially dependent on the control of posture, that the relationship between them has not been addressed in detail. Previous studies on sitting postural development and associated reaching movements have considered the trunk as a single segment, and thus, failed to address contributions of individual trunk regions to the development of postural stability and reaching performance. Studies have dealt with the lack of trunk control in their subjects by either using 1) supine or semi-reclined seating when infants are learning how to sit, which alters the effect of gravity on the trunk and consequently influences the performance of a reach (Thelen, Corbetta, & Spencer, 1996; Thelen & Spencer, 1998; van der Fits et al., 1999a); or 2) evaluated the infant during fully supported or unsupported conditions (de Graaf-Peters et al., 2007; Harbourne, Lobo, Karst, & Cole, 2013; van Balen, Dijkstra, & Hadders-Algra, 2012) and therefore failing to allow observation of the progressive control of specific trunk regions during the acquisition of upright sitting on reaching skills. Hence, the exact mechanisms by which typical infants acquire upright sitting control and the impact on reaching development are unknown.

RESEARCH AIMS

Considering all the aforementioned information, the research described in this dissertation challenges existing practices of modeling the trunk as a single segment for evaluating sitting postural control and its relation to reaching in infancy. With the use of an effective and practical method of securing the different segments of the trunk, the infant's ability to vertically align and stabilize the free segments while reaching were investigated. These results will contribute to the first documentation of the processes underlying the coordination of postural and reaching skills during the progressive development of segmental trunk control.

The main goal of the studies included in this dissertation (Chapters III and IV) was to test the contributions of the higher and lower segments of the trunk to postural and reaching performance in typically developing infants, using an external support at thoracic versus pelvic levels of the trunk, respectively.

Aim # 1: Determine whether or not there is an Effect of External Support on Posture and Reaching in Typically Developing Infants Grouped According to their Extent of Trunk Control.

A cross-sectional study was implemented to examine the effects of support (thoracic and pelvic) on posture and reaching in 17 typically developing infants that were grouped according to the extent of trunk control they had acquired. Group 1 infants were unable to sit independently but demonstrated postural control in the thoracic region, while Group 2 infants were independent sitters and demonstrated control in the thoracic and lumbar regions. Kinematic data were used to compare postural and reaching measures between groups, depending on the level of support provided.

It was hypothesized that with the use of an external support at thoracic level, all infants would have equivalent postural and reaching skills, given that both groups demonstrated postural control in the thoracic region. However, it was suggested that when the external support was limited to the pelvic level, infants who had already developed control of the lumbar region would have better performance and reaching success. To confirm that the effect of support contributes to changes in posture and reaching depending on the extent of trunk control infants have acquired, a follow-up, longitudinal study outlined in the second aim was executed.

The cross-sectional study is described in Chapter III and includes previously published, co-authored material. Victor Santamaria, Sandra L. Saavedra, Staci Wood, Francine Porter, and Marjorie H. Woollacott are co-authors.

Aim # 2: ***Quantify the Effects of an External Support on Posture and Reaching across the Progressive Development of Trunk Control in Typically Developing Infants from 2.5 to 8 Months of Age.***

A longitudinal study was conducted evaluating the effect of support (thoracic and pelvic) on posture and reaching in 10 typically developing infants from 2.5 months – 8 months. Behavioral, kinematic and electromyographic (EMG) recordings were compared between levels of support to examine intra-individual changes and to gain a deeper insight into the mechanisms underlying the progression of segmental trunk control acquisition and its contributions to reaching skills. More specifically, the objectives were to test the impact of external support across age on: reaching strategies, reaching/postural kinematics, and EMG responses of postural and arm muscles, in terms of frequency of activation, amplitude, latencies and recruitment order.

It was hypothesized that before the onset of independent sitting, infants would demonstrate a decreased ability to reach, impoverished reaching and trunk kinematics and inefficient postural muscle patterns when given pelvic in comparison to thoracic support. All these observations would be explained by the challenges in remaining balanced with pelvic support when infants have not yet acquired control of the lower trunk. Subsequently, as infants learned to control the lower trunk and pelvic regions and thus, acquired independent sitting, it was hypothesized that these effects would disappear and infants would demonstrate invariable reaching and postural patterns irrespective of the level at which they were supported. Hence, these results would confirm and further expand previous findings showing that there is a cranio-caudal acquisition of trunk control for independent sitting and that improvements in trunk control have direct consequences on the development of reaching.

The longitudinal study is described in Chapter IV and includes unpublished, co-authored material. Victor Santamaria, Sandra L. Saavedra and Marjorie H. Woollacott are co-authors.

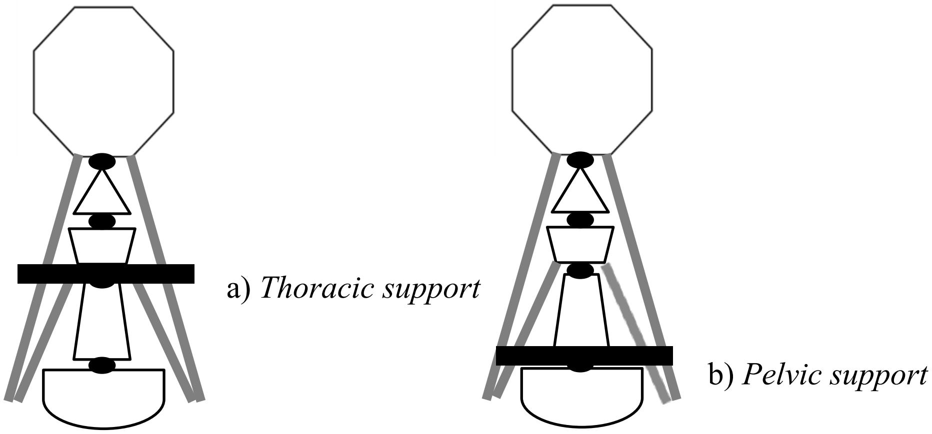
CHAPTER II

THEORETICAL CONCEPT AND GENERAL METHODOLOGIES

PRINCIPLE DESIGN PARADIGM

A new conceptual framework was used for evaluation of the development of upright sitting and its contributions to reaching, in which the trunk is modeled as a multi-segmented unit. The spine and head can be schematically represented as a physical system consisting of a vertical column composed of blocks (vertebral segments) with the top block (head) and wires (muscles) (Figure 2.1). They must exert adequate intrinsic stiffness (steady-state) and reflexive muscle-tendon forces (reactive balance) on the different vertebral subunits of the segments in order to program (anticipatory balance) and carry out the optimal motor response in each situation. The physical structure includes the vertebral segments: cervical, thoracic and lumbar vertebrae, connecting tissues, ligaments and muscles. The number, shape and connections of the different vertebrae determine the degrees of freedom to be controlled. Using this model, already applied in previous investigations (Saavedra et al., 2012), we created an innovative way to assess segmental trunk control by changing external levels of trunk support from a high level of support (thoracic level) to a lower level of support (pelvic level), in order to measure control of the thoracic and lumbar segments while reaching.

In this linked mechanical system, including the multi-segmented trunk, the forces generated at any one segment during a dynamic task, like reaching, will also generate passive forces on the other segments. It is known that a critical aspect of skilled movement is the ability to stabilize the linked segments against motion-dependent forces (Thelen & Spencer, 1998). In our experimental paradigm, the external support would be holding the targeted trunk region stable while the infant was reaching toward an object. Successful stabilization of the trunk segment/s over the support level requires activating the proper muscles, at the proper time, with optimal strength and coordination in order to resist the forces moving them away from the stability limits that are generated by the reaching task.



a) *Thoracic support*

b) *Pelvic support*

Figure 2.1. Representation of Linked Mechanical System. Representation of the linked mechanical system of the spine, including vertebral segments and connecting structures. Black semicircles indicate external trunk supports at a) thoracic level and b) pelvic level.

INFORMED CONSENT

The University of Oregon Institutional Review Board through Research Compliance Services and the Committee for Protection of Human Subjects formally approved the studies and protocols that compose this dissertation (Chapters III & IV). Prior to all studies, all the procedures and risks were discussed with the family. Additionally, a written informed consent was obtained from all parents prior to their infant's participation.

TRUNK STABILIZING DEVICE FOR THE REACHING TEST

Infants were seated on a bench with the pelvis firmly strapped in place. Two straps were placed over the top of the thighs and one strap surrounded the posterior-superior iliac spines so that the pelvis remained fixed in the vertical and horizontal planes throughout the experiment. Straps were made of non-elastic, heavy bonded thread. A rigid U-shaped, posterior support made of fiberglass that circled the trunk provided upright stability of the trunk below the level of interest. The trunk support was raised or lowered at specific levels of the trunk for evaluating the two main regions: 1) upper trunk region (thoracic segment of the trunk), with the use of a support at thoracic level and 2) upper and lower trunk region (thoracic and lumbar segment of the trunk), with the use of a support at pelvic level. Figure 2.2 shows an infant in the trunk stabilizing device at thoracic and pelvic levels of support. Placement accuracy and ability to limit trunk movement below the level of support have been verified in laboratory tests. Once the trunk was supported, the reaching test involved presenting the same colorful, circular object at approximately the infant’s arm length in front of their sternum.

LABORATORY MEASURES OF POSTURE AND REACHING

Video Recording

Video recordings at 30 frames per second were obtained for further visualizing and coding behavioral observations. A digital video camera was situated at the front corner of the infant to provide a front view of the infant’s activity and to capture the body and hand position as they reached toward the toy. The advantage of using video

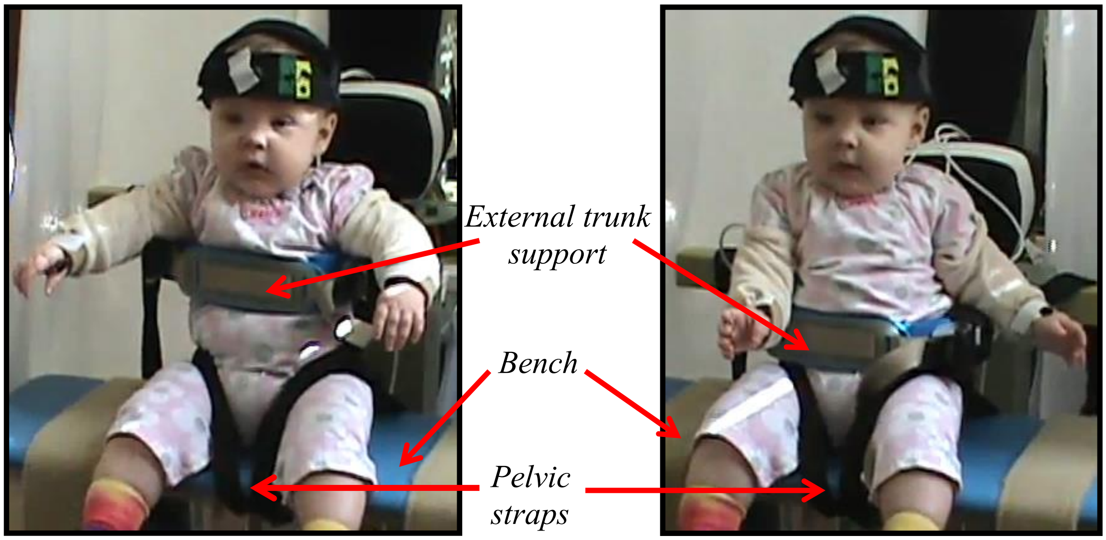


Figure 2.2. Example of Trunk Stabilizing Device. Example of infant seated on a bench with pelvic strapping and external trunk support device during the reaching test.

recordings for coding is to automate common analysis tasks and ensure accuracy in the data. Doing research with infants can be very challenging in that one cannot instruct them when to initiate the task of reaching. Therefore, with the use of video coding software, the coder can clearly distinguish intentional reaches toward the toy. Another advantage to the video coding software is that it temporally categorizes each event. With this, the coder was able to visualize, frame by frame, and code what type of movement occurred at what time and compare the sequence of events. Thus, every reach event had an onset and offset time in milliseconds and was categorized depending on the type of reach.

Motion Tracking

Postural stability and reaching performance were measured using magnetic tracking (miniBIRD system, Ascension Technology, Burlington, VT). The miniBIRD is a six degrees-of-freedom measuring device that is used to measure the position and orientation of a small sensor with respect to a transmitter, with an accuracy of 1mm and 1° (Acension Technology Coorporation, 2000). The transmitter was placed to the right side of the infant's head, at a 30 inch distance. The position and orientation of each sensor were sampled at 84 Hz. A total of four sensors were used for providing information regarding head, trunk and arm movements. Translational movements were recorded with respect to the global reference axes: X (+ to the left), Y (+ pointing forward) and Z (+ pointing downwards); as well as angular movements in the three orthogonal planes: Azimuth, Elevation and Roll angles. There are several advantages to using electromagnetic technology, especially when studying infant movement. First, sensors can be embedded inside any material and still track position and orientation with the same accuracy. This allowed us to attach the head sensor to a head-band for placing it on the infant's forehead, the trunk sensor with surgical tape for placing it on the infant's neck at the level of C7, and the arm sensors to neoprene wrist-bands for placing them on the infant's wrists. Second, in contrast to the use of cameras, a field of view is not necessary for continuous tracking. This means that it has the ability to track through people. With this advantage, the tester and if necessary, the parent were able to remain close to the infant.

Surface Electromyography

In the longitudinal study, trunk and arm muscle activity were recorded using a 16-channel surface electromyography system (MA300, Motion Lab Systems, Baton Rouge, LA). Bipolar, self-adhesive surface electrodes with poles placed 2-3 cm apart were placed bilaterally at the paraspinal muscles of the thoracic and lumbar segments of the trunk, as well as at the belly of anterior deltoid, triceps and biceps muscles. One extra channel was used for collection of the heart-beat for later subtraction of any heart-beat artifacts embedded in the EMG signal (see Appendix for further information on heart-beat subtraction method). Surface electrodes were attached to pre-amplifiers to increase the magnitude of the signal.

The EMG system consisted of two units (a backpack and desktop unit) attached with a connecting cable. Signals from the pre-amplifiers were digitized and processed within the backpack and transmitted as digital information to the desktop unit. The backpack had a gain setting for allowing complete control of the output signal and an additional control to limit the maximum EMG frequency for avoiding the possibility of recording signal aliasing errors. The EMG system also accommodated an optional internal band-pass filter to ensure that the EMG signals produced did not exceed the capabilities of the data collection system. Therefore, EMG signals were preamplified (gain X 20), band-pass filtered (10-375Hz), and then further amplified at a sampling rate of 1000Hz per channel. EMG data was timed-synched with position data with the use of a trigger channel.

CLINICAL MEASURES ON GROSS/FINE MOTOR SKILLS AND TRUNK CONTROL

In the study of motor development in infancy, the use of supplementary motor and postural scales is recommended for further categorization of the motor behavior being analyzed. These assessments assisted in the description of motor and postural progression and most importantly in identifying the critical windows and onsets of relevant motor abilities, such as head control and independent sitting.

Alberta Infant Motor Scale: AIMS

The AIMS is an observational motor assessment designed for the study of gross motor maturation during the first 19 months of age, from birth through independent walking. This scale is composed of 58 items that are organized in four different positions: prone (21 items), supine (9 items), sitting (12 items) and standing (16 items). Each item describes three aspects of motor performance: weight-bearing, posture and antigravity movements (Piper et al, 1992). The evaluator first determines the infant's developmental stage or window of development, at each position. The total score is then given by the sum of all the points within this window of development plus points prior to this window. The motor item is tested as present or not present at a specific point in development. Total score and age then determine the infant's status on one of the percentile curves, derived from the Canadian normative population. This scale has been standardized and currently presents a great reliability; it has also been validated in different countries and can be applied in pathological conditions as well (Barbosa, Campbell, Sheftel, Singh, & Beligere, 2003; Darrah, Bartlett, Maguire, Avison, & Lacaze-Masmonteil, 2014). This assessment was applied in the different studies of this dissertation in order to track the motor evolution of the participants. It provided an accurate description of the motor capacity of the sample and allowed us to define the onset of independent sitting in each infant.

Bayley Scales of Infant Development, 3rd edition (BSID-III): Gross and Fine Motor Development

The BSID-III evaluates the progressive functional development of infants from 1 to 42 months. It has been standardized based on a normative sample of the United States and it is widely used in clinics and child healthcare research. It is divided into five major developmental domains: cognitive, language, motor, social-emotional and adaptive behavior. The items of the motor domain were the only ones considered in the longitudinal study, consisting of 72 items for gross motor skills and 66 items for fine motor skills. The overall score is given by summing all of the items for which the infant is given credit, within the group of items that are specific to their age, and added to the sum of the items from earlier months (Bayley, 2005).

Segmental Assessment of Trunk Control: SATCo

In infant development, assessment tools for postural control, such as the AIMS and BSID-III, model and refer to the trunk as a non-dissociable unit, ignoring the fact that the trunk is made up of multiple segments. These clinical tests are reliable and effective in assessing limited aspects of functional balance while sitting and standing. For example the AIMS evaluates simple steady state sitting (arms propped or arms free), scoring sitting based on the amount of time the infant is able to sit securely. These scales do not test trunk control in detail, and more specifically, the contributions of distinct trunk regions to upright sitting balance. In addition, these assessments involve the use of other anatomical structures, such as the upper and lower extremities in order to evaluate dynamic trunk balance, failing to evaluate the neuromuscular coordination that must be achieved to sit independently, including the coordination of sacral, lumbar, abdominal, thoracic and cervical muscles used in maintaining equilibrium. In contrast, the SATCo is a more complete analytical and specific assessment of sitting balance that increases the accuracy of the initial assessment of trunk control.

The SATCo was originally designed for a population of children diagnosed with Cerebral Palsy. The SATCo is now shown to be a reliable and valid clinical measure of trunk control in both infants with typical development and children with neuro-motor disability (Butler, Saavedra, Sofranac, Jarvis, & Woollacott, 2010).

The test consists in evaluating control of vertical trunk posture as the evaluator progressively changes the manual support of the trunk from a high to a low level, with a total of 8 different levels. This means that, as the support level is lowered, the number of free segments increases and thus requires more intrinsic control of the trunk. For each segmental trunk level, static, active and reactive control, are scored as present or absent. The score is determined in relation to the specific level of the trunk (1 through 8) in which the infant loses control in any of these three aspects (static, active or reactive).

CHAPTER III

SEGMENTAL TRUNK CONTROL ACQUISITION AND REACHING IN TYPICALLY DEVELOPING INFANTS

This chapter is published in volume number 228 (1) of the journal *Experimental Brain Research* in July 2013. Victor Santamaria, Sandra L. Saavedra, Staci Wood, Francine Porter, and Marjorie H. Woollacott are co-authors. I performed the experimental work and led the project; Marjorie H. Woollacott formulated the conceptual framework with Sandy Saavedra, provided advice on data analysis and gave editorial assistance; Victor Santamaria contributed to the recruitment, data acquisition, data analysis and interpretation; Staci Wood and Francine Porter contributed to the recruitment and data acquisition; Sandy Saavedra also helped develop the protocol and gave editorial assistance. All co-authors formally approved this manuscript for submission.

INTRODUCTION

Postural control and reaching movements are two remarkable and complex motor milestones that are acquired progressively during the first years of life and are subsequently used throughout life in a variety of tasks (van der Heide et al., 2003). Although the maturational process of these two functions is different and emerges at various developmental stages during infancy, they are closely related to each other. It is widely acknowledged that motor development is not only a result of neural maturation, but is a dynamic process involving interaction between environmental constraints and sensorimotor systems. Reaching for an object is usually accompanied by postural adjustments prior to and during movement to provide mechanical stability and to maintain the body's equilibrium (Assaiante, Mallau, Viel, Jover, & Schmitz, 2005; van der Fits et al., 1999a).

Research regarding the sequence of development of trunk control is still a matter of controversy. For instance, evidence has shown that intentional reaching with the feet can be developed earlier than with the hands, at the age of 2 months, in a specified context (Galloway & Thelen, 2004), implying the possibility of a bottom-up sequence of trunk control. However, there is also evidence supporting the concept that head and trunk control defined as non-perturbance of head and torso during reach (Thelen & Spencer, 1998), are developed in a top-down order. For example, infants are able first to maintain their head in relation to the trunk when they are 2 - 3 months old, although head control is not complete at this developmental stage (Touwen, 1976; van Wullften & Hopkins, 1993). The more mature head control at 4 months of age is important for environmental exploration (Hadders-Algra, 2008) and it has also been suggested to be relevant in successful reaching (Thelen & Spencer, 1998). In addition to this evidence, a top-down direction-specific recruitment of cervical, thoracic and lumbar muscles is predominant at 4 months of age, also suggesting functional relevance of a top-down order (van Balen et al., 2012). Subsequently, the ability to sit upright without support occurs approximately at the age of 8-9 months (Harbourne, Giuliani, & Neela, 1993; McGraw, 1945; Saavedra et al., 2012). Beginning at that time and continuing up to 18 months there is a gradual replacement by a bottom-up recruitment preference, indicating that the focus of control moves towards the support surface (Assaiante, 1998; Hadders-Algra, 2008).

The presence of direction–specific activity of postural muscles and the complete top-down pattern of recruitment of postural muscles used in the control of independent sitting is not a prerequisite for the emergence of reaching movements, although the quality and success of reaching is associated with this recruitment (de Graaf-Peters et al., 2007). Postural control development appears to improve reaching kinematics because reaching is associated with self-produced complex and internal postural perturbations which change according to the infant's position and level of stability (de Graaf-Peters et al., 2007; Hopkins & Rönnqvist, 2002; Thelen & Spencer, 1998). These self-produced perturbations caused by the reach must be compensated by preparatory postural adjustments to allow an accurate reach to occur. Trunk control, which is the foundation of posture, is a critical element for early reaching. Studies have demonstrated this by enabling the emergence of reaching movements in newborn infants when given appropriate support of the entire trunk (Grenier & Amiel-Tison, 1981; von Hofsten, 1982). This interesting fact suggests that arm muscular strength or control of the arm's biomechanics may be a less significant factor in relationship to reaching efficiently once the trunk is supported.

The ability to reach appears when infants are about 3 months old but reaches are characterized by irregular trajectories and are unsuccessful in terms of grasping and holding objects (van der Fits et al., 1999b). It is not until the age of 4-5 months that the onset of functional reaching occurs (Gessell & Ames, 1947; von Hofsten, 1991). At this age, full-term infants are able to grasp stationary and moving toys (Grönqvist, Strand Brodd, & von Hofsten, 2011); infants aged 18 weeks can even grasp non-stationary toys moving at 30cm/s (von Hofsten, 1980). At 4-5 months, successful reaches, defined as including object contact, are characterized by large numbers of movement units (MUs) and non-regular trajectories towards the object (Gessell & Ames, 1947). After the age of

6 months, the reaching sequence during which infants orient and direct their hand toward a toy becomes straighter and shorter. Also, the movement is composed of fewer MUs (1-2) and the first MU is differentiated by being longer in length and duration than the second (Hopkins & Rönnqvist, 2002). At this time the kinematic parameters of a reach start to assume an adult-like form in which straightness and smoothness are correlated; fewer MUs are associated with a straighter trajectory of reaching, and peak velocity is achieved at a greater percent of the reaching path (von Hofsten, 1991).

Previous studies on the development of reaching skills have been designed to test muscular strength and control of arm mechanics of infants. These studies concluded that insufficient muscular strength or insufficient control over the unstable arm does not restrict early reaching and that movement becomes smoother as age increases (Konczak et al., 1997; Out et al., 1998). Although this research has given insights into the motor control of reaching, it has not addressed the issue of the infants' need for trunk control as a foundational element required for accurate reaching.

Though considerable research has been performed independently on both the development of postural control and the development of reaching, the relationship between the maturational transition of reaching kinematics and the progression of trunk control acquired during early infancy has not been thoroughly investigated. Previous studies have dealt with the lack of trunk control in 4 and 6 month old infants, by using supine or semi-reclined seating, which alters the effect of gravity on the trunk and subsequently influences the kinematics of reaching. In addition these studies evaluated the trunk as a single segment, and therefore often designed protocols to observe infants sitting in fully supported or unsupported states (de Graaf-Peters et al., 2007; Hopkins &

Rönnqvist, 2002; Thelen & Spencer, 1998), failing to allow observation of the contribution of individual regions to trunk control and reaching. Addressing the development of postural control from a multi-segment perspective is a novel technique that has yet to be fully explored. We suggest keeping the effect of gravity constant by using vertical alignment with higher versus lower levels of external trunk support to allow more precise analysis of the effect of trunk control on reaching.

In summary, though previous research has given extensive insights into the control of reaching development, it has not specifically addressed the contribution of upper and lower regions of trunk control to reaching. This study will seek to fill this gap through the use of two unique approaches. First we used vertical alignment with two levels of external support (thoracic and pelvic) to test effects of regional support on reaching in typically developing infants between the ages 4 and 6 months. Within this temporal period sitting posture control emerges, and infants master their reaching and grasping skills. Secondly, we classified our sample into two groups according to the infant's region of intrinsic trunk control as measured by the Segmental Assessment of Trunk Control (SATCo) (Butler et al., 2010). Group 1 infants demonstrated postural control in the thoracic region while Group 2 infants demonstrated control in the thoracic and lumbar region. Kinematic parameters of visually guided reaches towards a toy were examined as well as their success in grasping it. The hypothesis suggested was that with the use of the external thoracic support all infants would have equivalent reaching patterns and success since both groups demonstrated postural control in the thoracic region. In addition, it suggested that when external support was provided at the pelvic level, only the infants who already had developed control of the lumbar region would have better reaching performance and success.

METHODS

Participants

Seventeen healthy infants born at term were recruited for this cross-sectional study (9 males and 8 females). The infants were aged between 4 and 6 months. The recruitment was carried out by using flyers in different child care centers in Eugene and Springfield (Oregon, USA). This study was reviewed and accepted by the Institutional Review Board for Human Subjects Research at the University of Oregon.

Materials and Procedure

Subjects were asked to come to the laboratory for one session of approximately 90 minutes. During this visit, infants were clinically tested with the SATCo to determine their level of trunk control and the Alberta Infant Motor Scale (AIMS) to identify their level of gross motor function. In addition, the parents were asked to respond to a health questionnaire about their infants, were informed in detail about the experimental procedure and signed the informed consent. All infants were video recorded during the assessment. Table 3.1 shows the clinical characteristics for each group.

SATCo is a new clinical measure that allows a precise examination of balance control of the trunk at various levels of support. It tests the infant’s trunk control as the evaluator manually changes the level of trunk support from a high level of support at the shoulder girdle to assess cervical (head) control, through support at the axillae (upper thoracic control), inferior scapula (mid-thoracic control), lower ribs (lower thoracic control), below ribs (upper lumbar control), pelvis (lower lumbar control), and finally, no support, in order to measure full trunk control. It is designed to assess: 1. static control (maintaining a neutral trunk posture) 2. active or anticipatory control (maintaining a neutral posture during head movement) and 3. reactive control (maintaining or regaining trunk control following a threat to balance, produced by a brisk nudge). The infant's ability to maintain or quickly regain a vertical position of the free region of the trunk in all planes is assessed during static, active and reactive testing and scored accordingly as present or absent. The score reflects the region where infants lose control of posture in; 1 = head, 2 = upper thoracic, 3 = mid-thoracic, 4 = lower thoracic, 5 = upper lumbar, 6 = lower lumbar, 7 = pelvis, 8 = no loss of trunk control (Butler et al., 2010). Thus, for example, an infant with SATCo score 4, loses control of posture in static, active or reactive tests when the evaluator supports the lower thoracic region of the trunk (lower ribs). However, an infant with SATCo score 6, does not lose control until the evaluator supports the lower lumbar region of the trunk (the pelvis). In this study, we classified our sample into two groups according to their SATCo score: Group 1 = infants with SATCo scores 4 and 5 (demonstrating control in the thoracic region), Group 2 = infants with SATCo scores 6 and 7 (demonstrating control in the thoracic and lumbar region). Other tools such as the AIMS, inform us about the acquisition of infants' developmental gross motor milestones from term age through independent walking (Piper et al., 1992). Both of these tests follow a specific scoring criterion and have been shown to be valid, reliable measures of developmental change in infants (Butler et al., 2010; Piper et al., 1992; van Haastert, de Vries, Helders, & Jongmans, 2006). They thus can be used as clinical measures of the developmental level of trunk control and motor function.

Table 3.1. Group Characteristics

	n	Sex Ratio	SATCo	AIMS	Age	Sitting Ability
Group		*(Male:Female)*	*M(min-max)*	*M(min-max)*	*M(min-max)*	
Group 1	8	(5:3)	4.50 (4 – 5)	18.25 (15 – 24)	4.50 (4 – 5)	Non-sitters
Group 2	9	(3:6)	6.56 (6 – 7)	29.33 (23 – 41)	6.22 (5 – 6)	Sitters

Note: *M* = mean.

The reaching test was conducted at pelvic and thoracic levels of support for every infant. The support at the thoracic level was placed below the scapular girdle and the pelvic level of support was around the pelvis, corresponding to middle thoracic level and lower lumbar level of the SATCo, respectively. The design of the study was counterbalanced, with half the infants first being provided with thoracic support, and half first being provided with pelvic support, in order to eliminate fatigue or training effects as confounding variables.

The reaching test was synchronized with the collection of kinematic data using the Flock of Birds miniBIRD electromagnetic tracking sensors (Ascension Technology, Burlington, VT). Four sensors were placed on the infant: one superficial to the styloid process of the radius on each wrist, one on the posterior and prominent part of the cervical vertebra 7 (C7), and one on a headband with the sensor centered on the forehead. These sensors were used to track arm, trunk and head movements. Prior to starting the reaching test, digitized position markers were taken of the left and right tragus, the medial/lateral and anterior/posterior points of the external support (pelvic or thoracic). This allowed us to estimate the location of the head center of mass (HCOM) using the center of the distance between the midpoint of the two tragus markers and the head sensor. The center of the base of support (BOS) was defined as the midpoint of the two vectors created between the medial/lateral and anterior/posterior markers of the external level of support.

The reaching test involved the infant being placed in a seated position on a bench. The pelvis of the infant was secured to the bench with specially designed straps and Velcro. Three straps were firmly attached to the underside of the bench: two of them were used to wrap each hip joint and the third surrounded both posterior superior iliac spines (Butler et al., 2010). An adjustable support device located behind the bench provided trunk stability at one of the two levels studied. This device surrounded the trunk, offering strong stability at the level being studied and below (Saavedra et al., 2012). Once posture was stabilized, a colorful object was hung by the tester in front of the infant's sternum at approximately the arm's length. The toy was presented 15 times per level of support, but there were occasions in which this number had to be reduced due to fussiness of the infant. If that was the case, the infant's maximum number of trials was noted and the rest was counted as missing data. In addition, the tester occasionally presented a different toy (colored rings or blocks) in order to keep the infant engaged in the task of reaching. The entire session was video recorded to ensure differentiation between non-directed arm movements and reaching movements towards the toy during the analysis.

All reaches were visually analyzed by two coders using computerized video-coding software (www.openshapa.org) for further evaluation of the kinematic parameters. This program allowed us to determine the onset and offset of every visually guided intentional reach. A light emitting diode (LED), placed on the corner of the visual field, was used to synchronize video and kinematic data during each reaching trial. With this, we made sure that we were selecting reaches within the reaching test time. We defined the onset of a reach as the moment when the infant initiated a movement of the upper extremity towards the toy while looking at it. The offset of the reach was determined when the infant touched the toy with the intention of grasping it. If an infant initiated a reaching movement towards the toy and lost interest during the trajectory by stopping and looking away, these reaches were not selected. Inter-rater reliability was validated by having both coders evaluate 50% of the data and obtained a coefficient of agreement above 0.85.

Reaches were coded as unimanual or bimanual. We defined bimanual reaches as those in which we visually saw the infant touch the toy with both hands and which also had an onset time difference between both arms of less than 1000 ms. Occasionally, infants would begin unimanually and then switch to the other arm before reaching the toy. In this case, for the kinematic data analysis, only one arm, considered as the predominant arm, was selected. This selection was the same for the case of bimanual reaches. The arm predominance was determined based on the hand that manipulated the object once it was held. If infants used compensatory strategies like reaching with their head or dragging the toy with their forearm, these were not considered.

Data Analysis

Data were filtered with a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6Hz, prior to calculating the kinematic variables. All unimanual or bimanual reaches were pooled together and were analyzed at both thoracic and pelvic levels for each group, to output kinematic data. Additionally, the total number of successful and unsuccessful grasps of the toy was also counted. Kinematic data at each level of support were analyzed using custom algorithms with the software Matlab (The MathWorks, Inc., Boston, MA). We examined the following variables for each reach: movement time, straightness score, MUs, reach path divided by the number of MUs, angular head displacement, angular trunk displacement and percentage of successful grasps.

Movement time was calculated in seconds as the time between the onset and the end of the reach. Straightness score was calculated as the proportion between the actual resultant trajectory of the reach and the minimum possible one, determined by a straight line from start to the end of the reach. Using this method, values greater than one meant a more devious arm movement (von Hofsten, 1991). A MU was defined according to Grönqvist et al. (2011), as the portion of the arm movement between two velocity minima with a velocity peak that should be greater than 2.3 cm/s. Also, if the difference between the highest minima of one MU and the peak velocity of another MU was less than 8 cm/s they were considered as one MU. Path length per MU was calculated by dividing the total reach path by the number of MUs. In terms of postural control, the angular displacement of the head and trunk were analyzed as two different segments to distinguish their displacement during a reach. Head displacement and trunk displacement were calculated as the total angular displacement during a reach in the anterior-posterior plane. For the head displacement, the angle between the HCOM with respect to the C7 sensor was applied and for the trunk displacement, the angle between the C7 sensor and the BOS was used. This provided the angle of the trunk segment above the external support.

Statistical Analysis

The data analysis was carried out using SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA). The total number of successful/unsuccessful grasps and the kinematic parameters were computed by using the Linear Mixed procedure. This statistical approach is more accurate when data are more unbalanced since it allows for a more adequate modeling of the covariance structure and can deal with incomplete data. Bayesian Criterion-type model was used to select the covariance structure with the best fit; the structure exhibiting the smallest criteria values was considered the most desirable. The model selected was the Scale Identity covariance for the repeated measure. Follow-up pairwise comparisons based on the estimated marginal means were conducted to analyze significant main or interaction effects applying the Bonferroni adjustment. For all tests, the preset alpha level was .05.

RESULTS

Differences in Reaching Accuracy According to Level of Support

The graphs from Figures 3.1 and 3.2 are examples of a reach at the thoracic and pelvic level of support of a Group 1 and a Group 2 infant, in addition to the photographic image during the reach. The graphical representation of the arm trajectory shows how the two infants showed a similar reaching position trajectory with thoracic support and both infants seemed to look equally stable during the reach; however, the arm trajectories with pelvic support show that the Group 1 infant had a more jerky reach than the Group 2 infant. A total of number of 293 reaches was analyzed. Figure 3.3 shows statistical results for group effects at each level of support.

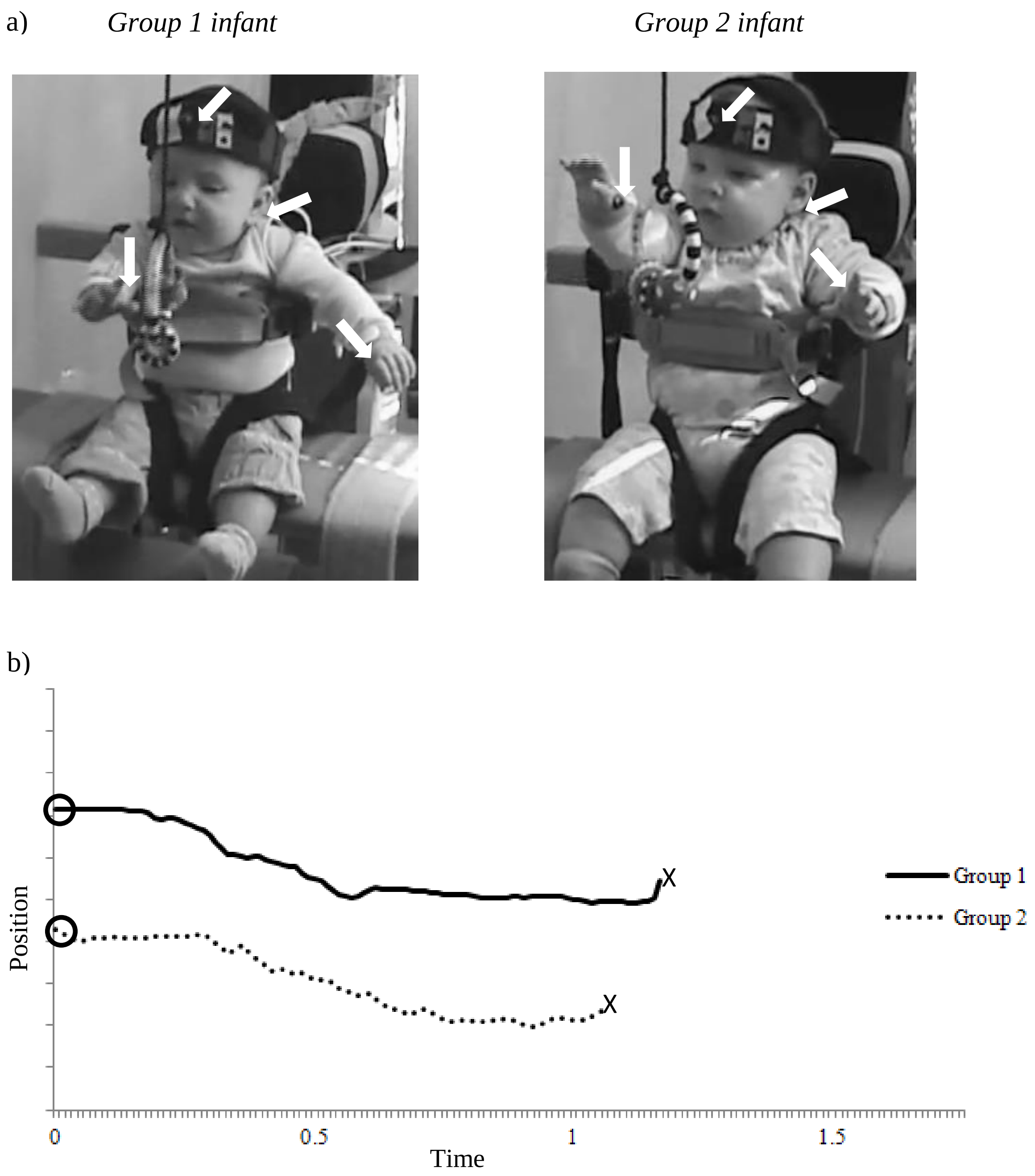


Figure 3.1. Thoracic Level of Support. a) Photographic images of a Group 1 and Group 2 infant during a reach. Arrows indicate location of sensors. b) Line graph represents resultant XYZ position from onset (○) to offset (X) of reach across standardized time (x – axis). Y-intercept is arbitrarily chosen to separate the trajectories for clearer viewing of one single reach of one infant in Group 1 (upper line) and one infant in Group 2 (lower line).

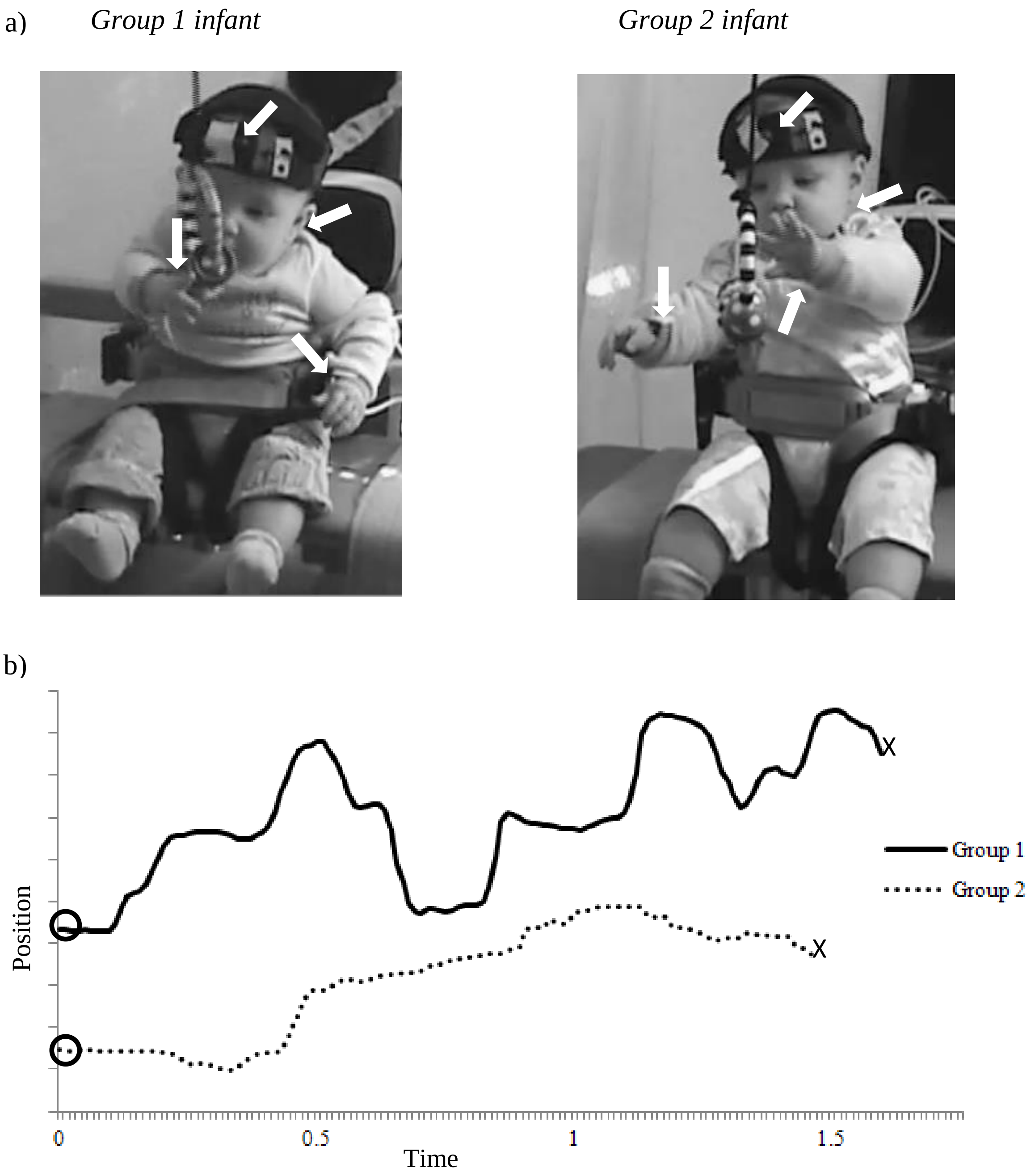
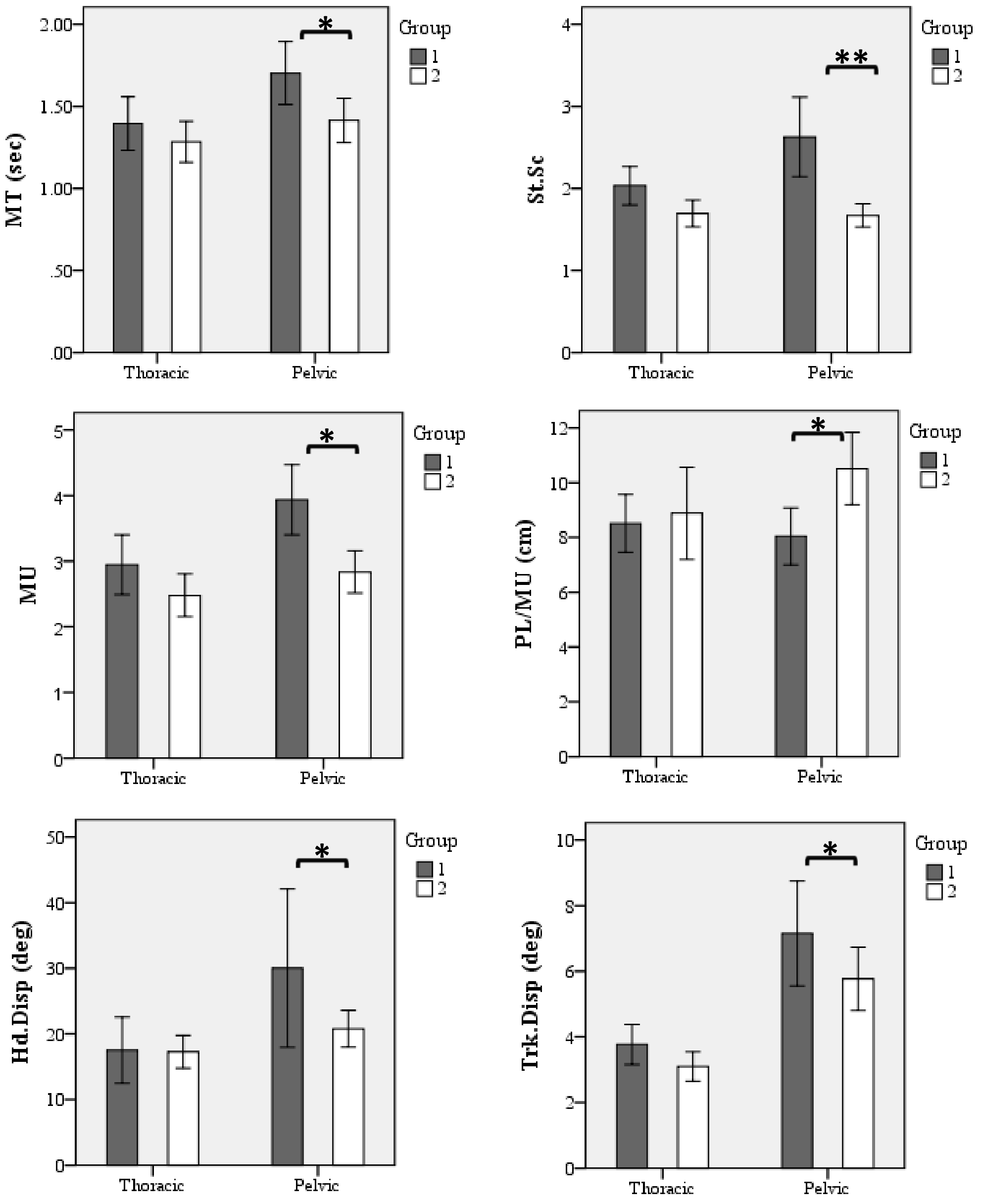


Figure 3.2. Pelvic Level of Support. A) Photographic images of a Group 1 and Group 2 infant during a reach. Arrows indicate location of sensors. B) Line graph represents resultant XYZ position from onset (○) to offset (X) of reach across standardized time (x – axis). Y-intercept is arbitrarily chosen to separate the trajectories for clearer viewing of one single reach of one infant in Group 1 (upper line) and one infant in Group 2 (lower line).



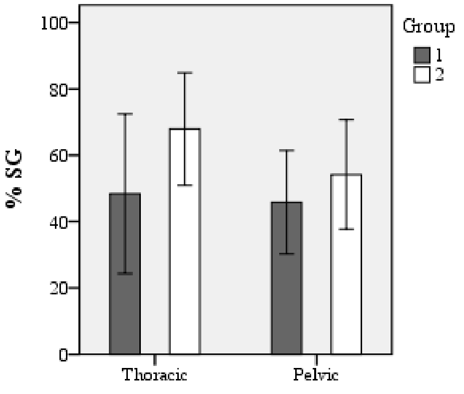


Figure 3.3. Group Effects across Levels of Support. Estimated group means for: movement time (MT), straightness score (St.Sc.), movement units (MU), path divided by number of MUs (PL/MU), angular head displacement (Hd.Disp.), angular trunk displacement (Trk.Displ.), and percentage of successful grasps (%SG); at both levels of support, Group 1 (dark gray bars) and Group 2 (light gray bars).
Error bars, +/- 2 SE. * = $p < .05$, ** = $p < .01$.

Thoracic Support. None of the variables analyzed showed significant effects of group for thoracic support. These results suggest that all infants were equally stable with thoracic support and had similar kinematic parameters during the reaching sequence.

Pelvic Support. All variables except for percentage of successful grasps showed a significant effect of group for pelvic support. Group 1 infants compared to Group 2 infants showed: greater movement time, $F(1, 289) = 6.82$, $p < .05$, a higher straightness score, $F(1, 289) = 24.90$, $p < .01$, a higher number of MUs, $F(1, 289) = 13.97$, $p < .01$, lesser path length per MU, $F(1, 289) = 6.49$, $p < .05$, greater head displacement, $F(1, 289) = 4.42$, $p < .05$ and greater trunk displacement, $F(1, 289) = 4.07$, $p < .05$.

Overall, these results show that when providing an external pelvic support, stability, determined by head and trunk displacement, is better in infants who had acquired control of their thoracic and lumbar region (SATCo scores 6 and 7); additionally they showed straighter reaches, less MUs and covered greater distance per MU.

DISCUSSION

The primary purpose of this study was to more specifically investigate the contribution of upper and lower regions of trunk control to reaching. We addressed this by using vertical alignment at two levels of support (thoracic and pelvic) and by grouping infants according to their region of intrinsic trunk control. In this manner, we confirm previous studies by showing that the infants' ability to control the trunk influences the quality of reaching (Hopkins & Rönnqvist, 2002; Spencer & Thelen, 2000). In addition, our results expand previous findings by providing evidence that depending on the intrinsic control of the trunk region acquired, the level of external support has an impact on the quality of reaching movements. In what follows, we discuss how reaching abilities of two groups of infants who demonstrated control of different regions of the trunk showed significant differences in their reaching patterns depending on whether they were given thoracic vs. pelvic support.

We predicted that if infants were provided with thoracic support, the two groups would demonstrate similar reaching behaviors and show similar patterns of control of their stability, given that both groups had trunk control at the thoracic region, according to their SATCo score. In contrast, we hypothesized that when provided with pelvic support the two groups would behave differently due to the difference of the extent of intrinsic trunk control they had developed. Our hypotheses was correct when comparing Group 1 and 2 for movement time, straightness score, MUs, path length per MU, head displacement and trunk displacement. However, percentage of successful grasps was the same between Group 1 and 2 at both levels of support.

Previous research showed that 6 month old infants have quicker reaches, straighter reaching trajectories, less MUs and increased path length per MU than 4 month infants (de Graaf-Peters et al., 2007; Fallang, Saugstad, & Hadders-Algra, 2000; Thelen & Spencer, 1998; von Hofsten, 1991). We expanded these findings by testing 4 to 6 month old infants in vertical alignment with external support at thoracic and pelvic levels and demonstrated that differences in reaching kinematics depend on the infants' region of intrinsic control. Both groups had acquired control in the thoracic region and demonstrated similar reaching patterns when given external support at the thoracic level. This is consistent with other studies showing the development of head and upper torso control as precursors for the emergence of successful reaching (Spencer & Thelen, 2000;

Thelen & Spencer, 1998). In contrast, Group 2 had also acquired control in the lumbar region and demonstrated significantly better quality of reach than Group 1 when provided external support at the pelvic level. Between Groups 1 and 2 there were many differences, such as age, experience and gross motor development. However the fact that differences between groups were only seen with pelvic support and not with thoracic support indicates that region of intrinsic control achieved is the main factor contributing to differences in quality of reaching observed in this study.

The variables related to postural stability during a reach corroborate those from the clinical data from the SATCo and AIMS evaluation of the infants. Group 1 infants had a mean SATCo score of 4.50 and were non-independent sitters, whereas Group 2 infants were independent sitters and had a mean SATCo score of 6.56. These results correspond well with data from the previous literature, which suggest that the motor strategies for independent sitting acquisition do not emerge until approximately 5 months of age (Bayley, 1969; Gessell, 1946), and that until that point, muscle response synergies underlying reaching movements are variable (Hadders-Algra et al., 1996; Hirschfeld & Forssberg, 1994). In addition, the SATCo scores for each group show a trend similar to the results found by Saavedra et al. (2012) regarding the segmental development of trunk control, and further expand these results by showing how the region of trunk control affects reaching parameters.

One specific item of the SATCo test is to analyze the active control of posture for each support level, which is assessed by encouraging the infant to actively turn their head to each side. This requires anticipatory postural adjustments to maintain the head and trunk in the midline and this is precisely what is being challenged during a reach. Group

1 infants had increased displacement of the head and trunk with external pelvic support as compared to Group 2, indicating excessive sway and thus loss of balance control. This was expected since Group 1 infants did not have the ability to actively control their trunk when manually supported at the lower lumbar or pelvic region during the SATCo evaluation. On the contrary, all infants showed active trunk control with mid-thoracic support and thus, kinematic parameters related to posture indicate that with external thoracic support, the ability to maintain stability during a reach was the same for both groups.

An unexpected result was the lack of difference in percentage of successful grasps between Group 1 and 2 with pelvic support. However, our findings are consistent with other studies showing that once onset of successful reaches appears, infants are equally successful in a variety of testing positions. For example, the study conducted by Van der Fits et al. (1999a) showed that 4-5 month old infants, when placed in three positions; supine, semi-reclined and in an infant chair, were equally able to produce successful reaches in all three testing positions. This suggests that once infants learn to successfully reach for a toy, their further improvement of intrinsic trunk control contributes primarily to increased quality of reaching.

CONCLUSIONS

Previous studies have shown that infants start reaching at 4 months of age before acquiring full trunk control (Fallang, Saugstad, Grogaard, & Hadders-Algra, 2003; Out et al., 1998; van der Fits et al., 1999a). It has also been shown that when given support both newborns and other young infants initiate reaching movements towards objects (Grenier

& Amiel-Tison, 1981; von Hofsten, 1982). Studies that have investigated the effects of trunk support in infants have not quantified either the amount of support provided or the infant's intrinsic level of trunk control. This study expands previous results by showing for the first time that the specific region of trunk control influences reaching ability. More precisely, the data suggest that reaching performance is tightly correlated with the progressive segmental acquisition of trunk control. This raises important questions regarding whether this correlation of reaching performance with trunk control is comparable to that seen in infants with developmental delays and neurological disorders. Similar information on children with neurological disorders could be used to implement more efficient therapeutic strategies to enable reaching in daily life activities.

BRIDGING THE FIRST AND SECOND STUDY

In the cross-sectional study, we found that depending on the extent of trunk control infants had acquired, the level of external support has an impact on postural stability and reaching performance. With an external thoracic support, all infants had equivalent postural and reaching patterns since both groups demonstrated control in the thoracic region of the trunk. However, when the external support was limited to the pelvic level, the group of infants that had already acquired control of the thoracic and lumbar regions outperformed the infants in the group that had acquired control of the thoracic region only, implying that they still had to learn and select those strategies that were optimal for controlling the lumbar region. However, kinematic data do not furnish detailed information on the strategies used by the nervous system to achieve the various kinematic motion paths. Data on muscle recruitment characteristics provide this level of information. Furthermore, cross-sectional studies have the limitation of providing information from individual infants only at a specific point in time. Longitudinal studies are able to detect development or changes across time and account for intra-individual changes occurring within the developmental time frame of the study. Another advantage of a longitudinal research design is that it eliminates cohort effects because one group of infants is examined over time, rather than comparing different groups of different ages.

Therefore, the aim of the second study was to longitudinally examine behavioral and kinematic changes in conjunction with electromyographic recordings, while providing an external support at pelvic and thoracic levels in typically developing infants from 2.5-8 months of age. Since infants first gain control of the upper trunk (thoracic) region followed by the lower trunk (lumbar) and pelvic regions for the acquisition of independent sitting, it was hypothesized that before the onset of independent sitting, infants would demonstrate a decreased ability to reach, impoverished reaching and trunk kinematics and inefficient postural muscle patterns when given pelvic in comparison to thoracic support, as a result of the instability they experienced with pelvic support. These differences between levels of support would then disappear once infants achieved independent sitting.

CHAPTER IV

THE DEVELOPMENT OF TRUNK CONTROL AND ITS RELATION TO REACHING: A LONGITUDINAL STUDY

This chapter is under review for publication in the journal *Frontiers of Human Neuroscience* and Victor Santamaria, Sandra L. Saavedra and Marjorie H. Woollacott are co-authors. I performed the experimental work and led the project; Marjorie H. Woollacott formulated the conceptual framework with Sandy Saavedra, provided advice on data analysis and gave editorial assistance; Victor Santamaria contributed to the recruitment, data acquisition, data analysis and interpretation; Sandy Saavedra also helped develop the protocol and gave editorial assistance. All co-authors formally approved this manuscript for submission.

INTRODUCTION

Sitting postural control and reaching for objects are two distinguishable yet inter-related motor milestones, which are progressively acquired during the first years of life. When the tasks are combined, during reaching while sitting, what appears to be a simple reach toward an object, nevertheless involves the interaction of highly specialized neurological systems and subsystems to optimize the movement. Moreover, the acquisition of posture and reaching skills during development is critical to subsequent perceptual, cognitive and social development (Lobo & Galloway, 2012; Sommerville, Woodward, & Needham, 2005; Soska, Adolph, & Johnson, 2010).

The relationship between posture and reaching is already observed in early stages of life. Authors have shown that when newborns are fully supported, either in a reclined or upright sitting position, the usual chaotic arm movements during a reach are more coordinated and directed toward a toy placed in front of them. This fact implies the existence of innate reaching behaviors, also known as pre-reaches that are influenced by postural support (Amiel-Tison & Grenier, 1983; Claes von Hofsten, 1982). Thus, it is important to include the examination of postural factors when studying reaching development.

Previous research has shown that, starting at 3 months, general arm reflexive movements are gradually replaced by goal directed reaches that are mainly unsuccessful in grasping the object. Grasping is typically achieved at the age of 4 months (de Graaf-Peters et al., 2007; van der Fits et al.,1999a); however, arm movements are jerky with nonlinear trajectories and have high numbers of movement units (MUs), identified as the number of accelerations and decelerations that characterize the velocity profile of the reach (von Hofsten, 1991). From this age onwards, there is a kinematic evolution of the arm trajectory during the reach and 6 months-old infants develop a straight path of the arm trajectory accompanied by a smaller number of MUs (von Hofsten, 1991). During this phase of goal-oriented reaching development, there are many factors that influence the arm trajectory, including visual perception, neuromuscular forces, biomechanical factors and proprioceptive information. However, the development and control of posture for maintaining stability during the ongoing motion of the arm is indispensable to all these other factors (Bertenthal & von Hofsten, 1998).

Research studies have shown that posture control has consequences for the development of reaching and exploration. Studies exploring postural muscle responses during reaching tasks in seated infants have shown that the development of postural adjustments follows a top-down recruitment sequence, with infants of 4 months of age showing the activation of neck muscles followed by trunk muscles, suggesting a functional preference for stabilizing the head while reaching (van Balen et al., 2012). This maturation in head control at 4 months of age has been shown to be important for environmental exploration (Hadders-Algra, 2008) and successful reaching (Thelen & Spencer, 1998). Postural adjustments using a top-down recruitment pattern of trunk muscles are accompanied by reaching movements with better kinematic quality (de Graaf-Peters et al., 2007). Subsequently, after the ability to independently sit upright is achieved, a bottom-up muscle recruitment is preferred, starting from the lower trunk, indicating that the focus of control moves toward the support surface (Assaiante, 1998; Hadders-Algra, 2008).

Thus, postural control in infancy could be considered a foundational requirement across development in that it allows the infant to explore the surrounding environment, and develop more abstract sensorial, cognitive and behavioral experiences (Elsner & Hommel, 2004). Authors have concluded that reaching and exploratory behaviors are dependent upon the biomechanical and gravitational forces of posture, in which postures such as lying supine or prone limit the reaching repertoire whereas a sitting posture enhances them (Out et al., 1998; Soska & Adolph, 2014). Within a sitting posture, the inability to sit independently does not limit the frequency of successfully reaching the toy; instead it reduces the amount of time the infant invests in exploring the toy since they often need their hands for postural maintenance (Harbourne et al., 2013). Nevertheless, it is known that while non-sitters are supported with the use of an external pelvic girdle, which provides the postural balance infants are lacking, reaching coordination and arm kinematics are significantly improved (Hopkins & Rönnqvist, 2002; Rochat & Goubet, 1995).

In summary, previous research affirms that reaching kinematics and behavior are influenced by the control of posture. But the question of how reaching is affected by the progressive development of postural control still remains unanswered. Postural control develops following a cranial-caudal progression, starting with the attainment of head stabilization on the trunk, occurring at about 2 or 3 months of age. This provides a stable frame of reference for reaching (Assaiante, 1998; Thelen & Spencer, 1998). Further control of the shoulder and thoracic musculature around 4-5 months enables infants to maintain stability and counteract the reactive forces generated by the forward extension of the arm to successfully reach (Hopkins & Rönnqvist, 2002). As infants gain increasing control of the head and upper trunk over time, they progress from prop sitting to sitting without support, indicating a greater vertical control of their trunk in sitting posture (Harbourne et al., 2013). Subsequently, the control of the lower trunk and pelvis, leg muscles and complete extension of the trunk provides them with the ability to maintain the center of mass within a stable base of support in upright sitting position while reaching (Assaiante, 1998; Harbourne et al., 2013; van der Fits et al., 1999a; von Hofsten & Woollacott, 1989). Thus, it is worth noting that there is a chronological cephalo-caudal progression of the ability to control an increasing number of trunk segments for the acquisition of independent sitting while reaching (Butler et al., 2010; Rachwani et al., 2013; Saavedra et al., 2012). However, a detailed analysis across development of upright sitting acquisition, examining the number of trunk segments involved and the relation of posture to reaching skills has only been partially addressed previously (Rachwani et al., 2013).

The current study sought to test and examine the relationship between reaching skills and the segmental progression of trunk control for the acquisition of independent sitting in healthy infants. Previous studies have not looked at this relationship since they either have 1) used supine or semi-reclined seating when infants are learning how to sit, which alters the effect of gravity on the trunk and consequently influences the performance of a reach (Thelen et al., 1996; Thelen & Spencer, 1998; van der Fits et al., 1999a); or 2) evaluated the infant during fully supported or unsupported conditions (de Graaf-Peters, et al., 2007; Harbourne et al., 2013; van Balen et al., 2012) and therefore failed to allow observation of the progressive control of specific trunk regions during the acquisition of upright sitting on reaching skills. Comparable to recent studies in our lab, we have kept the effect of gravity constant by creating vertical alignment with an external trunk support at thoracic and pelvic levels to address the contributions of the progressive development of control of the higher and lower regions of the trunk to reaching.

Hence, this is a longitudinal study examining intra-individual behavioral and kinematic changes in conjunction with electromyographic recordings. It was hypothesized that before the onset of independent sitting, infants would demonstrate a decreased ability to reach, impoverished reaching and trunk kinematics and inefficient postural muscle patterns when given pelvic in comparison to thoracic support. All these observations would be explained by the challenges in remaining balanced with pelvic support when infants have not yet acquired control of the lower trunk. Subsequently, as infants learn to control the lower trunk and pelvic regions and thus, acquire independent sitting, it was hypothesized that these effects would disappear and infants would demonstrate invariable reaching and postural patterns irrespective of the level at which they were supported.

METHODS

Participants

Ten healthy infants born at term (5 males and 5 females) with a mean age of 2.5 months (+/- SD: 0.5 months) were recruited and were tested twice a month until the age of 8 months, with a total of 12 sessions per infant. The recruitment was carried out by using flyers in different child care centers in Eugene and Springfield (Oregon, USA). All procedures of this study were reviewed and accepted by the Institutional Review Board for Human Subjects Research at the University of Oregon.

Materials and Procedures

Subjects were asked to come to the laboratory for sessions of approximately 120 minutes. At the first visit, parents were asked to respond to a health questionnaire about their infant, they were informed in detail about the experimental procedure and were asked to sign the informed consent. During each visit, in addition to the reaching test, infants were clinically tested with the Segmental Assessment of Trunk Control (SATCo) (Butler et al., 2010) to determine the level of intrinsic trunk control acquired, the Alberta Infant Motor Scale (AIMS) (Piper & Darrah, 1994) to identify their level of gross motor function, and the motor subscales of the Bayley Scales of Infant and Toddler Development, III edition (Bayley, 2005) to identify their level of gross and fine motor function. All infants were video recorded during each assessment. In addition, parents were asked to do the Timed Sitting test twice per week at home to corroborate the onset of independent sitting ability. In this test parents placed the child in sitting with legs in front and timed how long they could stay up with both hands free. Table 4.1 shows the clinical scores of all subjects at each month of age.

Table 4.1. Average Clinical Assessment Scores of All Infants across Age

	2 Months	3 Months	4 Months	5 Months	6 Months	7 Months	8 Months
SATCo score (*min-max*)	1.43 (1-2)	2.44 (1-4)	3.77 (2-6)	4.81 (4-8)	6.55 (4-8)	7.83 (6-8)	8.00 (8-8)
AIMS (*min-max*)	6.71 (3-10)	9.89 (4-20)	16.36 (7-23)	25.52 (14-33)	31.10 (22-47)	37.72 (26-50)	44.33 (35-51)
Bayleys: gross motor (*min-max*)	5.57 (1-11)	12.78 (4-23)	20.67 (11-27)	26.00 (18-33)	29.00 (21-36)	31.39 (24-36)	33.33 (26-37)
Bayleys: fine motor (*min-max*)	6.43 (4-9)	10.00 (7-14)	15.05 (7-24)	18.52 (11-25)	20.80 (16-25)	23.61 (19-27)	25.44 (23-28)

Segmental Assessment of Trunk Control. The SATCo is a clinical measure that examines balance control of the trunk while the evaluator manually supports the trunk at various levels, following a top-down sequence. The evaluator starts by supporting the trunk at a high level, at the shoulder girdle to assess cervical (head) control, through support at the axillae (upper thoracic control), inferior scapula (mid-thoracic control), lower ribs (lower thoracic control), below ribs (upper lumbar control), pelvis (lower lumbar control), and finally, no support, in order to measure full trunk control. During each level of manual support, the test is designed to assess: 1. static control (maintaining a neutral trunk posture) 2. active or anticipatory control (maintaining a neutral posture during head turning) and 3. reactive control (maintaining or regaining trunk control following a threat to balance, produced by a brisk nudge). The infant’s ability to maintain or quickly regain a vertical position of the free region of the trunk in all planes during the assessment of static, active and reactive testing is scored as present or absent. The score reflects the region where infants lose control of posture: a score of 1 = loss of control at the head level, 2 = upper thoracic, 3 = mid-thoracic, 4 = lower thoracic, 5 = upper lumbar, 6 = lower lumbar, 7 = pelvis, 8 = no loss of trunk control (Butler et al., 2010). Thus, the SATCo follows a Guttman scaling, meaning that if an infant has a SATCo score of 4, he/she loses control of posture in either static, active or reactive tests when the evaluator supports the lower thoracic region of the trunk but does not lose control of posture when being supported at the levels above that region. This test has been shown to be a valid and reliable measure of the development of trunk control in infants (Butler et al., 2010).

Reaching Test. The reaching test was conducted with an external support at pelvic and thoracic levels for every session. The support at the thoracic level was placed below the scapular girdle, and the pelvic level of support was surrounding the waist, corresponding to the middle thoracic level and lower lumbar level of the SATCo, respectively. The design of the study was counterbalanced for the first session and was evaluated using the same order throughout the longitudinal process for each infant, with half the infants first being provided with thoracic support, and half first being provided with pelvic support, in order to eliminate fatigue or training effects as confounding variables.

The reaching test involved the infant being placed in a seated position on a customized infant chair. The base of the chair was covered with stiff foam in order to create a flat surface. The hips of the infant were secured to the chair with specially designed straps and Velcro: three straps were firmly attached to the under-side of the chair: two of them were used to wrap each hip joint and the third surrounded both posterior superior iliac spines (Butler et al., 2010). A rigid U-shaped posterior support, covered with rigid foam, attached to the back of the chair circled the trunk and provided upright stability of the trunk below the level of interest. The reclined position of the infant chair was used as a safety device in the backwards direction, for securing the infants if they fell backwards. The posterior support was adjusted to allow evaluation of different trunk segments: thoracic and pelvic (Figure 4.1).

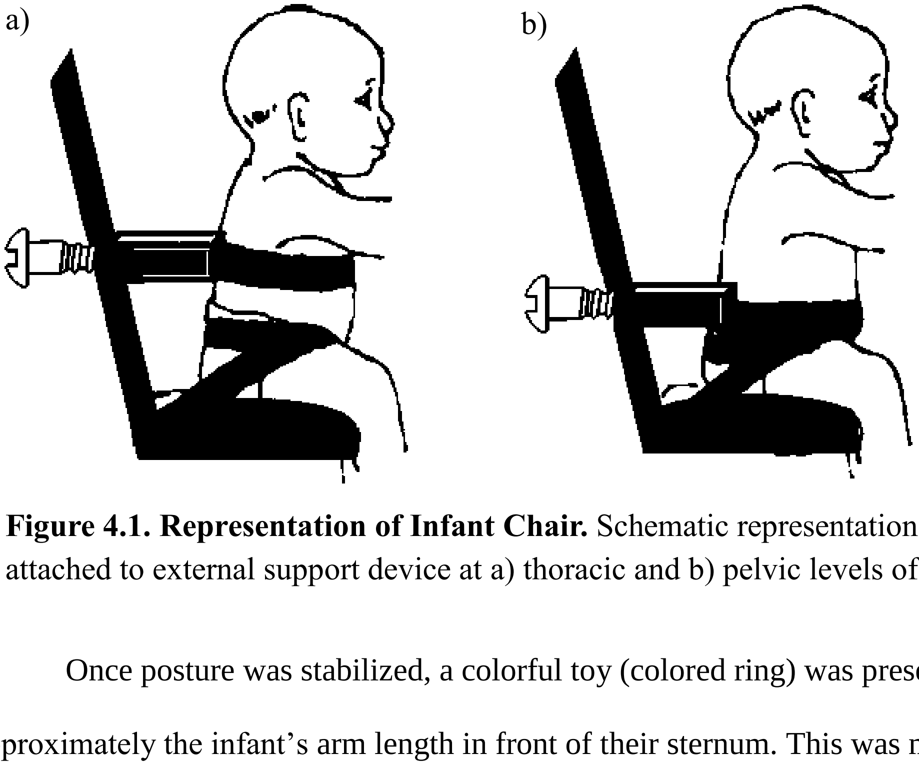


Figure 4.1. Representation of Infant Chair. Schematic representation of infant chair attached to external support device at a) thoracic and b) pelvic levels of trunk support.

Once posture was stabilized, a colorful toy (colored ring) was presented at approximately the infant's arm length in front of their sternum. This was measured by the tester prior to starting the reaching test. The presentation of the toy was consistent through every trial. This was done using a device placed over the infant's chair that consists of a horizontal brace made of fiberglass with an attachment for the toy. This attachment permits the measurement of the distance from the toy to the chest (anteroposterior axis) and calibration of the height of the toy at the sternum level (vertical axis). Once the exact distance was measured, a toy attached to a rod was introduced in the device and was introduced and removed by the tester from the top to the infant's visual field for every trial. The tester occasionally presented a different toy (blocks or squeaky toys) in order to keep the infant engaged in the task of reaching toward the colored ring. The toy was presented approximately 10 times per level of support, but there were occasions in which this number had to be reduced due to fussiness of the infant. If that was the case, the infant's maximum number of trials was noted and the rest of the trials were counted as missing data.

The reaching test was synchronized with the collection of kinematic data (sampling rate = 84 Hz) using magnetic tracking (Minibird system, Ascension Technology, Burlington, VT) and with a 16-channel electromyography (EMG) system (MA300, Motion Lab Systems, Baton Rouge, LA), (sampling rate = 1000 Hz) and video data (sampling rate = 60 Hz).

Kinematics. Four sensors were placed on the infant: one superficial to the styloid process of the radius on each wrist, one on the posterior and prominent part of the cervical vertebra 7 (c7) and one on a headband with the sensor centered on the forehead. These sensors were used to track arm and head movements. Prior to starting the reaching test, the position of the left and right tragus, the medial/lateral and anterior/posterior points of the external support (pelvic or thoracic) and sternal notch were recorded. This allowed us to estimate the location of the head center of mass using the center of the distance between the midpoint of the two tragus markers and the head sensor. The center of the trunk region being evaluated was estimated as the midpoint between the sternal notch and C7, and the center of the external support was calculated as the midpoint of the two vectors created by the anterior/posterior and medial/lateral markers of the external support. Position data of all four sensors were referenced to the center of the external support.

Electromyography. EMG was recorded via bipolar self-adhesive surface electrodes with poles placed 2-3 cm apart. EMG signals were preamplified (gain X 20), band-pass filtered (10–375 Hz), and then further amplified, sampled at a rate of 1000 Hz per channel, and time-synched with position data. Two dorsal muscle groups and three arm muscle groups were recorded bilaterally (paraspinal muscles at the thoracic spine (T7-8) and lumbar spine (L3-4), at the belly of anterior deltoid, triceps and biceps muscles) in addition to the heart beat (over the 7th intercostal space, below pectoralis major, and over the sternal angle), used during analysis to subtract any heart beat artifacts from the EMGs.

Since collection of EMG in infants can be a difficult process, we developed a way in that we could enclose all the preamplifiers into two strips, which were attached to both sides of the infant chair. The infant then wore a t-shirt covering the electrodes connecting the preamplifiers, enclosed within the sleeves to prevent grasping and dislodging of the sensors.

Data Reduction and Analysis

Video analysis. The video recordings during the reaching test served three purposes. First, the video was used to differentiate between non-directed arm movements and visually guided intentional reaching movements towards the toy. Second, the video was used for classification of the behavior of the movements of the arm during toy presentation. Third, initiation and end of reach were visually analyzed using computerized video-coding software (www.datavyu.org) for further evaluation of the kinematic and EMG parameters. Movements were classified as either 1) pre-reaching movements, also called "spontaneous arm movements" (i.e. oscillating movements of the extended arms or forward directed arm movements (van der Fits et al., 1999a), 2) reaching movements not ending in toy contact, associated with a loss of stability and/or requiring support while reaching (unsuccessful reaches), and 3) reaching movements which end in toy contact or grasping of the toy (successful reaches) (de Graaf-Peters et al., 2007). The following types of reaches were not selected for coding: 1) the infant initiated a reaching movement toward the toy and lost interest during the trajectory by stopping and looking away; 2) the infant hit the toy; 3) the infant reached with full trunk support, i.e. the infant leaned back against the infant seat prior to reaching; 4) the infant used compensatory strategies like reaching with the head or dragging the toy with the forearm.

All reaches were coded as unimanual or bimanual. We defined bimanual reaches as those in which we visually saw the infant touch the toy with both hands and which also had an onset time difference between both arms of less than 1000 ms. Occasionally, infants would begin unimanually and then switch to the other arm before reaching the toy. In this case, for the kinematic data analysis, only one arm, considered as the dominant arm, was selected. This selection was the same for the case of bimanual reaches. The arm dominance was determined based on the hand that manipulated the object once it was held.

It is not easy to distinctly determine the start of a goal-directed reaching movement in infants, since one cannot instruct them to start from a defined position or at a given time. Thus, the computerized video-coding program allowed us to determine the onset and offset of all reaches. A light emitting diode (LED), placed on the corner of the visual field, was used to synchronize video and kinematic data during each reaching trial. With this, we made sure that we were selecting reaches within the trial test time. We defined the onset of a reach as the moment when the infant initiated a movement of the upper extremity toward the toy accompanied by a visual fixation of the target. The offset of the reach was determined when the infant intentionally touched the toy.

To evaluate inter-rater reliability, a second coder scored approximately 25% of the video data. Coders agreed 85.9% of the time on the occurrence of a reach, its type (pre-reach, unimanual or bimanual) ($\kappa = 0.87$), and whether it was successful or unsuccessful ($\kappa = 0.67$). Intra-class correlation coefficient between primary and secondary coders for reach onset and offset times was above 0.90.

After video-coding all reaches, reaching onsets was verified and adjusted, if necessary, by using an interactive cursor display, by simultaneously plotting the XYZ resultant of velocity and position data of the corresponding wrist sensor with the time frame selected with the video. An increase in velocity profile immediately preceding the initiation of the reach, identified from the video-coding software, was then verified. All dependent variables were then calculated from the selected time duration of each reach sequence. Kinematic and EMG data were digitized for off-line analysis with custom MATLAB programs.

Kinematic Analysis. Kinematic data were filtered with a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6Hz to smooth the data and avoid high frequency components unrelated to the movement. We examined the following variables for each reach: movement time, MUs, straightness score, normalized jerk score, angular head displacement, and angular trunk displacement.

Movement time was calculated in seconds between the onset and the end of the reach. A MU was defined according to Grönqvist et al., (2011) as the portion of the arm movement between two velocity minima with a velocity peak that should be greater than 2.3 cm/s. If the difference between the highest minima of one MU and the peak velocity of another MU was less than 8 cm/s, they were considered as one MU. Straightness score was calculated as the proportion between the actual resultant trajectory of the reach and the minimum possible one, determined by a straight line from start to the end of the reach. Using this method, values greater than one meant a more devious arm movement (von Hofsten, 1991). The smoothness of the reach was quantified by calculating a time and distance normalized jerk score (NJS) measured in cm/ms^3. Time and amplitude were used to normalize the jerk score to eliminate dramatic increases with movement time. The following formula was applied to calculate NJS,

$$NJS = \sqrt{\frac{1}{2} \cdot \int (r''')^2 \mathrm{d}t \cdot (t^5/l^2)}$$

where r''' is the third time derivative of position data, *t* is movement time, and *l* is movement amplitude (Chang, Wu, Wu, & Su, 2005).

In terms of postural control, the angular displacement of the head and trunk were analyzed as two different segments to distinguish their displacement during a reach. Head displacement and trunk displacement were calculated as the summation of the resultant angular displacement during a reach in the anterior-posterior and medio-lateral planes. For the head displacement, the angle between the line defined by the head center of mass and c7 with reference to the vertical axis was applied, and for the trunk displacement, the angle between the line defined by the trunk center and the center of external support with reference to the vertical axis was used. This provided the angle of the trunk segment above the external support.

EMG Analysis. A frequency domain and Welch's power analyses on randomly selected sessions of the raw EMG signal were used to identify the most appropriate range of EMG signal frequency across the different muscles. Once we identified the most common frequency range, a modified version of the protocol used by Spencer and Thelen (2000) was applied: band-pass filter with cut-off frequencies at 20 and 160Hz, demean, full-wave rectification and BoxCar averaging with a windows size of 7 data points in order to remove high-frequency components. In addition to this filtering process, a customized algorithm was applied for identifying and subtracting the cardiac QRS-complex signal from each channel of raw EMG before rectification (Aminian, Ruffieus, & Robert, 1988). Lastly, the right and left sides of the paraspinal muscles of the thoracic and lumbar segments were added prior to onset identification.

Because this study was a within-subject design, the approach used for normalization and identification of EMG bursts was done relative to baseline EMG. This accounts for changes in baseline EMG magnitude and noise within-trials and across conditions for individual participants (William & Adam, 2012). For this purpose, EMG integrals of 10 ms bins were calculated across each muscle signal. A continuous three second time window of EMG-baseline signal for each muscle across the entire session was identified and the average integrated EMG of a bin was obtained during this baseline time window ($\int EMG_{Baseline}$). Each EMG integral ($\int EMG_{Integral}$) of a bin was then normalized relative to EMG-baseline bin,

$$\int EMG_{Norm.Integral} = \frac{\int EMG_{Integral} - \int EMG_{Baseline}}{\int EMG_{Baseline}}$$

where $\int EMG_{Norm.Integral}$ greater than 1 would indicate an increase in EMG activity and less than 1 would indicate inhibition of activity. Thus, for determining significant bursts onsets and offsets, we applied an automatic onset and offset selection: 8 consecutive bins had to have a normalized value of 1.5 or greater (for determining onsets) or smaller (for determining offsets), prior to or during a reach. An interval of 80 ms was used since this time has been shown to be the minimal delay in postural muscle reactions (Horak, Henry, & Shumway-Cook, 1997; Shumway-Cook & Woollacott, 2012c).

EMG analysis was structured in two main temporal windows: anticipatory postural adjustment stage (APA stage), the 500 ms prior to the reaching onset; and compensatory postural adjustment stage (CPA stage), which was variable depending on the movement time of the reach (Bigongiari et al., 2011). In comparison to previous studies, we decided to use a larger window size for the pre-defined APA stage since infants, especially during early stages of development, could possibly activate postural muscles well in advance to the reach onset. Frequency of muscle activation during the CPA stage was calculated as the number of times the EMG signal was active after the reach onset (%$\text{EMG}_{\text{ACTIVATION}}$ in CPA stage). Frequency of muscle activation during the APA stage was calculated as the percentage of times the EMG signal initiated its activation within the 500 ms preceding the reach onset and when its offset occurred at or after the reach onset (%$\text{EMG}_{\text{ACTIVATION}}$ in APA stage). To determine the amplitude of EMG, the integrated EMG of all bins that were activated, was summed (Total iEMG) during the CPA stage. For comparisons in onset latency of muscle activation (CPA Latency), the time interval between the reach onset and the onset of the muscles during the CPA stage were examined. Lastly, for those trials in which both trunk muscles were activated, we calculated the percentage of times a top-down vs. a bottom-up recruitment order of postural muscles had occurred.

Statistical Analysis

Mixed models, in comparison to traditional analyses that do averaging, provide much more flexibility, by taking the full data set into account and allowing subjects to have missing time points. Therefore, SPSS 22.0 for Windows (SPSS Inc., Chicago, IL, USA), was used to perform a Generalized Linear Mixed Model (GLMM) analysis of the relationship between reach outcomes across age and levels of external trunk support. GLMM is an extension of the LMM which allows fitting binary outcomes in addition to continuous outcomes into the model. As fixed effects, we entered age in months, level of external support (thoracic and pelvic) and also their interaction into the model. As random effects, we had intercepts for infants and for sessions within infants, accounting for by-infant variability and by-session-within-infant variability in overall reach outcomes. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity and normality. Post-Hoc comparisons using GLMM provided the ability to obtain post-hoc pairwise comparisons of the estimated marginal means for different levels of the fixed factors, such as level of external support across age. P-values were obtained from post-hoc analysis after applying Bonferroni´s sequential adjustment procedure that accounted for the multiple comparisons of the model.

RESULTS

A total of 1730 reaches met the selection criteria. Out of this number, 1587 reaches were successful and were pooled for further kinematic and EMG analysis.

Validity of the SATCo

Pearson's product moment correlation coefficient showed high correlation of SATCo scores with: age (r = 0.90), AIMS test (r = 0.86), and Bayley Scales of Infant and Toddler Development test (r = 0.83). According to the SATCo test, all infants except for two, achieved head control by the age of 3 months and upper thoracic control by 4 months. At the age of 6 months, seven out of the ten infants achieved independent sitting and by that age, all except for one infant had achieved control of the lower trunk and pelvic regions (Figure 4.2).

Differences in Reaching Behavior between Levels of External Support across Age

At two months of age, 6 out of the 10 infants attempted to reach toward the toy with the higher level of support, thoracic support. The number of attempts was small (M = 5 reaches per infant) and the majority were unsuccessful or were classified as pre-reaches (M = 3/5 unsuccessful reaches). With the lower pelvic support, only 2 out of the

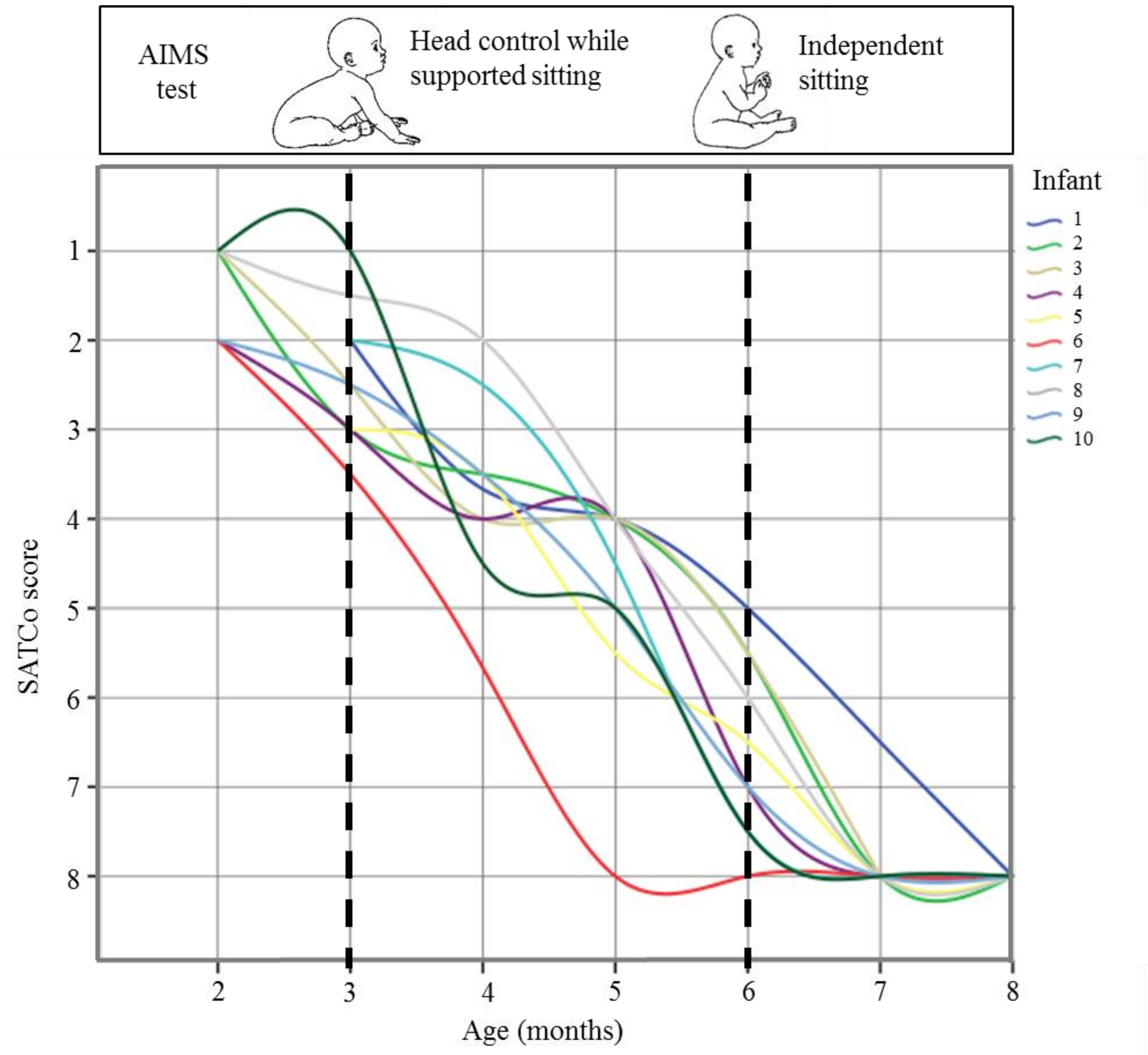


Figure 4.2. SATCo Scores across Age. Graph showing SATCo scores (1-8) across age (2-8 months) for each infant. Note that discrete values of SATCo scores are interpolated for visualizing the curve trend of each infant across development. Two main critical motor milestones according to the AIMS test are emphasized, head control while supported sitting and independent sitting (vertical dashed lines). The developmental time period when infants had not yet acquired control of the head while sitting, corresponds to SATCo scores 1 and 2. Once they had acquired head control while supported sitting but not yet independent sitting, it corresponded to SATCo scores 3, 4, which indicated that they are learning to control the upper trunk region. SATCo scores 5 and 6 corresponded to the time when they were learning to control the lower trunk regions. Once they acquired the ability to sit independently, around 6 months of age, it corresponded to SATCo scores 7 and 8, indicating that they had control of all trunk segments.

10 infants attempted to reach toward the toy at two months of age, as most could not balance with this level of support and were continuously falling backwards. One infant was completely unsuccessful during all attempts and the other one performed 2 successful reaches from a total of 4 attempts. This suggests that when infants were two months old, they attempted to reach more frequently only when they were provided with more trunk support, since with pelvic support, infants tended to fall backwards. Thus, for further analysis, 2 months old infant reaching was not included, due to the limited number of reaching attempts that infants were able to make with the external support at pelvic level.

Once infants were 3 months old, all of them attempted to reach with thoracic support and 7 out of the 10 infants attempted to reach with pelvic support. At 3 months, infants were still unsuccessful (50% of the time) but this was irrespective of the level of external support. The success rate at three months was significantly different from that at 4, 5, 6, 7, and 8 months, $F = 2.57(5, 1680)$, $p < .05$, for both levels of external support. This suggests that 3 month old infants were able to minimally maintain their trunk against gravity with different levels of external support; however, they were unstable, they did not have the ability to successfully reach during all attempts and their success rate was not related to the amount of support provided. Finally, at 4 months of age, all infants were 100% successful when reaching at both levels of external support.

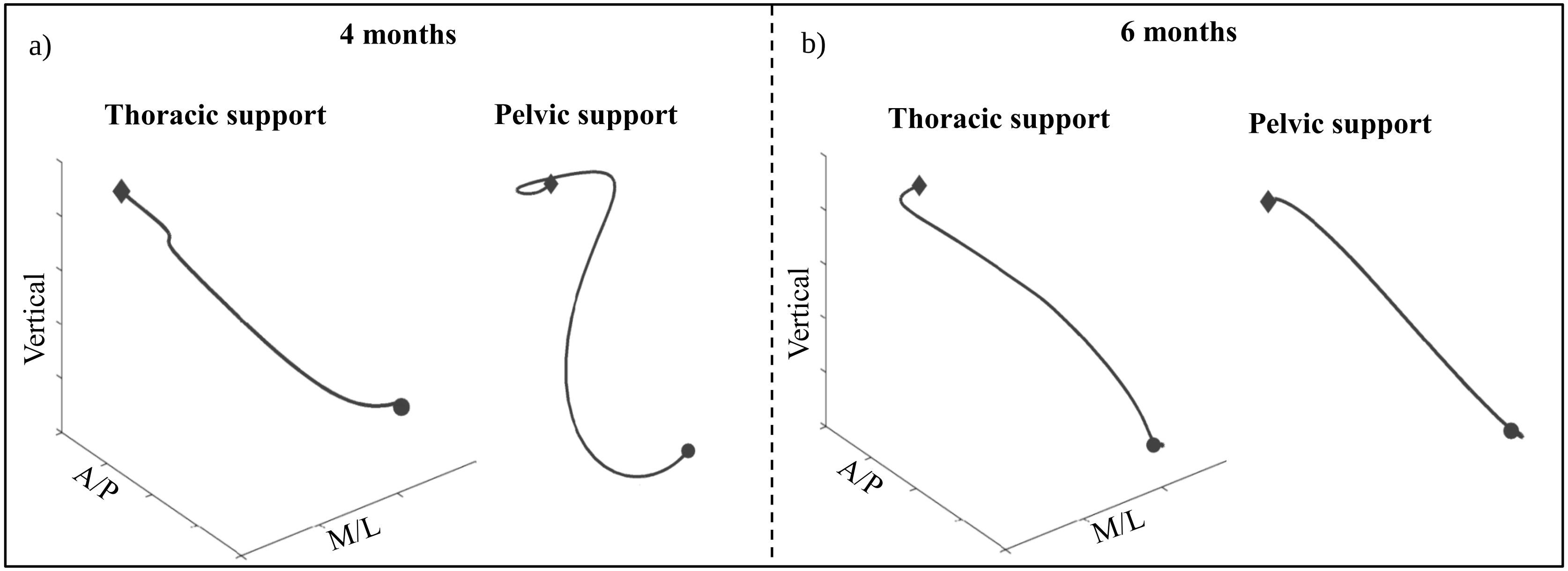
The type of reach (bimanual vs. unimanual) was variable across age and not related to the level of support provided. However, when infants were 3 months old, reaches that were unimanual were unsuccessful 40% of the time, while bimanual reaches were only unsuccessful 14% of the times.

Differences in Reaching and Postural Kinematics between Levels of External Support across Age

Major differences in reach outcomes between levels of external support were observed during the months prior to the onset of independent sitting ability (M = 6 months). The graphs from Figure 4.3 are examples of a reach at the thoracic and pelvic level of support of an infant during developmental stages prior to and after acquiring independent sitting; in addition, a photographic image is shown of a reach of the infant prior to the development of independent sitting. The 3-dimensional visual representation of the arm trajectory and the image show how the infant displayed a non-linear reach and was more unstable with pelvic support compared to thoracic support prior to the development of independent sitting ability, and this difference was not observed once this milestone was acquired.

These observations were further corroborated with the kinematic variables (Figure 4.4). In comparison to thoracic support, with pelvic support infants showed an increase in angular head displacement at 4 months, $F(1, 1561)= 4.90$, $p < .05$ and 5 months, $F(1, 1561)= 3.92$, $p < .05$ and angular trunk displacement at 4 months, $F(1, 1561)= 17.28$, $p < .01$ and 5 months, $F(1, 1561)= 10.83$, $p < .01$.

Reaching kinematics also showed differences between levels of support, being worse with pelvic support. With pelvic support infants showed an increase in: movement time at 3 months, $F (1, 1561) = 3.95$, $p < .05$; in straightness score at 4 months, $F(1, 1561) = 7.34$, $p < .01$ and 5 months, $F(1, 1561) = 12.30$, $p < .01$; and in normalized jerk score at 3 months, $F(1, 1561)= 6.69$, $p < .05$ and 4 months, $F(1, 1561)= 4.90$, $p < .05$.



c) Thoracic

d) Pelvic

Figure 4.3. Visual Representations of a Reach and Photographic Images. Graphs above showing 3D trajectory of a single reach, from onset (*circular shape*) to offset (*diamond shape*), of one infant with thoracic and pelvic support during a) the stage prior to independent sitting (4 months) and b) after independent sitting (6 months). Photographic images show infant reaching towards the toy with c) thoracic and d) pelvic support at 4 months. Arrows indicate location of kinematic sensors.

Movement units showed a significant effect of age, *F*(5, 1561)= 5.16, *p* < .01 irrespective of the level of support, indicating that there was a decrease in the number of MUs from 5 months onward.

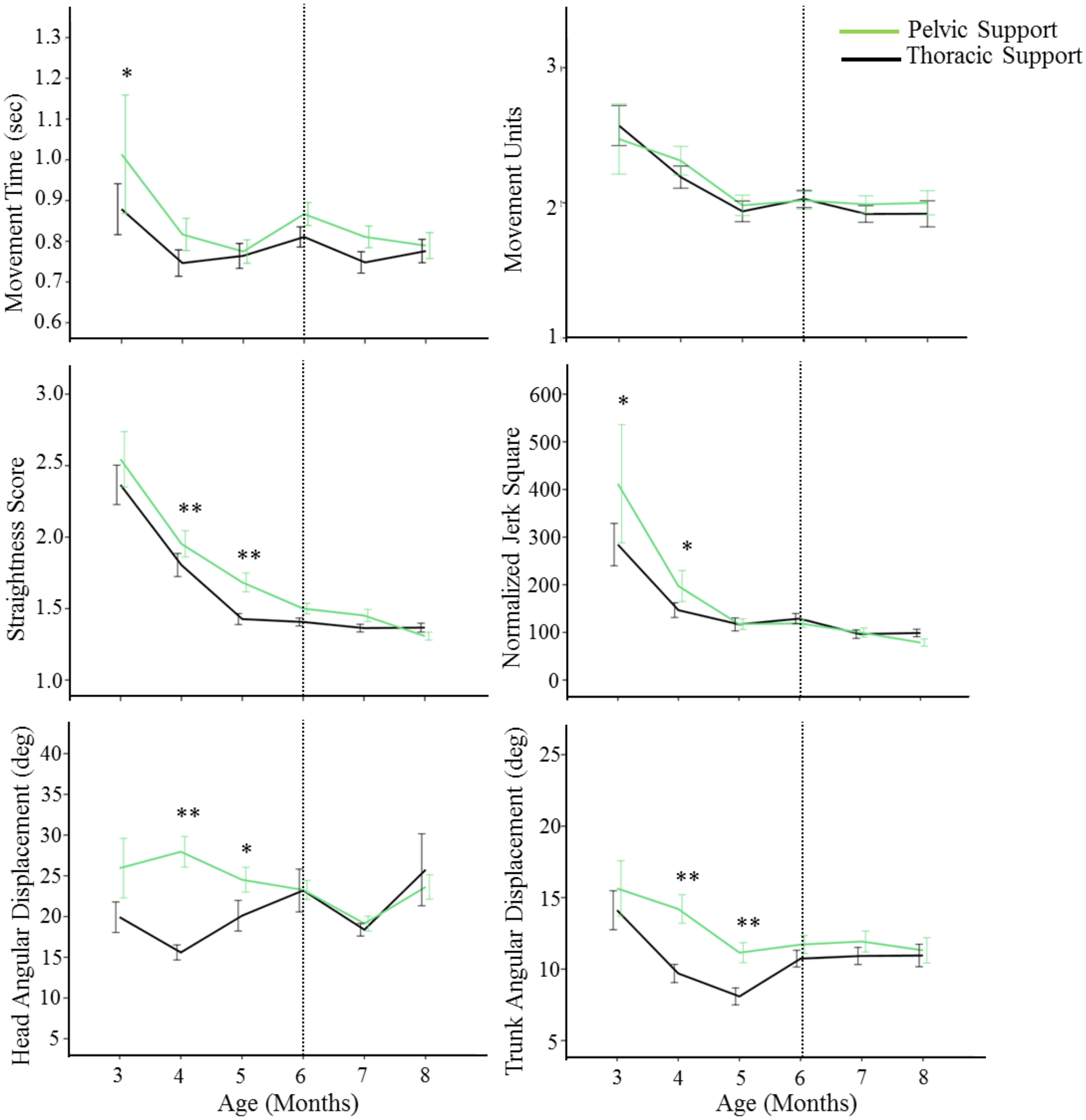


Figure 4.4. Kinematic Results. Estimated means across age for kinematic variables with thoracic (*black line*) versus pelvic (*green line*) support. Vertical dotted line represents average time of independent sitting onset. Error bars, ± 1 SE. * *p* < .05, ** *p* < .01.

Overall, these results show that when provided with external pelvic support, maintaining stability of the trunk (determined by head and trunk displacement) was more challenging for infants than when provided with thoracic support, only during the period when infants had not yet acquired the ability to independently sit. Consequently, this had an impact on their reaching performance, as indicated by their increase in time, straightness score and normalized jerk score.

Differences in Arm and Trunk EMG between Levels of External Support across Age

Frequency of Postural and Arm Muscle Activation during the Time Period for Compensatory Postural Adjustments (CPA). Differences between levels of external support in frequency of activation of postural muscles were mainly observed during months prior to independent sitting (M = 6 months). In general, thoracic and lumbar muscles were more frequently activated when infants were supported at pelvic vs. thoracic level and this was not observed once infants acquired independent sitting ability (Figure 4.5).

In comparison to thoracic support, with the support at pelvic level, infants showed an increased frequency of activation of: thoracic muscles at 4 months, $F(1, 1252) = 4.38$, $p < .05$ and 5 months, $F(1, 1252) = 10.74$, $p < .01$; and lumbar muscles at 3 months, $F(1, 1253) = 9.55$, $p < .01$ and at 4 months, $F(1, 1253) = 7.97$, $p < .01$.

Frequency of activation for the arm muscles was characterized as being highly variable between levels of support and across age; however, results showed a main effect of support, indicating that the triceps muscle was more frequently activated with thoracic support, $F(1, 1165) = 8.90$, $p < .01$ whereas anterior deltoid was more frequently activated with pelvic support, *F*(1, 1270) = 12.76, *p* < .01. On the contrary, biceps was always activated with both levels of external support (Figure 4.6).

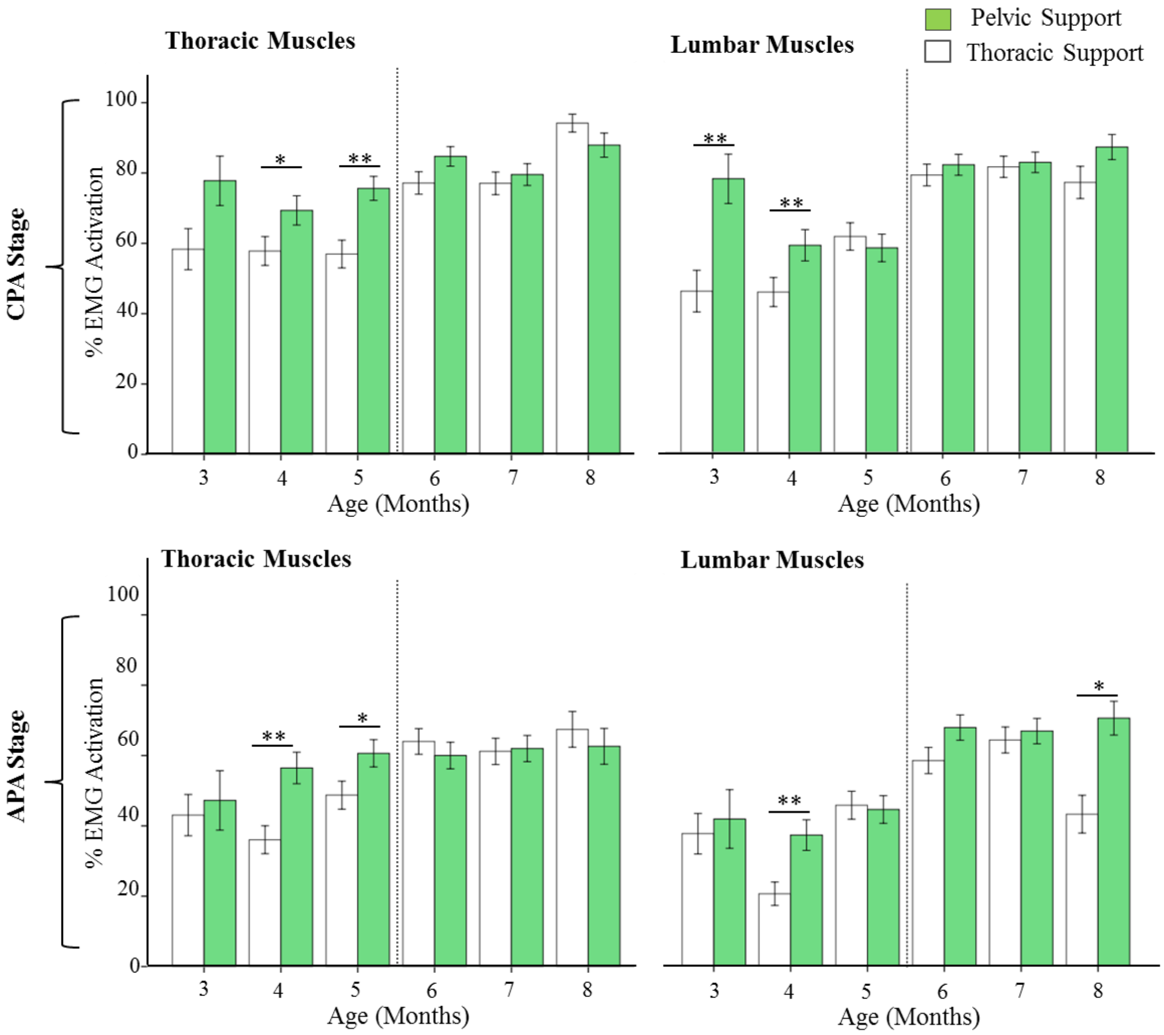


Figure 4.5. Paraspinal Activation Frequency. Estimated means for activation frequency, during CPA and APA stages, for postural muscles across age and with thoracic (*white bars*) versus pelvic (*green bars*) support. Vertical dashed line represents average time of independent sitting onset. Error bars, ± 1 SE. * *p* < .05, ** *p* < .01.

Frequency of Postural Muscle Activation during the Time Period for Anticipatory Postural Adjustments (APA). Similar to the results obtained for CPA frequency, we found that APAs of the thoracic muscles were also more often present with pelvic support at 4 months, *F*(1, 1252) = 14.35, $p < .01$ and 5 months, *F*(1, 1252) = 4.90, $p < .05$ in comparison to thoracic support. By the age of 6 months, the percentage of APAs had reached similar values across both levels of support (Figure 4.5).

Comparable results were observed for APA frequency of lumbar muscles. APAs were more frequently activated with pelvic vs. thoracic support at 4 months, *F*(1, 1253) = 7.32, $p < .01$ but reached similar values by the age of 6 months (Figure 4.5). However, at 8 months of age, APA frequency of lumbar muscles started to differentiate again between levels of support, this being significantly higher with pelvic in comparison to thoracic support, *F*(1, 1253) = 5.09, $p < .05$. The average onset time of APAs for thoracic and lumbar muscles was approximately -285 ms across all ages, irrespective of support.

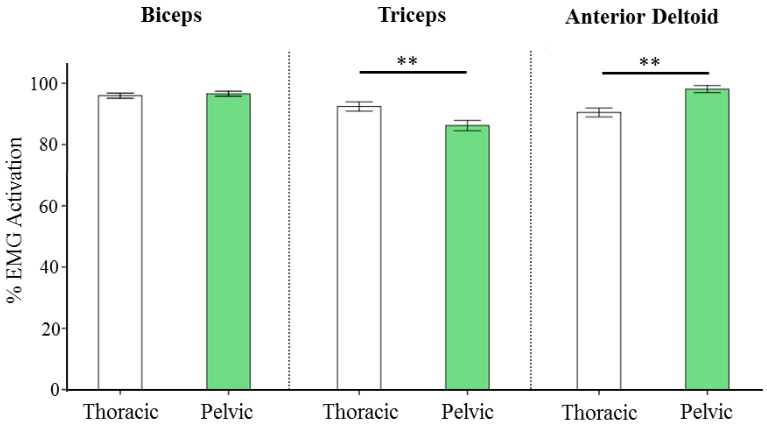


Figure 4.6. Arm Activation Frequency. Estimated means for activation frequency, during CPA, for arm muscles with thoracic (*white bars*) versus pelvic (*green bars*). Error bars, ± 1 SE. ** $p < .01$.

Total iEMG. No significant differences between levels of external support and across age were observed for total iEMG (integrated EMG of all bins activated during the CPA stage) of thoracic or lumbar muscles. However, there was a significant main effect of age for lumbar muscles, indicating that at 6 months there was an increase in iEMG of the lumbar muscles, $F(5, 1080) = 3.55$, $p < .01$, compared to 4 months (Figure 4.7).

Similarly, in terms of the arm muscles, iEMG of biceps and triceps displayed an interesting age effect. At the age of 6 months, iEMG of biceps was significantly enhanced, in contrast to 4 and 5 months, $F(5, 1507) = 4.16$, $p < .01$. A complete opposite trend was observed for iEMG of triceps, showing a significant decrease in iEMG of triceps at 5 months, $F(1, 1350) = 3.52$, $p < .01$ compared to 3 months (Figure 4.7). In addition, the level of support had a main effect on the anterior deltoid muscle, showing higher iEMG with pelvic support across all ages, $F(1, 1398) = 19.96$, $p < .01$.

CPA Latency. With regard to the postural muscles, there was a significant delay in CPA onset with pelvic support, during the months prior to independent sitting ($M = 6$ months) (Figure 4.8). EMG onset latency of the thoracic muscle at 3 months was significantly longer with pelvic support, $F(1, 887) = 7.27$, $p < .01$. After this age, EMG onset of the thoracic muscle was invariable between levels of support. The lumbar muscle on the contrary did not show an effect of support at any age. However, irrespective of support, there was a general trend for lumbar muscle latency to decrease with age, but this failed to reach significance ($p = 0.07$).

EMG onset latency of arm muscles once again showed high variability and results were inconclusive between levels of support. Instead, there was a difference in recruitment pattern, depending on the level of support. At early stages (3 or 4 months) infants first co-activated all arm muscles. With increased age and with thoracic support, infants tended to activate first biceps, followed by triceps and lastly anterior deltoid, whereas with pelvic support, infants first activated biceps, followed by anterior deltoid and lastly triceps.

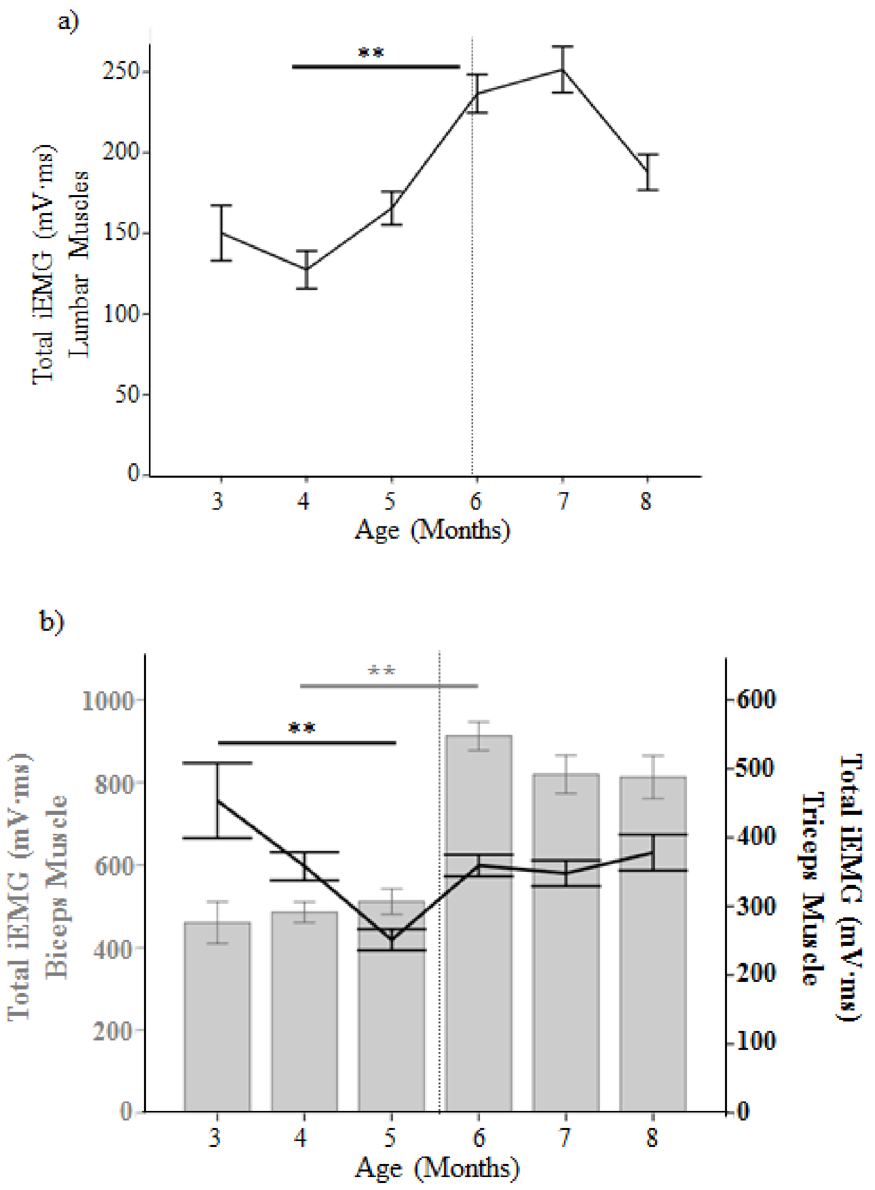


Figure 4.7. Integrated EMG. Estimated means of Total iEMG for a) lumbar muscles across age and b) biceps muscle (*grey bars*) and triceps muscle (*black line*) across age. Vertical dashed line represents average time of independent sitting onset. Error bars, ± 1 SE. ** $p < .01$.

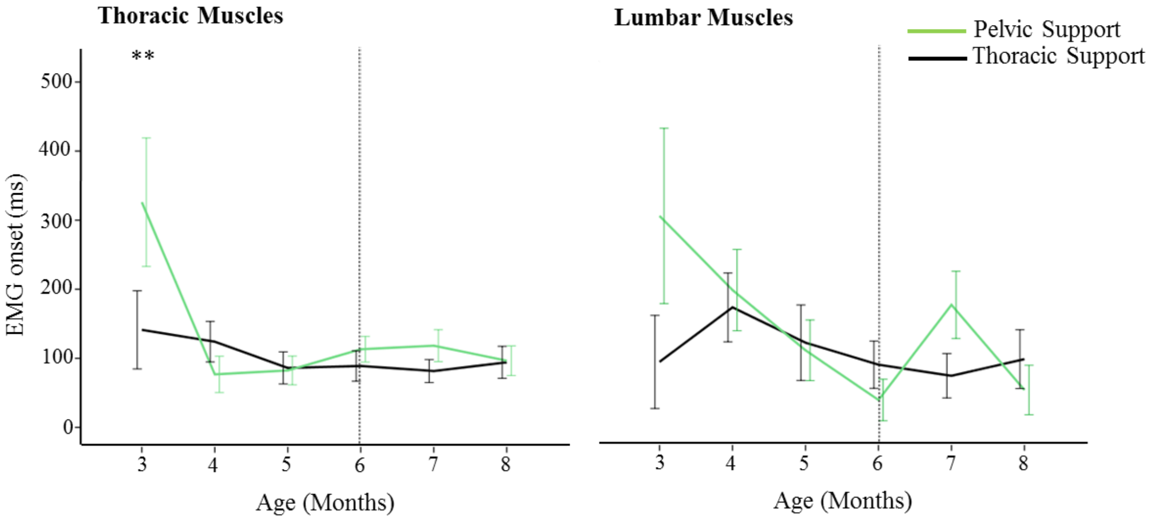


Figure 4.8. Onset Latency. Estimated means for CPA EMG onset latency for postural muscles across age and with thoracic (*black line*) versus pelvic (*green line)* support. Vertical dashed line represents average time of independent sitting onset. Error bars, ± 1 SE. ** $p < .01$.

Recruitment Order of Postural Muscles. For those trials in which both thoracic and lumbar muscles were activated, results showed a significant difference in recruitment pattern, depending on the age and level of support. At 4 months, infants showed a significant preference for a top-down pattern with pelvic compared to thoracic support, $F(1, 491) = 7.39$, $p < .01$. After the onset of independent sitting, infants showed the opposite, demonstrating a bottom-up preference with pelvic in comparison to thoracic support, this being significant at 7 months of age, $F(1, 491) = 3.90$, $p < .05$ (Figure 4.9).

Overall, these results, as with kinematics, indicate that when providing external support at the pelvic level, maintaining stability of the trunk is more challenging than when provided with thoracic support during the period when infants have not yet acquired the ability to independently sit. This is determined by three major findings: 1) activation frequency of postural muscles, during both APA and CPA stages, increased with pelvic support to counteract the balance disturbance encountered during the reach; 2) infants at 3 months were unable to quickly activate the thoracic muscles in a feedback mode during a reach with pelvic support, whereas this was possible with thoracic support; 3) infants at 4 months showed a higher percentage of top-down postural muscle recruitment order with pelvic support, indicating the functional preference for stabilizing the upper trunk in response to the instability.

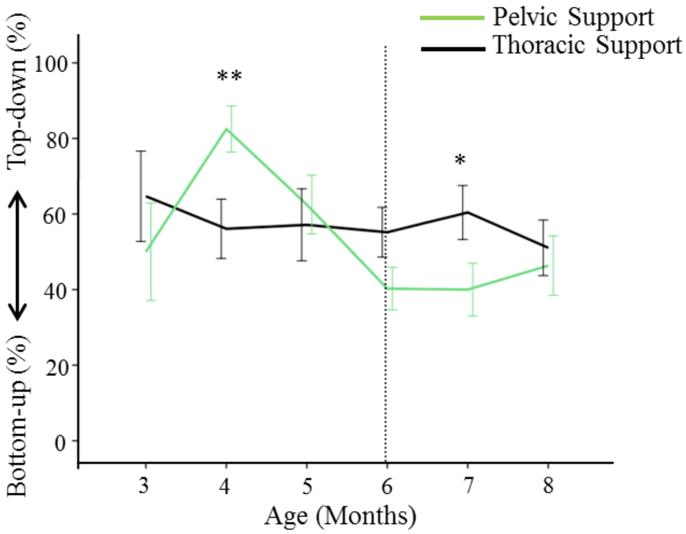


Figure 4.9. Recruitment Order. Estimated means for percentage for either top-down or bottom-up recruitment order of postural muscles with thoracic (*black line*) versus pelvic (*green line)* support. Vertical dashed line represents average time of independent sitting onset. Error bars, ± 1 SE. ** $p < .01$, * $p < .05$.

DISCUSSION

The purpose of this study was to investigate the relationship between reaching skills and the segmental progression of trunk control for the acquisition of independent sitting. This was addressed by conducting a longitudinal study on infants from 2.5-8 months of age that involved an experimental paradigm creating vertical alignment of the trunk in sitting position with two levels of external trunk support (thoracic and pelvic) during reaching. This allowed examination of the relationship between the higher and lower regions of the trunk during the development of sitting on reaching performance. Infants first gain control of the upper trunk region followed by the lower trunk and pelvic regions for the acquisition of independent sitting; and thus, we hypothesized that before the onset of independent sitting, infants would demonstrate a decreased ability to reach, impoverished reaching and trunk kinematics and inefficient postural muscle patterns when given pelvic in comparison to thoracic support.

In this regard, we confirm and expand previous results by showing that reaching success and the kinematic quality of the movement was substantially affected by the progressive development of postural control (de Graaf-Peters et al., 2007; Hopkins & Rönnqvist, 2002; Rachwani et al., 2013; Rochat & Goubet, 1995), such that with pelvic support, infants performed worse in comparison to thoracic support, during the months prior to independent sitting. Additionally, the lack of trunk control with pelvic support was further supported by EMG data. In the following paragraphs we discuss how posture and reaching performance demonstrated significant differences between levels of external support (thoracic versus pelvic) during the development of independent sitting.

Reaching Behavior between Levels of External Support across Age

Infants at young ages (2 months), showed a high level of difficulty in remaining stable in the sitting position when provided with an external support at the thoracic level, though they were able to do this minimally, with poor control. However, this ability was absent in most infants with the lower pelvic support, in which only 2 infants were able to maintain stability part of the time. Similar results were seen with respect to the number of reaching attempts that the infants made with the two levels of support. Thus, even though both motor milestones, upright sitting and reaching, were still immature during this developmental time period, a better support of the trunk was indeed associated with the ability to maintain stability and with the ability to perform more reaching attempts, as has been observed in previous studies (Amiel-Tison & Grenier, 1983; von Hofsten, 1982). This suggests that postural control significantly regulates the interaction of the infant with the surrounding environment during development, facilitating new actions, like reaching, which in turn can promote the emergence of cognitive skills and social behaviors (Gibson, 1988).

According to the AIMS and SATCo scores, infants started to master head control at 3 months of age, which is a critical motor milestone in infant development. With this mastery, infants increased their ability to touch/grasp the toy, highlighting the importance of head control for successful reaching (Thelen & Spencer, 1998). In order to lift the arm and successfully touch the toy infants must fixate the visual target, which requires both strength and control of the head in space as well as visual acuity. We hypothesized that reaching abilities would be reduced when postural instability was enhanced (i.e. with pelvic support); however, this was not supported at the age of 3 months or beyond. We found that infants continued to successfully reach with both levels of external support despite the challenging postural demands derived from the trunk support at the pelvic level. Harbourne et al. (2013) showed a similar effect in that non-independent sitters persistently and successfully reached in spite of the subsequent falls, disorganized muscle onsets and erratic trunk movements. This suggests that once infants acquire head control, reaching success is not perturbed by a decreased ability to control the regions of the trunk during vertical sitting.

With respect to the type of reach performed, differences between bimanual and unimanual reaches across age and level of support were not observed. Research has shown that interlimb coordination of infants during reaching tasks follows a fluctuating pattern and it is not object-scaled until the age of 2 years. These results agree with previous research and suggest that infants do not adapt unimanual or bimanual reaching with regard to the physical properties of the object or to the demands of the task in early stages of development (2.5 to 8 months) (Corbetta & Thelen, 1996). However, infants need to learn how to move to and cross the vertical midline with unimanual reaches in order to reach and grasp the toy (van Hof, van der Kamp, & Savelsbergh, 2014). Even though the progression of trunk development did not affect the type of reach performed, at 3 months of age, the number of successful bimanual reaches was greater than the number of successful unimanual reaches. This evidence highlights the effect of both age and maturation on the development of unimanual reaching.

Reaching and Postural Kinematics between Levels of External Support across Age

The effect of external support on postural stability while reaching was evident in that infants showed deterioration of postural kinematics with pelvic support when they had not yet mastered the control of the lower trunk region. Differences in maintaining stability of the trunk while reaching were observed in 4 and 5 month olds. Prior to this time period (i.e. 3 months of age), this was not the case, partly due to the fact that infants had not yet fully acquired control of both upper and lower regions of the trunk. Hence, infants were unstable with both levels of external support, though there was a tendency toward increased stability with thoracic support, as is depicted in Figure 4.4. A comparable trend was observed with respect to head stability. However, head angular displacement could reflect either the infant's moving the head to better visualize the surrounding environment or compensations for trunk movements while reaching. This could explain why infants appeared to maintain a fairly consistent head displacement across age, regardless of the level of trunk support. Nonetheless, it is worth noting the significant increase in head and trunk displacement that occurred with pelvic support at 4 and 5 months of age.

The external trunk support also had an impact on reaching kinematics, in that infants between 3-5 months of age showed a longer reach duration and a more devious and jerky reach with pelvic compared to thoracic support, due to the increased postural instability at pelvic level. In contrast to this, movement unit number remained invariable across levels of support, showing its independence from postural support. Similar results were observed by de Graaf-Peters et al. (2007) in which 4 month-old infants showed an invariable number of movement units in supine and sitting position; however, 6 month-old infants displayed less movement units in sitting position than at the age of 4 months. These results suggest that the ability to reduce the number of on-line corrections, or movement units in a reach, is a matter of maturation and might be improved with practice and motor experience. However, during this maturation period, other qualitative reaching parameters, like straightness and jerkiness, are significantly modulated by the progressive development of trunk control.

Reaching and Postural EMG Patterns between Levels of External Support across Age

Research has demonstrated on numerous occasions how postural muscle activity accompanying reaching movements increases with age (de Graaf-Peters et al., 2007; Harbourne et al., 2013; van Balen et al., 2012). Results from the current study show that postural muscle activity can be present even in early stages of sitting development, but it is dependent on the constraints of the task. Lumbar and thoracic muscle activity was more frequent when infants were provided with pelvic support at both 3-4 and 4-5 months. This implies that prior to acquiring independent sitting, infants were able to recruit postural muscles while reaching, and increased recruitment frequency when the postural task was more demanding. This means that postural muscle recruitment was situation-specific and depended on the degree in which balance was being perturbed (Hadders-Algra, 2008). Then, with increased age and maturation of the ability to sit independently, the overall activation frequency of postural muscles increased and infants showed similar values across levels of trunk support, implying that pelvic support was no longer a condition in which balance control was being challenged. Other research has also shown that once independent sitting ability was mastered, postural muscle activity accompanying reaching movements while sitting was consistently present (van der Heide et al., 2003) and thus became embedded in the task, although it could be further enhanced if the risk of losing balance and falling over was high (Hadders-Algra, 2005; van Balen et al., 2012).

Similarly, even though our sample demonstrated an infrequent use of APAs during early stages of development; with pelvic support, infants at 4-5 months displayed a higher percentage of APAs, mainly driven by thoracic muscles. This means that infants were able to control in a feed-forward fashion the disequilibrium that the reaching arm produced when they had not yet acquired full trunk control. With a higher support at thoracic level, these anticipatory effects were not observed as frequently at 3-5 months of age. However, from 6 months onward, APAs were more consistently present (50% of the time) and were independent of the type of support, suggesting that at this age, infants develop the ability to integrate feed-forward control into the task of reaching.

The study by Van der Fits et al., (1999a and 1999b) examining APAs in seated reaching concluded that APAs were seldom present in 3-5 month infants, were present in 20% of the trials at 6 months of age and became more consistent around the age of 13-14 months. These differing results, in contrast to what we obtained, might be explained by two major methodological differences related to the experimental paradigm and the temporal window of APAs that was selected for analysis. First, Van der Fits et al. (1999a) tested 3-6 month infants while placing them in an infant chair with complete support of the trunk, failing to evaluate the destabilizing effects of gravity and motion of the arm on the trunk *per se*. Second, Van der Fits et al. (1999b) used a more stringent criterion for defining APAs and evaluated APA activity within a 200ms time window prior to prime mover activation; whereas in the current study, we defined a 500ms time window. Feed-forward control emerges in parallel to the development of different postural frameworks in infancy and increase both in consistency and in temporal specificity with experience of the motor task (Witherington et al., 2002). Thus, we propose that APAs should be analyzed within a broader period of time before the reaching event in infants since timing of APAs during development would appear to be less specific to the reach onset than in adults.

It is thus concluded that during early developmental stages of upright sitting, APAs accompanying reaching movements are present to some degree, especially when the postural task is more demanding. These APAs are characterized by immature temporal features. Then, with age, APAs start to play a major role in the postural mechanisms for seated reaching once independent sitting has been established; at this point their activation is not dependent on the level of postural stability, but they are consistently activated well in advance of the reach.

Contrarily to our hypothesis, we did not expect differences in APAs to occur at later stages of development. However, the lumbar muscles showed a significantly higher frequency of APAs with pelvic support in comparison to thoracic support, not only at 4 months but also at 8 months, when infants were well coordinated in independent sitting. Therefore, there was an effect of support on APA activity of lumbar muscles even when trunk control was fully acquired, suggesting the existence of distinct feed-forward mechanisms that are related to specific segmental regions of the trunk, in later stages of development.

Postural muscles serve to stabilize posture and control equilibrium during a reach in two ways. The muscles of the upper region of the trunk are used to oppose the reaction forces generated by the arm movement, whereas the muscles of the lower trunk serve to keep the center of mass within the stability limits (van der Fits et al., 1999a). In this study, the activation of both thoracic and lumbar muscles was significantly enhanced with pelvic support during the learning process of independent sitting. This outcome implies the need to maintain stability prior to and during the ongoing motion of the arm.

However, postural muscle onset latencies reflect the ability to actively control the goal-directed movement once it has been initiated; a slower latency would indicate less efficient control. Results showed significant differences between levels of trunk support for thoracic muscle onset, depending on the age of the infant. At 3 months, a slower latency was observed with pelvic support, whereas with the help of additional support at thoracic level, this latency was significantly faster. This suggests that even though infants were able to consistently recruit postural muscles to counteract the unbalancing effects of the self-triggered perturbation through reaching, the temporal mechanisms were significantly delayed with the absence of full trunk control at 3 months. Nevertheless, these mechanisms were improved by facilitating higher levels of external postural supports, highlighting the effects of both age and support on the development of postural muscle onset latencies.

A similar effect was observed when calculating the percentage of trials with either a top-down or bottom-up postural muscle recruitment order. With thoracic support, the preference for either pattern remained invariable across age. On the contrary with pelvic support, there were a higher percentage of times that postural adjustments followed a top-down sequence, at 4 months of age, suggesting a functional preference for stabilizing the upper trunk in response to the instability. This strategy shifted toward a bottom-up pattern after the onset of independent sitting. These observations have been previously observed in numerous studies (de Graaf-Peters et al., 2007; van Balen et al., 2012; van der Fits et al., 1999a). However, we expand the results obtained from previous literature by showing that postural adjustments following a top-down sequence is related to increased postural demands during the development of upright sitting, since such preference can be reduced with higher levels of trunk support. Being able to sit independently then marks the hallmark for shifting toward a bottom-up pattern, when stabilization of the trunk is no longer challenging, and thus, the focus of control is at the support surface (Assaiante, 1998; Hadders-Algra, 2008).

Reaching and Postural EMG Patterns across Age

Unexpectedly, some of the EMG parameters were not dependent on the progression of trunk control; instead age had a major effect. For instance, muscle amplitudes of compensatory postural adjustments showed no changes between levels of support, suggesting the independence to posture. This supports previous research, indicating that changes in the degree of contraction of postural muscles to changes in position do not occur until 9-10 months of age (Hadders-Algra, 2005).

Moreover, we observed that 6 months was the age when significant changes in compensatory muscle amplitudes occurred and did not depend on the type of support. By this age, infants had increased lumbar muscle amplitude during seated reaching. It could be surmised that this general increase was related to the development of independent sitting and may serve as a preparation for the ability to move in and out, or rotate in sitting position. We also found that during early stages, triceps muscle amplitude (the antagonist) was high and decreased by 6 months of age, whereas biceps muscle amplitude (the agonist) was low during early periods and by 6 months onward, it had substantially increased. These results, also found in other studies, suggests that during early stages of development, reaches were associated with a more "active extension" strategy, meaning that reaches were accompanied by increased extensor muscle amplitude (Konczak et al., 1997). With increasing reaching proficiency and with the achievement of independent sitting, infants shifted to a more "passive extension" strategy, which is more energy efficient. That is, infants were able to produce more biceps activity and thus, more flexion of the arm to accomplish the task of forward reaching while sitting.

Lastly, our findings related to arm muscles indicate that patterns of muscle frequency, amplitudes and onsets in early infancy are characterized as being highly variable and are not influenced by the progression of the development of trunk control during the acquisition of independent sitting. At 3 and 4 months, there was a co-activation of all arm muscles, which was associated with the onset of reaching (Thelen et al., 1993). It is known that activation of both agonist and antagonist muscles at a joint often occurs when the individual has lower skill levels since it stiffens or stabilizes the entire limb. However, from 5 months onwards, infants adopted different arm muscle activation strategies depending on the level of support they were provided. This might suggest that the use of external devices can produce changes in the neuromuscular control of the arm, which is unrelated to the intrinsic control of the trunk that infants had acquired.

CONCLUSIONS

This study sought to examine the relationship between reaching performance and the progressive development of control of specific trunk regions for the acquisition of independent sitting. Results reinforce and further expand previous findings showing that improvements in trunk control have direct consequences on the development of reaching. It is concluded that there is a cranio-caudal acquisition of trunk control for independent sitting and the regional extent of trunk control infants have acquired has an impact on the kinematic quality of reaching movements and accompanying postural muscle patterns, attributed to frequency of activation and timing mechanisms. However, with the help of additional support, infants experience drastic improvements in their reaching skills and subsequent muscular parameters during the development of independent sitting. This correlation of reaching and the progressive development of trunk control should also be examined in children with motor deficits in order to determine if they might benefit from the use of external trunk support and consequently implement more efficient therapeutic strategies.

CHAPTER V

FINAL CONCLUSIONS

GENERAL SUMMARY OF FINDINGS

Postural achievements in infancy develop in a cephalo-caudal direction, as originally described by Gesell and Amatruda (1945). Newborns have limited postural control, but within a few months, they develop head control followed by trunk control. The development of trunk control will allow infants to first sit with support and eventually to sit without any kind of support. Then, by the age of 1 year, infants achieve independent standing which consequently leads to the ability to walk, run and skip.

Research from this dissertation provides additional evidence to support the concept that the development of trunk control for upright sitting follows a progressive cephalo-caudal direction, starting with the upper regions and subsequently the lower and pelvic regions of the trunk. This progression is a fundamental prerequisite for maintenance of functional positions of the body, such as upright sitting. The ability to control upright sitting position is necessary for stability, balance, and orientation within the performance of more complex skills (Shumway-Cook & Woollacott, 2012a). Appropriate orientation ensures that the configuration of the body segments is maintained with respect to one another during a movement or task. For example, when performing a reaching task, the trunk needs to maintain stability with respect to the base of support, prior to, and during the ongoing motion of the reach (Zimmermann, Meulenbroek, & de Lange, 2012). Therefore, trunk stability is essential for effective postural maintenance and reaching accuracy, since reaching proficiency is highly dependent on the control of posture.

The results from this dissertation demonstrate that the stability of the trunk depends on the extent of trunk control that infants have acquired. In the cross-sectional study we found that when infants had partial trunk control, they relied on an external trunk support that facilitated postural stability, in order to perform more efficient reaches that were similar to the ones made by infants with complete trunk control.

Furthermore, in the longitudinal study, it was observed that measures of stability (head and trunk angular displacement) and reaching performance (movement time, straightness score, normalized jerk score) between levels of external trunk support (pelvic vs. thoracic support) had non-linear changes across development. In most cases, these reflected impoverished stability and reaching measures with pelvic support during the development of upright sitting. These differences were at their highest when infants were 3-4 months and gradually declined to reach their lowest levels at 6 months, when infants had acquired the ability to independently sit. From this age onward, further improvements in posture and reaching across age were not observed and measures were insignificant between levels of external support.

Electromyographic recordings associated with reaching and underlying trunk stability displayed a similar, non-linear trend across development. Infant reaches with pelvic support were characterized by high postural muscle activation frequencies in response to the instability, at 3-5 months of age. First, onset latencies of postural muscles were significantly delayed with pelvic support, at 3 months of age. Then, the occurrence of APAs was more consistent with pelvic support, at 4-5 months of age, suggesting the role of APAs for postural maintenance during reaching when stability is compromised. From 6 months onward, APAs, postural muscle activation frequencies and onset latencies accompanying the reach attained consistent values and were no longer dependent on the level of external support. Therefore, 6 months, i.e. the age when infants learned to sit independently, is an age of transition, when they are finally able to adapt postural activity to the specifics of the support condition.

Additionally, there were other parameters that changed with increasing age but were independent of the segmental progression of trunk control. For instance, lumbar muscle amplitude increased with age, and peaked at 6 months, highlighting its association with an increased capacity to sit independently. Also, in terms of the reaching arm, MUs decreased with age, and obtained their lowest values from 6 months onward; similarly, biceps muscle amplitude increased whereas triceps muscle amplitude decreased. When taken together, these points suggest that even though the ability to reach and sit overlap in developmental time, there are specific parameters embedded in the maturational time course of each milestone that are not perturbed by one another.

LIMITATIONS OF RESEARCH

It is important to acknowledge that postural control is only one of the many critical factors that must be acquired for infants to sit independently and perform skillful reaches, since factors such as muscle strength, appropriate body proportions, sensitivity to visual flow, the ability to detect affordances, and motivation are also influencing factors (Thelen & Smith, 1994). Each of these factors has a different developmental time course. From a developmental systems perspective, the goal of developmental analysis is to understand the paths, interrelations and causal mechanisms of the time course of each contributing factor (Adolph & Robinson, 2008). Therefore, defining complete trunk control as an endpoint to the development of upright sitting and reaching skills might be a risky proposition, since it may very well depend on rearing or testing conditions, as well as individual and cultural variations.

However, this dissertation was motivated by the notion that the development of sitting postural control and reaching behavior are highly interdependent functions. Full attempts were made to tease out the causal effects of postural control on reaching. First, having applied measures across a broad range of ages in a longitudinal design, we were able to explore a critical window of postural development prior to independent sitting, corresponding to ages 2-5 months. Second, with the use of experimental manipulations, we had the means to model the type of postural support that infants progressively generated for themselves. More specifically, we supported the thoracic and pelvic regions of the trunk for comparing the effects of increased vs. decreased postural support on reaching. With the higher support at thoracic level, reaching movements during pre-sitting stages were smoother and more mature than when the support was limited to the pelvic level. Increased postural support had a direct impact on reaching performance. Then, as infants developed across age, they improved in many domains, including sitting posture and thus, reaching movements were freed from balance constraints of the trunk. Infants no longer required the additional help of a higher support for producing coordinated reaching. With this, we can conclude that postural control is one of the main causes contributing to reaching proficiency, regardless of whether posture is improved naturally across age or with the help of an experimental set-up. This information creates the basis for a wide range of future studies that can be applied in assessment and rehabilitative protocols in children with postural dysfunctions.

CLINICAL IMPLICATIONS

Basic studies in animal models conjointly with research in infant behavior have been crucial in understanding normal development and critical temporal windows at which behaviors are acquired. In addition, knowledge about typical development is a prerequisite for understanding abnormal development. It is during the first years of life when major changes occur in the nervous system and motor behavioral outputs. Hence, it is imperative to localize those critical temporal windows during development and define how abnormal behavior deviates from typical behavior so that professionals in health science can assess and apply therapeutic techniques in a timely manner.

Studies have shown that for children with cerebral palsy, achieving independent sitting early in time is a key determinant of independent ambulation and future motor skill development (Wu et al., 2004). Results of this research examine principles underlying the development of trunk control for independent sitting and its consequences for the performance of functional activities, like reaching. Thus, the knowledge obtained from typically developing infants could also be compared in children with cerebral palsy in order to test how they vary from typical development at different points in time. If a similar correlation between the progressive achievement of trunk control and the emergence of effective reaching performance is observed, then this might provide new insights into specific improvements in both postural control and consequent reaching ability in children with cerebral palsy. These insights can be used to improve current approaches to training trunk postural control, and thus independent sitting, which has a direct impact on the manual abilities for this vulnerable population.

Pediatricians often encounter children with delays of motor development in their clinical practices. Motor delays may be the first or most obvious sign of a global developmental disorder. It is often the case that children whose developmental trajectories are at risk may experience challenges in meeting early motor milestones (Noritz & Murphy, 2013). A timely diagnosis may reduce the prognostic uncertainties. If clinicians become aware of the fact that trunk control is developed cranio-caudally and is a prerequisite for independent sitting and subsequent reaching ability, they may refine their clinical evaluations in a timely manner to include more precise evaluation of trunk control. Segmental evaluation of the trunk will undoubtedly lead to new innovative ideas concerning how to impact trunk control and reaching in the clinic as well as at home.

FUTURE DIRECTIONS FOR RESEARCH

This research has demonstrated that distinct levels of postural trunk control can be differentiated during the development of independent sitting, and that reaching performance is influenced by level of trunk control. This paradigm offers the foundation for future exploration both in typical development as well as in children with neurological deficits.

Future studies should be implemented to test whether there is a segmental progression of postural control for the development of independent stance in typical infants. During the process of learning to stand independently, infants must learn to control many additional degrees of freedom compared to independent sitting, as they add the coordination of the leg and thigh segments to those of the trunk and head. Research in healthy adults has modeled the body during quiet stance as a multilink pendulum with two coexisting modes of control for describing sway during quiet stance: ankle strategy or a hip strategy. These two control strategies have also been described for recovery of perturbed stance (Shumway-Cook & Woollacott, 2012c). The question of whether infants follow a top-down progression of control across the multi-link segments at the level of the hips, knees and ankles for acquiring independent stance, is yet to be answered.

However, of primary importance for clinical purposes would be a study to evaluate the effects of segmental trunk support on posture and reaching in children with cerebral palsy or even other pathological populations, such as adults with moderate to severe stroke, for the intended goal of improving trunk control and reaching. In the severe cases of stroke, trunk stability is compromised which subsequently impairs arm function. However, knowledge related to the relationship between impaired trunk postural control and loss of independent arm function following a stroke is still limited. This is a critical barrier to progress in assessment and treatment of patients with severe to moderate stroke, since most of their activities of daily living are performed while seated. Thus, future studies must assess whether improvements in reaching and manipulation skills can occur when patients with severe trunk deficits are given external trunk adapted to their level of trunk control. In addition, the more detailed information about control of the trunk in individual patients could help specify the clinical goals and guide the implementation of training protocols directed at improving control in the specific area of the trunk rather than treating the trunk as a non-dissociable, single unit (Butler et al., 2010; Butler, 1998).

APPENDIX

METHODOLOGY FOR HEARTBEAT SUBTRACTION

A modified version of the algorithm used by Aminian et al. (1988) was used for subtracting the heartbeat artifact. A six stage process was used to identify and remove EKG interference that may have been present in each channel of the EMG used in this data analysis.

1) User is presented with a graph of the EKG signal collected by the subject being processed. The user is asked to select an amplitude threshold to differentiate heartbeat signal from activity originating in the surrounding musculature. The polarity of the threshold selected determines if the particular peaks sought will be the Q (negative polarity) or R (positive polarity) of the EKG complex.

2) The EKG signal is examined forward from the beginning, looking for points that exceed the amplitude threshold set in the first stage. When such points are found, the forward examination continues, counting how long the signal stays above that threshold point. If this duration exceeds 7 ms, then that peak is kept for further consideration. The value of 7ms was empirically determined to have the best performance when the algorithm was first implemented by previous graduate students.

3) When a peak point is detected, the signal around it is explored for the peaks that complete the QRS complex (mainly searching for inflection points) and the directionality of the search is determined by the polarity of the selected threshold. Once the complete QRS is found, ten milliseconds are added on to each end of the inflection points to note the time location of the entire PQRST complex.

This process continues until the search reaches 40ms before the end of the EKG signal. The search terminates here as any EKG signal that begins in these final 40ms is highly likely to be an incomplete PQRST complex.

In addition to the third stage, the amplitude of each peak deemed valid above is averaged. Any PQRST regions whose peaks exceed this average by 2 standard deviations are discarded. The reasoning for deciding to remove these peaks was that any abnormally large spikes in the EKG signal were likely to be due to either extraneous muscle contractions, or other unusual sources of electric interference.

4) For each channel of EMG, the average EKG signature was generated by averaging together the waveform found within each PQRST boundary deemed valid from the above stages. Then, the averaged EKG signal for that EMG channel is created by including the average EKG signature within the PQRST time boundaries on a flat signal, with a same duration as the original EMG signals.

5) The user is presented with three graphs for each EMG channel: the unaltered EMG signal, the averaged EKG signal for that channel, and the EMG signal with the averaged EKG signal subtracted (Figure 6.1). For each channel, the user is asked to choose whether the unaltered or subtracted signal is the better of the two. If the averaged EKG signal selected is not of sufficient quality, the user has the option to return to the first stage and pick a new amplitude threshold.

6) Finally, the algorithm removes the averaged EKG signal from those EMG channels the user elected to remove it from, and processing on the EMG signals continues.

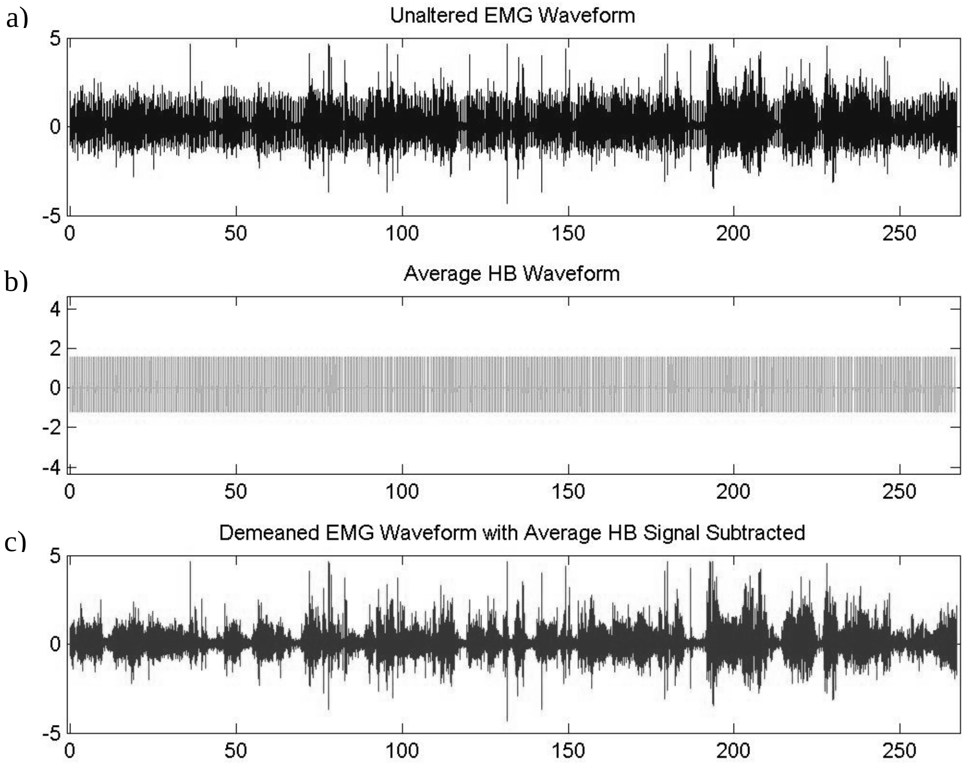


Figure 6.1. Example of Hearbeat Subtraction. Graphs indicating a) the unaltered EMG waveform, b) the averaged heartbeat signal for that channel, and c) the EMG signal with the averaged heartbeat signal subtracted.

REFERENCES CITED

Acension Technology Coorporation. (2000). *MiniBIRD® Position and orientation measurement system.* Burlington, VT: Ascension Technology Corporation.

Adolph, K., & Berger, S. (2006). Motor development. In W. Damon & D. Lerner (Eds.), *Handbook of child psychology: Cognition, perception, and language* (2nd ed., Vol. 2, pp. 161–213). New York, NY: Wiley.

Adolph, K., & Berger, S. E. (2005). Physical and motor development. In M. Bornstein & M. Lamb (Eds.), *Developmental science* (pp. 223–281). Mahwah, NJ: Lawrence Erlbaum Associates.

Adolph, K., & Robinson, S. (2008). In defense of change processes. *Child Development*, *79*, 1648–1653.

Amiel-Tison, C., & Grenier, A. (1983). Expression of liberated motor activity (LMA) following manual immobilization of the head. In C. Amiel-Tison & A. Grenier (Eds.), *Neurological evaluation of the newborn and the infant* (pp. 87–109). New York, NY: Masson Publishing USA.

Aminian, K., Ruffieus, C., & Robert, P. (1988). Filtering by adaptive sampling (FAS). *Medical and Biological Engineering and Computing*, *26*, 658–662.

Assaiante, C. (1998). Development of locomotor balance control in healthy children. *Neuroscience and Biobehavioral Reviews*, *22*(4), 527–532.

Assaiante, C., Mallau, S., Viel, S., Jover, M., & Schmitz, C. (2005). Development of postural control in healthy children: a functional approach. *Neural Plasticity*, *12*(2-3), 109–118.

Barbosa, V., Campbell, S., Sheftel, D., Singh, J., & Beligere, N. (2003). Longitudinal performance of infants with cerebral palsy on the Test of Infant Motor Performance and on the Alberta Infant Motor Scale. *Physical and Occupational Therapy in Pediatrics*, *23*(3), 7–29.

Bayley, N. (1969). *Bayley scales of infant development.* New York, NY: Oxford University Press.

Bayley, N. (2005). *Bayley scales of infant and toddler development* (3rd ed.). San Antonio, TX: Pearson.

Bernstein, N. (1967). *The co-ordination and regulation of movements* (1st ed.). New York, NY: Oxford, Pergamon Press.

Bertenthal, B., & Von Hofsten, C. (1998). Eye, head and trunk control: the foundation for manual development. *Neuroscience and Biobehavioral Reviews*, *22*(4), 515–520.

Bigongiari, A., de Andrade e Souza, F., Franciulli, P. M., Neto, S. E. R., Araujo, R. C., & Mochizuki, L. (2011). Anticipatory and compensatory postural adjustments in sitting in children with cerebral palsy. *Human Movement Science*, *30*(3), 648–657.

Brandt, T., Paulus, W., & Straube, A. (1986). Vision and posture. In W. Bles & T. Brandt (Eds.), *Disorders of posture and gait.* (pp. 157–175). Amsterdam: Elsevier Ltd.

Butler, P. (1998). A preliminary report on the effectiveness of trunk targeting in achieving independent sitting balance in children with cerebral palsy. *Clinical Rehabilitation*, *12*, 281–293.

Butler, P., Saavedra, S. L., Sofranac, M., Jarvis, S., & Woollacott, M. H. (2010). Refinement, reliability and validity of the segmental assessment of trunk control (SATCo). *Pediatric Physical Therapy*, *22*(3), 246–257.

Butterworth, G., & Hicks, L. (1977). Visual proprioception and postural stability in infancy: a developmental study. *Perception*, *6*, 255–262.

Chang, J. J., Wu, T. I., Wu, W. L., & Su, F. C. (2005). Kinematical measure for spastic reaching in children with cerebral palsy. *Clinical Biomechanics*, *20*(4), 381–388.

Corbetta, D., & Thelen, E. (1996). The developmental origins of bimanual coordination: A dynamic perspective. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(2), 502–522.

Darrah, J., Bartlett, D., Maguire, T., Avison, W., & Lacaze-Masmonteil, T. (2014). Have infant gross motor abilities changed in 20 years? A re-evaluation of the Alberta Infant Motor Scale normative values. *Developmental Medicine and Child Neurology*, *56*(9), 877–881.

De Graaf-Peters, V. B., Bakker, H., Van Eykern, L. A., Otten, B., & Hadders-Algra, M. (2007). Postural adjustments and reaching in 4- and 6-month-old infants: An EMG and kinematical study. *Experimental Brain Research*, *181*, 647–656.

Elsner, B., & Hommel, B. (2004). Contiguity and contingency in action-effect learning. *Psychological Research*, *68*(2-3), 138–154.

Fallang, B., Saugstad, O. D., & Hadders-Algra, M. (2000). Goal directed reaching and postural control in supine position in healthy infants. *Behavioural Brain Research*, *115*(1), 9–18.

Fallang, B., Saugstad, O., Grogaard, J., & Hadders-Algra, M. (2003). Kinematic quality of reaching movements in preterm infants. *Pediatric Research*, *53*, 836–842.

Forssberg, H., & Hirschfeld, H. (1994). Postural adjustments in sitting humans following external perturbations : muscle activity and kinematics. *Experimental Brain Research*, *97*(3), 515–527.

Galloway, J. C., & Thelen, E. (2004). Feet first: object exploration in young infants. *Infant Behavior and Development*, *27*(1), 107–112.

Gesell, A., & Amatruda, C. (1947). *Developmental diagnosis* (2nd ed.). New York, NY: Harper and Row.

Gessell, A. (1946). *The ontogenesis of infant behavior. Manual of child psychology*. Hoboken, NJ: John Wiley & Sons Inc.

Gessell, A., & Ames, L. (1947). The development of handedness. *Journal of Genetic Psychology*, *70*, 155–175.

Gibson, E. J. (1988). Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology*, *39*, 1–41.

Gibson, E. J., & Pick, A. (2000). *An ecological approach to perceptual learning and development.* New York, NY: Oxford University Press.

Grenier, A., & Amiel-Tison, C. (1981). Liberated-motricity by holding the head during the 1st weeks of life. *Archives for Pediatrics, 5*, 557–561.

Grönqvist, H., Strand Brodd, K., & von Hofsten, C. (2011). Reaching strategies of very preterm infants at 8 months corrected age. *Experimental Brain Research.*, *209*(2), 225–233.

Hadders-Algra, M. (2000). The neuronal group selection theory : a framework to explain variation in normal motor development. *Developmental Medicine and Child Neurology*, *42*, 566–572.

Hadders-Algra, M. (2005). Development of postural control during the first 18 months of life. *Neural Plasticity*, *12*(2-3), 99–108.

Hadders-Algra, M. (2008). Development of postural control. In M. Hadders-Algra & E. Brogren Carlberg (Eds.), *Postural control: A key issue in developmental disorders* (pp. 22–73). London: Mac Keith Press.

Hadders-Algra, M., Brogren, E., & Forssberg, H. (1996). Ontogeny of postural adjustments during sitting in infancy: variation, selection and modulation. *The Journal of Physiology*, *493*, 273–288.

Harbourne, R. T., Giuliani, C., & Neela, J. (1993). A kinematic and electromyographic analysis of the development of sitting posture in infants. *Developmental Psychobiology, 26*, 51–64.

Harbourne, R. T., Lobo, M. A., Karst, G. M., & Cole, J. (2013). Sit happens : Does sitting development perturb reaching development , or vice versa ? *Infant Behavior and Development*, *36*(3), 438–450.

Harbourne, R. T., & Stergiou, N. (2003). Nonlinear analysis of the development of sitting postural control. *Developmental Psychobiology*, *42*(4), 368–377.

Hedberg, A., Carlberg, E. B., 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*, *47*(5), 312–320.

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, 157*, 10–17.

Hirschfeld, H., & Forssberg, H. (1994). Epigenetic development of postural responses for sitting during infancy. *Experimental Brain Research*, *97*, 528–540.

Hopkins, B., & Rönnqvist, L. (2002). Facilitating postural control: effects on the reaching behavior of 6-month-old infants. *Developmental Psychobiology*, *40*(2), 168–182.

Horak, F., & Diener, H. (1994). Cerebellar control of postural scaling and central set in stance. *Journal of Neurophysiology*, *72*, 479–493.

Horak, F., Henry, S., & Shumway-Cook, A. (1997). Postural perturbations: new insights for treatment of balance disorders. *Physical Therapy*, *77*, 517–533.

Horak, F., Nutt, J., & Nashner, L. (1992). Postural inflexibility in parkinsonian subjects. *Journal of the Neurological Sciences*, *111*, 46–58.

Kapandji, A. (2008). *The physiology of the joints: The vertebral column, pelvic girdle and head (vol III).* (6th ed.). Churchill Livingstone: Elsevier Ltd.

Konczak, J., Borutta, M., & Dichgans, J. (1997). The development of goal-directed reaching in infants II. Learning to produce task-adequate patterns of joint torque. *Experimental Brain Research*, *113*(3), 465–474.

Lobo, M. A, & Galloway, J. C. (2012). Enhanced handling and positioning in early infancy advances development throughout the first year. *Child Development*, *83*(4), 1290–1302.

Macpherson, J., & Fung, J. (1999). Weight support and balance during perturbed stance in the chronic spinal cat. *Journal of Neurophysiology*, *82,* 3066–3081.

Macpherson, J., & Horak, F. (2013). Posture. In E. Kandel, J. Schwartz, T. Jessell, S. Siegelbaum, & A. Hudspeth (Eds.), *Principles of neural science* (5th ed., pp. 935–959). New York, NY: McGraw-Hill Companies.

McGraw, M. (1945). *The neuromuscular maturation of the human infant.* London: Mac Keith Press.

Mihara, M., Miyai, I., Hatakenaka, M., Kubota, K., & Sakoda, S. (2008). Role of the prefrontal cortex in human balance control. *NeuroImage*, *43,* 329–336.

Motion Lab Systems. (2008). *A software user guide for EMG graphing and EMG analysis.* Baton Rouge, LA: Motion Lab Systems, Inc.

Noritz, G., & Murphy, N. (2013). Motor delays: Early identification and evaluation. *Pediatrics*, *131*(6), 2016–2027.

Out, L., Van Soest, A. J., Savelsbergh, G. J., & Hopkins, B. (1998). The effect of posture on early reaching movements. *Journal of Motor Behavior*, *30*(3), 260–272.

Panjabi, M. (1992). The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *Journal Spinal Disorders*, *5*(4), 383–389.

Park, R., Tsao, H., Cresswella, A., & Hodges, P. (2014). Anticipatory postural activity of the deep trunk muscles differs between anatomical regions based on their mechanical advantage. *Neuroscience*, *261*, 161–172.

Peiper, A. (1963). *Cerebral functions in infancy and childhood.* New York, NY: Consultants Bureau.

Piek, J. (2006). *Infant motor development.* Champaign, IL: Human Kinetics.

Piper, M. C., & Darrah, J. (1994). *Alberta Infant Motor Scale*. Canada: Elsevier - Health Sciences Division.

Piper, M., & Darrah, J. (1994). *Motor assessment of the developing infant.* Philadelphia, PA: WB Saunders Company.

Piper, M., Pinnell, L., Darrah, J., Maguire, T., & Byrne, P. (1992). Construction and validation of the Alberta Infant Motor Scale (AIMS). *Canadian Journal of Public Health*, *83,* 46–50.

Rachwani, J., Santamaria, V., Saavedra, S. L., Wood, S., Porter, F., & Woollacott, M. H. (2013). Segmental trunk control acquisition and reaching in typically developing infants. *Experimental Brain Research*, *228*(1), 131–139.

Reed, E. S. (1989). Changing theories of postural development. In M. H. Woollacott & A. Shumway-Cook (Eds.), *Development of posture and gait across the lifespan* (pp. 3–24). Columbia, SC: University of South Carolina.

Rochat, P., & Goubet, N. (1995). Development of sitting and reaching in 5- to 6-month-old infants. *Infant Behavior and Development*, *18*(1), 53–68.

Saavedra, S. L., van Donkelaar, P., & Woollacott, M. H. (2012). Learning about gravity: segmental assessment of upright control as infants develop independent sitting. *Journal of Neurophysiology*, *108*(8), 2215–2229.

Shumway-Cook, A., & Woollacott, M. H. (2012a). Development of postural control. In A. Shumway-Cook & M. H. Woollacott (Eds.), *Motor control: Translating research into clinical practice* (4th ed., pp. 195–222). Baltimore, MD: Lippincott Williams & Wilkins.

Shumway-Cook, A., & Woollacott, M. H. (2012b). Motor control: Issues and theories. In A. Shumway-Cook & M. H. Woollacott (Eds.), *Motor control: Translating research into clinical practice* (4th ed., pp. 3–20). Baltimore, MD: Lippincott Williams & Wilkins.

Shumway-Cook, A., & Woollacott, M. H. (2012c). Normal postural control. In A. Shumway-Cook & M. H. Woollacott (Eds.), *Motor control: Translating research into clinical practice* (4th ed., pp. 161–193). Baltimore, MD: Lippincott Williams & Wilkins.

Sommerville, J. A., Woodward, A. L., & Needham, A. (2005). Action experience alters 3-month-old infants’ perception of others' actions. *Cognition*, *96*(1), B1–11.

Soska, K. C., & Adolph, K. E. (2014). Postural position constrains multimodal object exploration in infants. *Infancy*, *19*(2), 138–161.

Soska, K. C., Adolph, K. E., & Johnson, S. P. (2010). Systems in development: motor skill acquisition facilitates 3D object completion. *Developmental Psychology*, *46*(1), 129–138.

Spencer, J. P., & Thelen, E. (2000). Spatially specific changes in infants’ muscle coactivity as they learn to reach. *Infancy*, *1*(3), 275–302.

Sporns, O., & Edelman, G. (1993). Solving Bernstein’s problem: A proposal for the development of coordinated movement by selection. *Child Development*, *62*, 336–353.

Sutherland, D., Olshen, R., Cooper, L., & Woo, S. (1980). The development of mature gait. *Journal of Bone and Joint Surgery, 62*, 336–353.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J. P., Schneider, K., & Zernicke, R. F. (1993). The transition to reaching: mapping intention and intrinsic dynamics. *Child Development, 64*(4), 1058–1098.

Thelen, E., Corbetta, D., & Spencer, J. P. (1996). Development of reaching during the first year: role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance, 22*(5), 1059–1076.

Thelen, E., & Smith, L. (1994). *A dynamic systems approach to the development of cognition and action.* Cambridge, MA: MIT Press.

Thelen, E., & Spencer, J. P. (1998). Postural control during reaching in young infants: a dynamic systems approach. *Neuroscience and Biobehavioral Reviews, 22*(4), 507–514.

Touwen, B. (1976). *Neurological development in infancy.* Philadelphia, PA: JB Lipincott.

Touwen, B. (1993). How normal is variable, or how variable is normal? *Early Human Development, 34,* 1–12.

Van Balen, L. C., Dijkstra, L. J., & Hadders-Algra, M. (2012). Development of postural adjustments during reaching in typically developing infants from 4 to 18 months. *Experimental Brain Research, 220*(2), 109–119.

Van der Fits, I. B., Klip, A. W., Van Eykern, L. A., & Hadders-Algra, M. (1999a). Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life. *Behavioural Brain Research, 106*(1-2), 75–90.

Van der Fits, I. B., Otten, E., Klip, A. W., Van Eykern, L. A, & Hadders-Algra, M. (1999b). The development of postural adjustments during reaching in 6- to 18-month-old infants. Evidence for two transitions. *Experimental Brain Research, 126*(4), 517–528.

Van der Heide, J. C., Otten, B., Van Eykern, L. A, & Hadders-Algra, M. (2003). Development of postural adjustments during reaching in sitting children. *Experimental Brain Research, 151*(1), 32–45.

Van Haastert, I., de Vries, L., Helders, P., & Jongmans, M. (2006). Early gross motor development of preterm infants according to the Alberta Infant Motor Scale. *Journal of Pediatrics, 149*, 617–622.

Van Hof, R., van der Kamp, J., & Savelsbergh, G. J. R. (2014). The relation of unimanual and bimanual reaching to crossing the midline. *Child Development*, *73*(5), 1353–1362.

Van Wullften, P., & Hopkins, B. (1993). A longitudinal study of neural maturation and early mother-infant interaction. *Journal of Child Psychology and Psychiatry*, *34*, 1031–1041.

Von Hofsten, C. (1979). Development of visually directed reaching: The appraoch phase. *Journal of Human Movement Studies*, *5*, 160–178.

Von Hofsten, C. (1980). Predictive reaching for moving objects by human infants. *Journal of Experimental Child Psychology*, *30*(3), 369–382.

Von Hofsten, C. (1982). Eye-hand coordination in the newborn. *Developmental Psychology*, *18*(3), 450–461.

Von Hofsten, C. (1991). Structuring of early reaching movements: a longitudinal study. *Journal of Motor Behavior*, *23*(4), 280–292.

Von Hofsten, C., & Rönnqvist, L. (1993). The structuring of neonatal arm movements. *Child Development*, *64*(4), 1046–1057.

Von Hofsten, C., & Woollacott, M. H. (1989). Postural preparations for reaching in 9-months-old infants. *Neuroscience Abstracts*, *15*, 1199.

William, P., & Adam, J. (2012). The role of electromyography (EMG) in the study of anticipatory postural adjustments. In C. Steele (Ed.), *Applications of EMG in clinical and sports medicine*. InTech.

Witherington, D. C., Von Hofsten, C., Rosander, K., Robinette, A., Woollacott, M. H., & Bertenthal, B. I. (2002). The development of anticipatory postural adjustments in Infancy. *Infancy*, *3*(4), 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*, *19*, 167–186.

Woollacott, M. H., Assaiante, C., & Amblard, B. (1996). Development of balance and gait control. In A. M. Bronstein, T. Brandt, & M. H. Woollacott (Eds.), *Clinical disorders of balance, posture and gait* (pp. 41–63). London: Oxford University Press.

Woollacott, M. H., Burtner, P., Jensen, J., Jasiewicz, J., Roncesvalles, N., & Sveistrup, H. (1998). Development of postural responses during standing in healthy children and in children with spastic diplegia. *Neuroscience and Biobehavioral Reviews*, *22*, 583–589.

Zimmermann, M., Meulenbroek, R. G. J., & de Lange, F. P. (2012). Motor planning is facilitated by adopting an action's goal posture: an fMRI study. *Cerebral Cortex*, *22*(1), 122–131.