THE EFFECT OF DIFFERENT LEVELS OF EXTERNAL TRUNK SUPPORT ON POSTURAL AND REACHING CONTROL IN CHILDREN WITH CEREBRAL PALSY

by

VICTOR F. SANTAMARIA GONZALEZ

A DISSERTATION

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

March 2015

DISSERTATION APPROVAL PAGE

Student: Victor F. Santamaria Gonzalez

Title: The Effect of Different Levels of External Trunk Support on Postural and Reaching Control in Children with Cerebral Palsy

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. Gina Biancarosa	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 March 2015.

© 2015 Victor F. Santamaria Gonzalez

DISSERTATION ABSTRACT

Victor F. Santamaria Gonzalez

Doctor of Philosophy

Department of Human Physiology

March 2015

Title: The Effect of Different Levels of External Trunk Support on Postural and Reaching Control in Children with Cerebral Palsy

This dissertation aimed to investigate the relationship between posture and reaching in both healthy and pathological conditions, approaching the trunk as a multi-segmented structure. For this purpose, neuromuscular and kinematic profiles were recorded from trunk and arm during seated reaches providing mid-rib vs pelvic levels of trunk support.

Healthy adults with mature postural and reaching abilities displayed invariant arm kinematics during the reach. However, participants displayed increased anticipatory control and earlier activation of cervical muscles with mid-rib support. Participants also presented increased compensatory responses of paraspinal muscles when responding to the increased trunk balance demands with pelvic support.

Children with moderate/severe cerebral palsy (CP) cannot maintain an upright sitting position and thus cannot create a stable postural frame around which upper limb movements are planned and executed. A second set of studies examined postural and reaching characteristics in these children, while applying axillae, mid-rib or pelvic levels of support. Participants were classified according to their intrinsic level of trunk control as mild, moderate and severe. With higher levels of support children with moderate to severe impairments in trunk control showed improvements of head and trunk control along with enhanced reaching performance. Participants with mild trunk dysfunction were able to sit independently and thus did not demonstrate significant changes in postural and reaching proficiency across levels of external trunk support.

Electromyographic profiles were more variable depending on the severity of intrinsic trunk control. Overall, participants in the mild group presented more refined timing mechanisms for both anticipatory (closer to reaching onset) and compensatory (reduced latency) postural adjustments during the reach across all levels of support. Participants in the moderate group displayed earlier muscle onsets and more efficient arm/trunk muscle amplitudes with higher levels of support. Participants in the severe group showed very limited capability of anticipatory control of paraspinal muscles, delayed muscle onsets and variable muscle amplitudes across levels of support.

These results emphasize the complex neuro-anatomical nature of trunk control during reaching. Also, they highlight that inefficient postural control while sitting significantly impacts children with CP and trunk dysfunction.

This dissertation includes previously unpublished co-authored material.

CURRICULUM VITAE

NAME OF AUTHOR: Victor F. Santamaria Gonzalez

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene (US)
University of Salamanca, Salamanca (Spain)
University of Rey Juan Carlos, Madrid (Spain)
International University of Catalunya, Barcelona (Spain)
University of Malaga, Malaga (Spain)
Laboral University, Malaga (Spain)

DEGREES AWARDED:

Doctor of Philosophy, Human Physiology, 2015, University of Oregon
Master of Neuroscience, 2010, University of Salamanca
Master of Neurological Pathology: Physical Therapy and Occupational Therapy Interventions (60 ECTS), 2009, University Rey Juan Carlos
Postgraduate Specialization in Pediatric Physical Therapy, 2008, International University of Catalunya
Bachelor Degree in Physical Therapy, 2007, University of Malaga
Technical Degree in Environmental Chemistry, 2004, Laboral University

AREAS OF SPECIAL INTEREST:

Neurological and Pediatric Pathology
Neurorehabilitation
Neuroscience
Movement Sciences

PROFESSIONAL EXPERIENCE:

Graduate Research Fellow, Department of Human Physiology, University of Oregon, September 2012 – November 2014: Motor Control

Graduate Teaching Fellow, Department of Human Physiology, University of Oregon, January 2014 – March 2014: Motor Control

Graduate Teaching Fellow, Department of Human Physiology, University of Oregon, April 2013 – June 2013: Motor Control

Graduate Teaching Fellow, Department of Human Physiology, University of Oregon, January 2013 – March 2013: Nutrition

Graduate Teaching Fellow, Department of Human Physiology, University of Oregon, April 2012 – June 2012: Motor Control

Pediatric and Neurologic Physical Therapy: 2007-2011

Physical Therapy in Traumatology and Orthopedics: 2007-2008

Physical Therapy in Geriatrics: 2007

Technician in Environmental Chemistry in ANAYCO Laboratories®

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

Membership of Spanish Society of Pediatric Physical Therapy (SEFIP)

Membership of Society for Neuroscience (SFN)

Membership of American Physiological Society (APS)

Membership of International Society for Posture and Gait Research (ISPGR)

GRANTS, AWARDS, AND HONORS:

Eugene Evonuk Award, University of Oregon (UO), March, 2014

Accesit Reward of Investigation. Illustrious Professional College of Physical Therapists of Andalucia (ICPFA), 2010.

PUBLICATIONS:

Santamaria, V., Rachwani, J., Saavedra, S., Woollacott, M. (2014). The impact of segmental trunk support on posture and reaching in children with moderate and severe cerebral palsy II: An electromyographic study. (Submitted)

Santamaria, V., Rachwani, J., Saavedra, S., Woollacott, M. (2014). The impact of segmental trunk support on posture and reaching in children with moderate and severe cerebral palsy I: A kinematic study. (Submitted)

Rachwani, J., Santamaria, V., Saavedra, S., Woollacott, M. (2014). The development of trunk control and its relation to reaching in infancy: A longitudinal study. *Frontiers in Neuroscience. (*Submitted)

Santamaria, V., Rachwani, J., Manselle, W., Saavedra, S., Woollacott, M. (2014). The Impact of Segmental Trunk Support on Posture and Reaching while Sitting in Healthy Adults. *Experimental Brain Research.* (Submitted)

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 (SEFIP)* [Barcelona, Spain].

Rachwani, J., Santamaria, V., Saavedra, S.L., 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 de Fisioterapia,* 39(1), 68-77.

Santamaria, V. (2008). Literature review: XVII Scientific document. Infantile obesity & Pickwick syndrome. *Spanish Society of Pediatric Physical Therapy* (SEFIP) [Barcelona, Spain].

ACKNOWLEDGMENTS

I want to acknowledge my supervisor, mentor and friend, Dr. Marjorie Woollacott for giving me these four wonderful years as a PhD student by her side. Thanks for your guidance, mentorship, and always believing in me.

Thanks to Dr. Anita Christie, who has provided me with valuable mentoring as a graduate teaching fellow during my classes in Motor Control and new concepts in Neurophysiology. Thanks to Dr. Andrew Karduna, who has been integral to my dissertation and whose knowledge in biomechanics has been indispensable for my research. The committee member external to the department, Dr. Gina Biancarosa, not only has offered endless insights about my experimental and statistical design but also has demonstrated to be an outstanding person, taking care of her students in those moments when it was most needed.

I would also like to express my most sincere appreciation to Dr. Anne Shumway-Cock for her valuable professional advice in my research and her warm support. Also, I owe a big *thank you* to Wayne A. Manselle for his technical support, computer programming lessons and friendship, especially during those longer days in the laboratory.

Last but not least, I want to present my gratitude to my lovely wife Jennifer, with whom I have had the pleasure to share my studies in Physical

Therapy, Masters and PhD. Without her unconditional love, company and knowledgeable support, day after day, this doctoral program would have been inevitably more difficult. Thanks for making those arduous days in the lab funnier and this stage of my life unforgettable.

Finally, and from the bottom of my heart, I would like to dedicate the end of these acknowledgments to my exemplar family, my dad Francisco, mum Maria Teresa, and sister Raquel for their incalculable love and support along my days as a student and career in Spain and in the United States of America. Thanks for teaching me how to fight for what I desire in life and how to overcome the most difficult situations.

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 Eugene Evonuk Memorial Graduate Fellowship.

TABLE OF CONTENTS

Chapter Page

LIST OF FIGURES

Figure Page

Figure Page

LIST OF TABLES

Table Page

CHAPTER I

INTRODUCTION

Cerebral palsy (CP) is a heterogeneous syndrome caused by different etiologies, such as cerebrovascular injury, genetic disorders or abnormal neural migration (Govaert, Ramenghi, Taal, de Vries, & Deveber, 2009; Tsutsui, Nagahama, & Mizutani, 1999). Though there are many subtypes of CP, the pathognomonic sign[1] in this neuropathology is the motor disorder resulting from the brain insult. CP is accompanied by neurological and orthopedic dysfunctions that will affect extremity movements, motor coordination, balance and posture. Also, upper limb control is very often severely impaired in children with CP, presenting deterioration in the ability to reach, grasp and manipulate objects. These functional impairments in children with CP have a drastic impact on their social and community interaction during daily life activities (WHO, 2001).

Posture and arm control are acquired at different stages of development, yet these functions are interdependent and each contributes to successful reaching in different positions (Hopkins & Ronnqvist, 2001; Out, Van Soest, Savelsbergh, & Hopkins, 1998). The postural and arm deficits seen in CP during infancy and childhood can have catastrophic consequences that lead to either the lack of or delayed acquisition of high-order motor functions such as writing, speaking, eating or playing whilst sitting.

---

[1] **Pathognomonic:** The most typical clinical feature of a determined pathology.

Even though previous research has described in detail impairments at the level of postural and reaching control in children with CP (Hadders-Algra, van der Fits, Stremmelaar, & Touwen, 1999; Petrarca et al., 2009; van der Heide et al., 2004; van der Heide, Fock, Otten, Stremmelaar, & Hadders-Algra, 2005), the current dissertation expands this research and hypothesizes that there is a critical contribution of biomechanical and neuromuscular control at specific trunk segments. This segmental trunk control underlies the efficient planning and execution of upper limb movements and thus impairments at this level of postural control constrains reaching skills in children diagnosed with CP. An understanding of the contributions of trunk segments to sitting postural control will contribute to better evaluation and rehabilitation strategies in children with moderate and severe cases of CP; and most importantly, to the implementation of therapeutic strategies of trunk control in early stages of life when these infants are acquiring the ability to sit, reach and grasp.

As noted above, there are limited studies in the literature that have thoroughly investigated the interaction between trunk and arm control in children with moderate and severe CP. Also, the research that has explored such motor interaction is restricted, in that it has considered the trunk as a single unit, rather than taking into account the multi-segmental features of the trunk in addition to the increased degrees of freedom (DOF) and wide range of joint motions provided by the upper body and arm in reach-to-grasp tasks.

Hence, this dissertation emphasizes how segmental intrinsic trunk stability influences posture and arm control in reach-to-grasp tasks. The results obtained in the group of studies included in this dissertation are expected to substantially change the paradigm of systematically assessing and treating trunk control as a non-dissociable unit in children with moderate to severe CP.

MOTOR CONTROL THEORIES IN THE STUDY OF NEUROLOGICAL MOVEMENT DISORDERS

A variety of theoretical frameworks have been used as the basis for research in motor control and neurorehabilitation (Shumway-Cook & Woollacott, 2011). In this chapter, the concepts and theoretical approaches which we have used to guide our experimental approach and how movement is perturbed in children with CP from a neurophysiological, biomechanical and functional perspective are highlighted. These concepts justify the importance of research and neurorehabilitative therapies during infancy and childhood, when the central nervous system (CNS) is still developing and neural pathways are being refined through sensory and motor experience obtained through diverse environmental interactions.

THE PROBLEM OF DEGREES OF FREEDOM AND CONTROL OF THE BIOMECHANICS OF MOVEMENT

As stated by the pioneer neurophysiologist Nicholai Bernstein in 1967, in healthy conditions, there are diverse ways to control the joints in order to coordinate the different sub-movements that compose the global trajectory of goal-oriented actions. This concept is defined as the motor equivalence, or the degrees of freedom, problem (Bernstein, 1967).

This degrees of freedom problem is faced by the child learning to control posture and volitional movements, such as vertical sitting and reach-to-grasp tasks. When the goal of a movement requires the participation of a large number of joints, upper limb articulations and the vertebral column, there will be different plausible solutions available to maintain sitting balance in order to accomplish the reaching task. The goal of the task assists to define how the different joints and anatomical segments should be organized and coordinated for an appropriate execution of the movement. These large numbers of DOF provide a physiological redundancy, or abundancy, of joints and motion in which the CNS must find the optimal solution at a kinematic level (Bernstein, 1967).

Research examining the way in which the nervous system solves the degrees of freedom problem suggests that the nervous system plans movements with regard to the end-point kinematics of the anatomical segment involved in the movement. In the case of reaching, the arm trajectory would be determined by the transformation of end-point kinematic properties between the object's location and hand position (end-effector) into coordinated joint angles and angular displacements. Then, through inverse dynamics[2], the accuracy of the kinetic properties of the movement could be regulated along the ongoing motion. An appropriate programmed set of muscle patterns would carry the on-line optimal control of the trajectory, accounting for mass of the anatomical segment, inertia and stiffness through interaction forces and joint torques of the upper limb during the reaching task. Thus, the dynamic properties of the movement would be controlled though pre-programmed and online modes of control during the motor task (Atkeson & Hollerbach, 1985; J. Hollerbach, 1990; M. Hollerbach & Flash, 1982; Wolpert, Ghahramani, & Jordan, 1995).

Humans do not use the full repertoire of possible trajectories due to the infinite number of trajectories available to perform movements. When examining reaching movements in healthy adults, research shows that there are invariant kinematic parameters that support the internal representation of movements in the CNS. Research on reaching tasks has demonstrated some of these invariant features in arm movements like straight paths, single-peaked trajectories and bell-shaped velocity profiles that are independent of initial and final hand positions in the workspace. However, velocity profiles and joint angular

---

[2] **Inverse Dynamics:** Method for computing forces and torques based on the properties of the motion, or kinematics.

positions of upper limbs are indeed variable depending on the dynamic constraints of the task and endpoint kinematics of the hand (Atkeson & Hollerbach, 1985; Hollerbach & Flash, 1982). Additionally, from an optimal control approach[3] based on kinematics (minimum jerk model) or kinetics (minimum torque change model), Wolpert and colleagues (1995) demonstrated that invariance in arm trajectory is principally based on geometrical time-based kinematic properties of motion: positions and velocity/acceleration profiles.

THE DYNAMIC SYSTEM THEORY

This theoretical approach proposes that complex systems are designed to search for a situation of stability and equilibrium at low energy cost through self-organizing processes (Kugler et al, 1980). According to this principle, the CNS has to solve the problem of motor coordination in a system with a redundant number of DOF created by the features of the movement, muscles and joints (Bernstein, 1967; Thelen, 1995). This theory proposes that the emergence and control of new motor skills in infants and children would be the result of the interaction between three main elements: neural maturation, cognitive development and interactions with a changing environment. During the acquisition of motor skills, often called developmental motor milestones, variability in motor behavior represents an intermediate step in which the CNS is

---

[3] **Optimal control approach:** Cost functions evaluate the performance of the system under control. This concept can be applied to explain the invariant kinematic features of arm trajectories.

organizing and coordinating the large number of DOF included in movements. The acquisition of such motor milestones as central commands would be driven by the transition from a low level of organization of motor patterns to a higher level of organized motor sequences. In this latter stage, these DOF would be mastered and reduced for efficiently acquiring the goal of the motor action at low energy cost (Bernstein, 1967; Thelen, 1988). Additionally, this motor progression would be characterized by the ability to organize and coordinate movements across the different spatial frames of reference between the organism and the environment (Feldman & Levin, 995).

According to the Dynamic Systems Theory, in motor skill acquisition there would be an interaction between intrinsic factors (e.g. muscle strength, body weight, postural support, infant's mood and brain development) and external factors (e.g. task requirements and environmental context) in pursuance of a situation of equilibrium. Therefore, the organism is in a continuous state of change, stability and instability in which environmental factors principally affect sensorimotor learning and modulate motor behavior (Thelen, 1988, 1995). Nonetheless, this approach does not consider the relevance of the endogenous ontogenesis[4] of living organisms, which is driven by pre-programmed, but dynamic, genetic codes and molecular expression (Edelman, 1987; Evans, 1998; Hadders-Algra, 2008).

---

[4] **Ontogeny:** Development of an organism from fertilization to its most mature morphology. This term should be differentiated from phylogeny, which refers to the evolutionary aspect of species.

THE NEURONAL GROUP SELECTION THEORY

This theoretical approach in motor control highlights the essential role of genetics, in addition to body-environment interactions, in the development of complex motor behavior and in neurological disruption associated with developmental pathology, such as in children with CP (Hadders-Algra, 2008).

Within the genotype, the non-coding DNA[5] (58% of the total DNA sequence) is where the genetic control elements (promoters, enhancers and genetic switches) necessary for ontogenesis are located (Evans, 1998; Gabor-Mikolos & Rubin, 1996). All these elements are of extreme importance in the expression or silencing of the genetic code during development, ecological interaction, and pathological events. This complex process in which the genetic expression, or cellular phenotype, can be modified without alteration of the nucleotide sequence is called *epigenetics* (Bird, 2007; Jones & Takai, 2001).

Knowing the relevant role of genetics, Gerald Edelman theorized the "Neural Darwinism: Neuronal Group Selection Theory." This theory has three main aspects. First, the anatomical networks and connectivity in the brain occur during development through explicit neurochemical and neuromechanical events that are pre-programmed and modified through genetics and epigenetics, respectively. This sequence of events generates a primary repertoire of variable neural structures. Secondly, these diverse anatomical structures and circuitry are

---

[5] **Noncoding DNA**: DNA sequence or sequences that do not encode protein sequences. Long time ago, it was defined as "junk DNA" because its function was, and remains, unknown.

then modified through epigenetics during postnatal behavioral experience, creating a secondary repertoire or variability. The final area of this theory, "*reentry*", claims that specific neuronal groups carry self-organizing processes that in turn are derived from the stimuli and actions that result as a response of real-world interactions (Edelman, 1987). Therefore, the ensemble of genetically pre-determined, but modifiable, cortical and sub-cortical circuits are dynamically organized and established through experience and environmental interactions (Changeux, 1997; Hadders-Algra, 2008; Polleux, 2005).

The CNS starts to stabilize and reach its complete adult configuration at the approximate age of 40 years; nonetheless, before this point is achieved, there are two principal phases during development and motor acquisition. In the first stage, in fetal life and early infancy, once the neural networks are established and become functional, the subject is characterized by a general motor repertoire called *primary variability*. In the second stage, the CNS utilizes afferent information resulting from behavior and experience and consequently shaping the CNS and adapting motor actions to environmental constraints. This stage, named *secondary variability*, is distinguished by the selection of precise motor strategies based on trial and error practice (Hadders-Algra, 2008). The selection, organization and learning of the motor strategy that best fits the ecological problem occur at two different neural levels: 1) Strength of synaptic and neural connectivity between inter- and intra-neuronal groups; and 2) temporospatial tuning of motor output. In terms of neuroanatomical structures, the basal ganglia are key structures in motor strategy selection during motor learning. Also, the cerebellum is a key component in specifying temporal and quantitative parameters of motor outputs. Lastly, current research has demonstrated that motor thalamus[6] and thalamic sensorimotor connectivity are essential in motor learning, maintaining posture and inter-coordinating general movements (Bosch-Bouju, Hyland, & Parr-Brownlie, 2013; Di Prisco, 1984; Graybiel, 2005; Hadders-Algra, Brogren, & Forssberg, 1996; Hadders-Algra, 2008; Scheck, Boyd, & Rose, 2012).

The aforementioned theories provide a possible explanation for the stereotypical, disorganized and restricted repertoire of motor patterns observed in children with CP. According to them, the study of motor control in pathological conditions of the CNS during development should include the environment surrounding the child, the type of motor task being investigated, numbers of DOF involved in the movement, neural insult typology, and age at which the CNS lesion occurs. Thus, the investigated experimental paradigm simulates an ecological context where the participants are sitting and have to reach in a self-paced manner for an object while an external device restricts the number of DOF to be controlled by the trunk during reaching. Furthermore, in

---

[6] **Motor Thalamus:** It is formed by ventral anterior and ventral lateral thalamic nuclei. It encompasses thalamic nuclei placed between motor cortex and the two subcortical networks: basal ganglia and cerebellum.

the set of experiments, healthy adults were recruited for studying how a non-pathological and mature CNS would respond to such an experimental setup. Then, children with and without upright sitting abilities as a result of trunk dysfunction were recruited to investigate the impact of the trunk on postural and reaching control while manipulating the number of trunk segments involved in postural support during the reach.

NEUROANATOMICAL AND NEUROPHYSIOLOGICAL OVERVIEW OF REACH-TO-GRASP TASKS AND POSTURE

SENSORY SYSTEMS

Neural Coordination and Biomechanical Control of Reaching and Grasping

The performance of reach-to-grasp tasks has four distinct phases that need to be considered. The first, l*ocating a target or visual regard*, requires the coordination between eye and hand movements. Second, *arm transport*, or the *reaching component*, is the transportation of the arm and hand through space up to the target. Third, the g*rasping component* is defined as hand orientation, grip formation and finger positioning. Lastly, *in-hand manipulation skills* are those dexterous movements of hand and fingers (Shumway-Cook & Woollacott, 2011).

Depending on the goal of the task, the motor control and biomechanical properties of the upper limb motion will vary. For instance, in pointing targets the arm is controlled as a unit; whereas in a reach-to-grasp action, the arm carries out two separate phases, the transport phase and the hand-grasping phase[7]. In terms of neural control, this means that hand and arm are activated separately but simultaneously coordinated as part of a unique motor plan.

A kinematic analysis of the upper extremity using velocity profiles and movement duration in healthy individuals shows that this coordination differs depending upon the goal of the reaching task. A reach that involves grasping an object shows longer movement duration than pointing to a target. When grasp preparation is needed, the acceleration of the reach is shorter than the deceleration phase, in comparison to a pointing task, in which the opposite effect is observed. Also, in a grasping-throwing task, the global duration of the movement is shorter than grasping and fitting an object in a small box. These series of observations show the influence of environmental and task constraints on the kinematic parameters of the reach movement (Marteniuk et al., 1987; Jeannerod, 1990).

Although the neural control of reaching and grasping is partially independent, the transport phase of the arm has to be coordinated with the shaping phase of the hand to ensure the coupling between arm displacement and successful grasping of the object. This coordination can be measured through fixed kinematic parameters, such as the ratio of maximum grip aperture to the

---

[7] **Reaching phases:** Overall, reaching can be classified in two main phases. The first is arm transport, which covers the displacement of the upper extremity through the space. The second part is the grasping component and it is related to hand orientation and finger positioning.

total movement time of the hand transport (Jeannerod, 1996; Wallace et al., 1990). Maximum grip aperture occurs at 75-80% of the movement time of the reach. It remains relatively invariant across conditions, like different initial postures of the fingers before reaching including those seen in neurological impairments such as CP. Experiments focusing on perturbation of the transport phase, by displacing the objects during arm displacement, and the formation of grip aperture, by changing the object's size at the moment of the grasping, showed that the two phases modulate each other. This fact indicates that these two motor stages are coupled in time, are dynamic and are not characterized by a stereotyped structural relationship (Jeannerod, 1996; Paulignan et al., 1990).

Another environmental constraint that changes the quality of the reaching trajectory is when the arm has to cross the midline in order to grasp or point at a target. In this type of reaching, if an object is placed in the contralateral visual field, the reaching performance becomes slower and less accurate. Otherwise, when the target is located in the same visual field of the reaching arm, these reaches are more accurate. In comparison to contralateral reaches, ipsilateral reaching is characterized by shorter latency, greater maximum velocity, and faster arm movements (Fisk & Goodale, 1985).

Sensorimotor Transformation and Planning of Reaching Movements

Neurons within the retinotopically organized visual receptive field[8] of primary and secondary visual cortex will detect the spatial location of the target (Goesaert, Van Baelen, Spileers, Wagemans, & Op de Beeck, 2014). There are two main visual pathways involved in reach-to-grasp tasks. The dorsal projections, or dorsal visual stream[9], inform the nervous system about the position or location of the object's features: position and orientation. Also, the ventral visual projections, or ventral visual stream[10], provide input about the perception of the object: the identification and recognition of what is being reached and storage in long-term memory (Goodale & Milner, 1992; Goodale et al., 1991).

In the proactive or feedforward control of reaching both visual and somatosensory inputs, in addition to inputs regarding the initial postural orientation, anticipate, conduct and correct the direction of the arm motion while reaching (Jeannerod, 1988; Zimmerman, Ruud, Meulenbroak, & de Lange, 2012). The sensory inputs used for localizing the position of the body and the object to be reached are presented in different coordinate frames: vision in an eye-centered set of coordinates, hearing in a head-centered set of coordinates and somatosensation in a body-centered set of coordinates. All these frames of

---

[8] **Retinal receptive field or retinotopy**: It is the retinal response area while a visual stimulus is presented in the visual field

[9] **Dorsal Stream:** It goes from V1, passing through V2, to V6 (or dorsomedial area) and V5 (or MT), and finally to the posterior parietal cortex.

[10] **Ventral Stream:** It goes from V1, passing through V4, and then to inferior temporal cortex.

reference are used to build up the sequence of motor commands that will execute the movement. The brain normally can compute this sensorimotor transformation according to an eye-centered coordinate system (displacement vector) or a body-centered coordinate system (position vector). Neurons in the posterior parietal cortex (PPC) are activated during these sensory and motor-related events necessary for the sensorimotor transformation of the reaching and grasping tasks. Therefore, the PPC contributes to both the planning and control of arm movements. The strongest neural activity during reaching occurs in the superior parietal lobe, including Brodmann's area 5 and the parietal reach region (PRR), also called the medial intraparietal cortex (MIP). The PRR neurons encode the current position of the hand and the target in the Eye-Centered Coordinate system. They also encode reach-related variables in the Limb-Centered Coordinate system and in the Eye and Limb centered coordinate systems together. Evidence suggests that the PRR transforms the spatial information between the two different frames. Also, within the parietal cortex, the lateral intraparietal cortex (LIP) contributes to sensory attentional processing for reaching an object placed within the current sensorimotor map of the individual, when the target is reachable in extrapersonal space (Bruneo & Andersen, 2006) (Galletti, Kutz, Gamberini, Breveglieri, & Fattori, 2003).

In non-human primates, the internal intentional maps that plan movements are located in the PPC. The LIP is specialized for planning saccades, needed for spatial target location. The PRR plans the sequence of the reaching phase. The medial superior temporal region (MST) plans smooth pursuit eye movements[11]. The anterior intraparietal area (AIP) mainly plans the grasping phase and collaborates significantly in the sensorimotor transformation of the reaching task.

In this regard, a study in monkeys demonstrated how a reversible lesion in the AIP generated deficits in hand shaping before grasping (Andersen and Bruneo, 2002). This same damage is also observed in humans with abnormal activity of the PPC region like vascular damage of the inferior division of the posterior cerebral artery (Main, Paxinos, & Voss, 2008). Patients with damage of this area present with optic ataxia that is characterized by deficits of reaching direction, finger positioning and hand orientation. These motor deficits are also very typical in cases of CP.

A broader injury of the parietal lobe leads to the inability to use information about size, shape and location of the objects to program the reaching task. Nonetheless, this same information can be used for identifying the objects through the ventral visual stream. Also, damage of the superior parietal lobe generates problems with scaling the maximum grip aperture to the size of the object to be grasped. In reach to grasp tasks, the coordination between cerebral

---

[11] **Smooth pursuit eye movements:** This eye movement represents the ability to fluently pursue an object without the involvement of saccades (automatic rapid eye movements). This visuomotor property allows to shifting gaze and following moving objects with the eyes.

areas during a precision grip is required. This has been demonstrated through neuroimaging studies, which show a coordinated activation of AIP, premotor, sensory and primary motor cortexes, and posterior parietal cortex in reach to grasp tasks (Binfofski et al., 1998; Castiello, 2005; Goodale & Milner, 1992).

Special attention has been paid to the cingulate cortex, anterior and middle areas, in motor planning and decision making processes. Specifically, in reaching and grasping, the motor program has to be selected in accordance with not only intrinsic features of the object but also based on motor goals that correspond to the meaning and purpose of the object to be grasped. In this regard, the ipsilateral side of the middle frontal gyrus (included in the dorsal premotor cortex) to the arm being used in the reach is importantly involved in motor planning of the grasping task (Begliomini et al., 2014).

Essential sensory information in action-perception is also sent from the cerebellum, basal ganglia and sensorial ascending fibers from the spinal cord to premotor and primary motor and sensory cortexes via the thalamus (ventrolateral nucleus and ventral anterior nucleus, respectively). White matter injury, including corticospinal, interhemispheric fibers and thalamic radiations during maturation of the CNS are of special interest in CP, since this group of axons is commonly affected regardless of the clinical subtype of CP. Damage of these networks, consequently leads to disrupted perception and action (Guillery, 2003; Kalaska & Rizzolatti, 2013; Scheck et al., 2012).

Visual Contribution to Reach and Grasp

Visual feedback is used for the attainment of final accuracy in the reach. The visual input about the object's features programs in anticipation the forces needed in precision grip tasks. Also, vision and somatosensation together update the visual and proprioceptive maps of the body for accurately programming the reach. For example, subjects who do not see their hand before reaching for a target show more errors. Some researchers propose that using a particular thumb-hand position could be a strategy for providing visual feedback regarding the end point of the limb (Wing & Frazer, 1983). Also, reaches associated with visual feedback present longer duration than those without visual feedback.

Surprisingly, monkeys with visual cortex lesions are able to reach objects moving in space presented within their visual field; however, these reaches are not accurately performed. It was hypothesized that the superior colliculus is one of the main neural structures responsible for this residual target location in reaching behaviors (Humprhey & Weiskrantz, 1969). Additionally, research in humans with visual-cortex lesions has showed that subjects can perform pointing tasks (though with constant errors) if the target is within their blind visual field. They either overshot the target when they were 30 degrees within the midline or undershot it if they were 30 degrees beyond the midline (Perenin & Jeannerod, 1975; Weiskrantz et al., 1974).

Somatosensory Contributions to Reach and Grasp

Researchers have shown that vision is important, but it is not the only source of sensory information involved in the modulation of precise arm movements. Vision compensates for a lack of proprioceptive integration, for example. A study in deafferented[12] monkeys showed that the recovery of reaching accuracy after motor practice showed specific transitions during the functional improvement. At the beginning, the monkeys swept the objects over the floor, then the reaching evolved to a primitive grasp with 4 fingers, and finally the grasp became a crude pincer task (Taub & Berman, 1968). Other research performed on monkeys that learned a pointing task prior to being deafferented showed that single-joint pointing movements without vision are reasonably accurate. The authors concluded that once a motor task has been learned, the central motor program is not substantially affected by the lack of kinesthetic feedback (Polit & Bizzi, 1979). In this regard, investigations on humans with severe neuropathy have shown similar results, indicating that simple motor tasks can be performed with no visual input without a substantial motor impoverishment. However, in drawing, tapping actions and repetition of motor sequences, when the participants were instructed to repeat these actions without the support of vision, the performance significantly deteriorated. For these reasons, the somatosensory information is assumed not to be essential in

---

[12] **Deafferentation:** Interruption of peripheral sensory information.

simple and non-repetitive movements. Nonetheless, this sensory modality significantly impacts planning and on-line corrections of repetitive and complex multi-joint motor activities (Jeannerod, 1990).

In terms of reaching control through peripheral somatosensory feedback, research has demonstrated that joint receptors are important for position sense and mainly activated at the extremes of the range of joint motion instead of at midpositions (Jeannerod, 1990). A significant experiment was crucial in understanding the functional role of muscle spindles in both sensing arm position and antagonistic movements. Vibration was applied to the muscle in order to stimulate the Ia fibers, creating the illusion that the muscle was stretched. In this way, the vibration generated a subsequent sensation of movement in the opposite direction. For instance, biceps vibration would be associated with the sensation of elbow extension (Goodwin, 1972).

The cutaneous afferents contribute significantly to position sense as well. The mechanoreceptors of the glabrous area of the hand are highly activated in isotonic movements of the fingers (Hulliger et al., 1979). Investigations point out the relevance of cutaneous information coming from the mechanoreceptors for modulating grip forces in grasping actions. When grasping slippery objects, the stimulation of these cutaneous afferents increases the muscle activity of fingers and decreases the muscle activation of shoulder and elbow so that the acceleration of the arm is sufficiently slow for prioritizing sophisticated control of hand movements. Additionally, when the fingers are anesthetized in order to decrease the afferent feedback provided by cutaneous receptors, the subjects tended to increase the grip forces as a compensatory motor response. Moreover, the coordination between the grip and load forces was lost in the anesthetized experimental group, while in the control group grip force was finely modulated in phase with the load force (Witney et al., 2004; Randall et al., 1992). Other experiments have shown how in patients with severe polysensory neuropathy, the grip force generated during the holding-phase of the grasp declined significantly in an interval of 20-30 seconds compared to healthy controls, and some subjects even dropped the object at least once (Augurelle et al., 2003; Monzee et al., 2003; Witney et al., 2004). Altogether, this information suggests that somatosensory afferents are critical in the control of hand movements, such as holding objects, applying isometric forces, modulation of grip aperture, finger positioning during grasping and in-hand manipulation of objects.

In children with CP, the neural damage is localized within the CNS and thus the neural processing and perception of visual and somatosensory peripheral information is disrupted. However, the consequences of this CNS damage will also be reflected in the sensorimotor processing of movements by the peripheral nervous system, affecting the online control of reaching and fine modulation of grasping tasks.

MOTOR SYSTEMS

Motor Execution: Primary Motor Cortex

Research examining the function of primary motor cortex using intracortical stimulation has shown that the representation of upper limb muscles, like the middle head of the deltoids and the extensor carpi radialis, overlaps across cortical motor areas (Humphrey and Tanji, 1991). This cortical overlapping suggests that movement is not simply controlled through independent muscles but also as synergistic muscle sequences. The activity of primary motor neurons also changes 100ms or more before the movement is produced. In fine motor grasping, the fast and direct corticomotoneuronal connections with alpha-motor neurons will allow the precise control of individual or multiple joints.

Another important functional property of the primary motor cortex that affects arm control is that some of these cortical motor neurons receive tactile and propioceptive information from the muscles they innervate. This information is sent from other sensory cortical areas to the motor cortex via transcortical circuits. These direct intracortical connections between motor and sensory cortexes provide fast on-line modulation of voluntary actions, like arm trajectories while reaching for an object (Kalaska & Rizzolatti, 2013).

At the primary motor cortex level, the maximum firing rate of motor neurons is correlated with particular movement directions and joint displacements. Single-cell recordings in primary motor cortex of monkeys showed that during the flexion of the wrist, these neurons varied their activation rate depending on the force applied along the joint displacement. Also, the baseline activity of some primary motor neurons changed when the animal was waiting for a light that indicated the beginning of the movement in an instructed delay task (see below). This pattern of activation was identified as preparatory set (Evarts, 1966; Evarts and Tanji, 1976). Research also pinpoints the idea that movement direction is coded by the net action of a large population of motor neurons, as was observed in a study conducted in monkeys that had to move a joystick toward eight possible visual targets in the horizontal plane with a common starting position. Interestingly, the vector representation obtained from the firing rate of each neuronal population to a specific movement coincided closely with the direction of the arm movement. Additionally, this directionality strongly depended on the forces generated for displacing the limb. If the load opposed the cell's preferred direction, there was an increase in the firing rate; but if the load followed the preferred direction of the neuronal population, the firing rate decreased (Georgopolus et al., 1982).

All this evidence leads one to conclude that the primary motor cortex is mainly involved in controlling explicit motor parameters, such us the direction and force that grade the kinematic and also kinetic properties of upper limb movements. With regard to motor control in children with CP, the contributions of motor cortex to reaching is essential to consider because the pyramidal tract will be one of the most common pathways disrupted in the descending motor system (Scheck et al., 2012; Sterr, Dean, Szameitat, Conforto, & Shen, 2014).

Brain Areas Contributing to Motor Planning and Coordination: Premotor Cortex

The premotor areas of the cortex code more intricate properties of movements. Although, some of the efferent axons from the premotor cortices overlap with those coming from the primary motor cortex at some areas of the spinal cord, lesions of the premotor brain areas produce more complex functional impairments. For instance, studies in monkeys with a lesion of the supplementary motor cortex show that animals cannot coordinate the bimanual reach and hand manipulation for retrieving a peanut placed inside of a crystal box (Brinkman, 1984; Krauker & Ghez, 2000). Motor planning and coordination in bimanual reaches and hand manipulation are generally impaired in CP, even in mild cases of CP like hemiplegia (Charles & Gordon, 2006).

Self-initiated motor tasks require the activation of the supplementary motor cortex. The lateral dorsal premotor cortex is concerned with delayed actions (executed later and based on external cues) and the lateral ventral premotor cortex is concerned with grasping (it shapes the hand according to the physical aspect of the objects to grasp).

Research applying EEG over medial motor regions has shown a negative potential, referred to as the preparatory or Bereitschaft potential, that occurs 1 second before the movement is executed. Studies measuring regional cerebral blood-flow, after injecting a short-lived radioactive tracer into the bloodstream, while subjects performed simple, complex and imagined tasks demonstrated that repeated forceful finger flexion on a spring-loaded movable cylinder only recruited contralateral sensorimotor hand-control cerebral regions; whereas the execution of a complex sequence of finger movements required the supplementary motor area. Interestingly, when this sequence was only imagined, there was a bilateral activation of the anterior area of the supplementary motor cortex. This pre-supplementary motor area provides the main input to the supplementary motor cortex and it shows a high pattern of activation while learning motor sequences. Therefore, the medial motor cortex, mainly supplementary and pre-supplementary motor areas, is involved not only in motor planning but also in learning complex motor sequences (Krauker & Ghez, 2000).

Additionally, the role of the supplementary motor cortex in internal representation of reaching movements has also been studied in single-cell recordings of motor and premotor cortex in monkeys during an instructed-delay reaching task[13]. The primary motor cortex cells were active either when the task was learned prior to the visual cue or when it was just guided by the visual panels. On the other hand, the neurons of the lateral premotor area just fired when the external visual cues were present and the neurons of the supplementary motor cortex were active only in trained reaching tasks. Furthermore, these supplementary motor neurons are usually activated in combinations of specific motor sequences, like pushing after turning a handle. Thus, the supplementary motor area is assumed to participate in movement preparation in the absence of external cues (Mushiake et al., 1991)(Rizzolatti & Kalaska, 2013).

The lateral premotor cortices are strongly related to the learning of motor tasks guided by environmental visual or auditory stimuli. An experiment in monkeys practicing an instructed-delay motor task showed that the dorsal lateral premotor neurons discharged when the task was associated with a particular sensory event (associative learning). Interestingly, the anticipatory cue did not indicate any spatial direction that the arm had to follow for reaching the target. After bi-hemispheric removal of this area, the monkey was retrained in the same reaching task in association with the same visual cues. The results indicated that the animals did not reacquire associative learning, but they recovered the ability to voluntarily displace the arm to the target again (Weinrich & Wise, 1982).

---

[13] **Instructed-delay reaching task:** Motor sequence of arm and hand that can be executed after prior learning of the task or externally cued

In motor learning, the intensity of the neural activation of premotor and primary motor neurons is not always the same over time; it changes progressively when the movement is learned. Research on manual tasks in monkeys has demonstrated an interchange of neural information across motor cortices. When the task is being learned, the supplementary motor cortex is very active, but this level of neural activation disappears after 12 months of overtraining, and just the primary motor cortex is activated. However, an experimental injury of the motor cortex and re-training of the task during 22 days post-lesion again recruits the supplementary motor cortex. This evidence pinpoints the role of the supplementary motor area not only in learning but also in re-learning motor sequences (Roland et al., 1980. Krauker & Ghez, 2000).

Generally, it is understood that the visuomotor transformations for grasping and reaching involve two different neural pathways. Reaching is controlled by a dorso-dorsal neural stream, that is, one that connects the superior parieto-occipital extrastriate area with the dorsal premotor area. Some connections of this circuit are direct and others include the medial parieto-frontal network, relying on the medial intraparietal area at the boundaries with areaV6A (anterior bank of parieto-occipital sulcus) before reaching the dorsal premotor cortex. This neural network transforms visual information about the location of objects in extrapersonal space into the movement directions and motor commands for controlling the arm. Grasping is controlled via the lateral ventrodorsal stream that connects the dorsal extrastriate cortex (V2-V5) to the ventral and also dorsal premotor cortexes passing through the anterior intraparietal area (AIP). New evidence suggests the specific participation of the inferior frontal gyrus and the dorsal part of the middle frontal gyrus at the boundaries of the pre-central sulcus. This system transforms visual information about the properties of the object into commands for effective grasping (Begliomini et al., 2014) (Krauker & Ghez, 2000).

There is not a very clear distinction between perception and action in the premotor cortices and some areas of the parietal lobe. In grasping, the AIP area codes the type of object for the entire grasp in visual coordinates, whereas areas of the premotor cortex just code parts of the grasp sequence according to body coordinates (Castiello, 2005; Andersen & Bruneo, 2002). The parietal area 5 computes the direction of the reach, while some neurons of the lateral ventral premotor cortex are mainly active during the transport phase of the reach before grasping the object. These cells fire during different patterns of hand shaping such as, precision grips, power grips or swiping movements. Therefore, the lateral ventral premotor cortex organizes grasping guided by visual information about the object shape; however, arm displacement would be controlled by area 5 of the posterior parietal cortex.

Behavioral and neuroanatomical research has demonstrated the independence of reaching and grasping actions as well. Newborns are able to reach for a moving object when they are only 1 week old; however, they do not have the ability to grasp at this time. This motor ability appears at 10-22 weeks (Bruner and Koslowski, 1972). In monkeys, the grasp component appears around 8 months of age, which coincides with the maturation of the neural connections between the pyramidal tract and the spinal motor neurons (Kuypers, 1962). An injury of the corticospinal tract alters the individual control of fingers, but it does not severely disrupt the synergistic control of fingers for power grips. For instance, children with CP commonly display morphofunctional disruption of corticospinal axons and also present grasping problems without severe impairments of the reaching component. In humans, this suggests that other sub-cortical structures, like the red nucleus and the reticular formation, may have significant roles in controlling the more proximal muscles involved in reach-to-grasp tasks. Additionally, some authors have demonstrated the specificity of neurons in the primary motor cortex in reaching and grasping behaviors (Lemon et al., 1986; Muir & Lemon, 1983; Rizolatti and Kalaska, 2013). Neurons that fire in precision grip tasks with heavy and light forces do not fire intensively in a power grip task, where the whole hand participates in the movement. Also, these neurons present a short-latency burst onset of 11ms before the muscle activation that indicates a monosynaptic connection with the motor neuron pool (Lemon et al., 1986; Muir & Lemon, 1983).

Modulation of Movement Parameters: Subcortical Structures

The cerebellum has an important role in the control of reach-to-grasp tasks as well as in posture; however, these aspects are discussed in the next section (see: *Sub-cortical Control of Postural Control in Reaching and Grasping*).

Basal ganglia are composed by (1) striatum (caudate nucleus, putamen and nucleus accumbens), (2) subthalamic nucleus, (3) globus pallidus (internal and external portions) and (4) substantia nigra (pars compacta and pars reticulata). Even though there is no clear relationship between basal ganglia and reaching control, two main structures, the striatum and subthalamic nucleus, should be taken into account.

In general, striatum cells seem to participate in facilitating and scaling cortically initiated movements. Specifically, neurons in the caudate nucleus and anterior part of the putamen, areas that receive inputs from the premotor and prefrontal cortexes, fire during movement preparation. This neural activity is time locked to instructional cues: "whether to move" (set) or "to move" (go). This fact could explain in part the delay in programming and executing internally triggered movements in hypokinetic rigid syndromes, like Parkinson's disease. We should recall, that some effects of hypokinesia such as bradykinesia, dyskinesia, dystonia and dysarthria are frequently observed in children with CP.

In the subthalamic nucleus, 90% of the neurons fire 50ms prior to the movement onset. Additionally, during movements, the majority of these neurons increase their activity with respect to the direction of the movement. This observation could mean that this area participates in both triggering and modulating the trajectory of a self-initiated goal-oriented reach.

The internal portion of the globus pallidus is the main source of output related to limb movements. It receives inputs from the subthalamic nucleus (excitatory) and striatum (inhibitory). In addition, the subthalamic nucleus receives inputs from the frontal lobe and the striatum from almost all the cerebral cortex. The internal part of the globus pallidus show activity with limb-movement direction not related to joint position, amplitude, velocity, or force production. During reaching, around 25% of the neurons are active in movement preparation and 50% of the neurons fire during movements between EMG onset and movement onset.

Finally, the neurons of the substantia nigra pars compacta are important in terms of motor learning. These cells do not respond to specific parameters of reaching; otherwise, they are active in significant behaviors associated with rewards and instructional cues during motor tasks. This motor learning is through long-term potentiation and depression of the striatal neurons by dopaminergic connections (Mink, 2008).

POSTURAL CONTROL IN REACHING AND GRASPING

Cortical Control of Postural Control in Reaching and Grasping

The supplementary motor area has been studied regarding its influence on reaching and posture (Viallet et al., 1995). Three different conditions were investigated in a group of subjects sitting with flexed elbow and a weight placed on the wrist. In the first condition, subjects removed the weight by themselves (active form). In the second condition, the experimenter took away the load (passive form). And in a third condition, the subjects removed the load with an electromechanical device.

The results showed that in the active condition, the biceps was inhibited concurrently when the weight was lifted without any delay. However, the participants did not keep the static elbow flexion in the other conditions, either when the tester lifted the load or when the subjects used the electromechanical device. Applying a similar methodology, authors have investigated the control of bimanual tasks in patients with damage in the supplementary motor cortex or with callosal section. They found that healthy individuals and subjects with callosal section were able to keep the elbow statically flexed when lifting the load, showing preparatory muscle adjustments of the postural arm during reaching and lifting an object that was on the flexed arm. However, subjects with injured supplementary motor cortex did not maintain the arm flexed: the postural arm moved upward when the object was lifted from it by the other arm.

The conclusion was that the contralateral supplementary motor cortex, in association with premotor/motor cortices, activates the phasic anticipatory postural adjustments to ensure postural maintenance. On the other hand, the primary motor cortex deals with voluntary movements, and indirectly through collateral axons, it activates preselected sub-neural circuits for controlling the associated postural adjustments (Hugon, Massion & Wiesendanger, 1982; Viallet et al., 1995).

Sub-cortical Control of Postural Control in Reaching and Grasping

In addition to the volitional modulation of posture via cortical regions, the subcortical system also provides a sophisticated control of arm and posture.

One aspect of postural control, the automatic steady-state and reactive postural and head control are principally commanded by the medial descending tracts. Of these tracts, the reticulospinal tract is most related to postural activity in volitional reaching. The pontine reticular formation is composed by the reticularis pontis oralis and reticularis pontis caudalis, and leads to the medial reticulospinal system that activates axial extensor muscles. The medullary reticular formation is the origin of the lateral reticulospinal system. It makes monosynaptic synapses and inhibits the neck and back extensors; whilst providing polysynaptic excitation to the flexors. Recent studies in cats highlight the role of the pontomedullary reticular formation in eliciting ipsi- and contralateral complex patterns of postural activity in voluntary reaching movements (Schepens & Drew, 2006; Shinoda, Sugiuchi, Izawa, & Hata, 2006).

Anticipatory posture control, or pro-active balance, is a critical factor in skillful and accurate reaches. When animals are trained to perform a leg-lifting task of one of the forelegs (equivalent to upward reaches in a human, for instance), they activate postural muscles of the other three legs before lifting the trained paw. Interestingly, the experimental excitation of the forelimb area of the motor cortex as well as the red nucleus provokes this feedforward response in postural muscles (Massion, 1979). Noteworthy research in postural control has already shown that humans display the same anticipatory postural reactions and stereotyped muscle synergies in the hip and legs while generating quick arm elevations (Belenkii, Gurfinkel, & Paltsev, 1967; Cordo & Nashner, 1982). These groups of postural synergies are dynamic and adaptable to task and environmental constraints (Hall, Brauer, Horak, & Hodges, 2010; Ting & Macpherson, 2005).

Within the brainstem, the peduncopontine tegmental nucleus is a heterogeneous area of the dorsal tegmentum that also influences postural control and automatic movement patterns. This nucleus receives inputs from the motor cortex, and it sends reciprocal axons to the basal ganglia (subthalamic nucleus, internal portion of globus pallidus and substantia nigra), to the thalamus and hypothalamus and it is connected to other areas of the brainstem (medial pontomedullary reticular formation). The peduncopontine tegmental nucleus also sends axons to spinal motor neurons. Functionally, this tegmental area is related to arousal and behavioral state as well as muscle tone (Benarroch, 2013). The arousal state is a basis component to consider in spastic and hypertonic neuromotor disorders. Some subtypes of CP show a clear influence of emotional states on the control of movement.

The cerebellum is a key element in the temporal organization of postural reactions. This structure participates in the scaling process and activation frequency of anticipatory postural adjustments (APAs) (Cordo & Nashner, 1982; Horak et al., 1989). Studies on reaching and posture in patients with cerebellar dysfunction demonstrate that even though these patients had well-learned APAs, they could not scale the timing of these anticipatory postural adjustments to changing task demands. The APA response was poorly timed and characterized by earlier muscle activations compared to healthy subjects. Also, if the patients did not present APAs in tasks that were not practiced before the cerebellar lesion, they did not display feedforward modes of movement control (Diedrichsenet al., 2005).

With respect to cerebellar control of reaching, the primary motor cortex sends a corollary discharge to the intermediate lobe of the cerebellum as an efference copy of the motor plan. Around 93% of the output neurons of cerebellum are more active while reaching out and grasping than when gripping

(Castiello, 2005; Gibson et al., 1994). However, research has shown that damage of the dentate nucleus or its afferents is associated with disruption in scaling force and computing the time duration of the grip (Fellows, Ernst, Schawrz, Topper, & Noth, 2001). In pathological conditions this is seen in comparing hemiparetic subjects who can anticipate grip forces, to patients with cerebellar damage, who cannot organize predictive responses while gripping (Monzee & Smith, 2004; Babin-Ratte et al., 1999; Boudreau and Smith, 2001; Wiesendanger & Serrien, 2001; Witney et al, 2004). Recent research has shown that patients with cerebellar ataxia present a specific type of disrupted timing of arm muscles (intra-limb ataxia) in pre-planned finger movements, although the sequence of muscle recruitment remained intact (Bruttini et al., 2014).

CEREBRAL PALSY

HISTORICAL PERSPECTIVE OF CEREBRAL PALSY

Throughout history, documentation about neurological disorders has been presented across cultures, like the ancient Mesopotamian, Indian Ayurvedic scripts, Renaissance Italian and Greek times. In these ancient times, CP was explained by supernatural causes (Aisen et al., 2011). Some historical files already described the presence of neuromotor signs present in human diseases. For instance, Hippocrates documented the clinical motor outcomes of epilepsy in a child with hemiplegia in the manuscript "The Sacred Disease" (A. Williams & Kirkham, 2011).

One of the pioneers studies in muscle spasticity and orthopedic deformities in cerebral paralysis (currently named, cerebral palsy), was presented by Dr. William Little in 1853 (Morris, 2007). He was one of the clinical leaders in attributing muscle spasticity and deformity to brain damage, as one of the main causes, in addition to the long-term periods of flexed joint positioning typically observed in cerebral paralysis. Also, he brought into consideration the concept that the motor impairment was the primordial problem in this pathology, and epilepsy and other behavioral disorders were concomitant symptoms that were not always present in such a pathology (Dunn, 1995).

Sigmund Freud also contributed to the definition of cerebral paralysis (1893). He attributed the etiology of this disease to being a combination of the initial lesion and repair process that were partially related to clinical manifestations. He also included prenatal events as one of the causes of cerebral paralysis and highlighted that extended labor was not the main origin of the neurological problem (Aisen et al., 2011; Morris, 2007).

Around 1889, Dr. William Osler published a monograph entitled the 'The Cerebral Palsies of Children'. This work created the novel classification of children diagnosed with CP into infantile hemiplegia, bilateral spastic hemiplegia and spastic paraplegia (Morris, 2007). In accordance to this categorization of patients with cerebral paralysis, Dr. Mansel Sympson published a detailed description of two hemiplegic cases. In this manuscript, the author reports the principal clinical features of the child with CP as well as the prescribed medical and physical treatment. Interestingly, the medical description already included the typical motor signs observed in CP: rigid position of the arm in semiflexion, lack of muscle tone in the hand and forearm, excitability of reflexes, clonus[14] and spasticity. In the same issue of that journal, Dr. Thomas Oliver described the case of one hemiplegic child associated with aphasia, indicating a more complex and extensive damage of the brain that was corroborated by a postmortem neuroanatomical and histological examination (Mansel Sympson & Thomas, 1890).

It was in 1925 that Dr. Pyles published one of the first scientific papers in CP thoroughly describing the orthopedic and surgical treatment used for this condition. In this article, the author already referred to CP as an "incurable condition in which the brain has been retarded in its normal development by some injury which either partially or totally destroyed its anatomical and physiological integrity." The author basically described the surgical techniques used at that time for reducing the typical deformity of lower extremities in adduction, flexion and internal rotation, as can be currently observed in cases of

---

[14] **Clonus:** Condition defined described by continuous reflexive and oscillatory movement of an anatomical segment, like the ankle, after the stimulation of a tendon reflex. These movements are large and can last a few seconds. It is secondary to upper motor lesions or pyramidal damage.

spastic diplegia. The goal of these surgical techniques was to alleviate these deformities so that the lower extremities would stay in a resting state, or as it is named in the paper, "in physiological rest" (Pyles, 1925).

Almost 20 years later, Dr. Fay published one of the first papers dedicated to the rehabilitation, neurophysiology-based therapy and problems associated with cerebral paralysis in children (Fay, 1946a, 1946b, 1948). Since then until modern times, the concept of CP, early diagnosis, rehabilitation techniques and life expectancy have considerably evolved thanks to vast medical and research advancements. Also, the appearance of new specialties in neurorehabilitation has expanded the therapeutic modalities for treating CP. Some techniques applied are: the comprehensive PT approach, strength training protocols, constraint induced movement therapy (CIMT), upper limb training with trunk constraints, hand-arm bimanual bilateral training (HABIT), sensorimotor training programs, balance training and neuromuscular electrical stimulation (Anttila, Autti-Rämö, Suoranta, Mäkelä, & Malmivaara, 2008; Butler, 1998; Gordon et al., 2011; Novak, McIntyre, Morgan, Campbell, & Dark, 2013; Schneiberg et al., 2010; Wright, Durham, Ewins, & Swain, 2012).

In spite of the noticeable advancement in the medical and therapeutic fields in CP, in one of the last systematic reviews published by Novak and colleagues (2013) about evidence-based therapy in neurorehabilitation of children with CP, it was determined that the efficacy of most of the current treatments applied in CP is not supported by scientific evidence. The conclusions drawn in this elegant review bring into consideration the necessity of applying scientific rigor to research evaluating the neurorehabilitation techniques utilized in children with CP.

EPIDEMIOLOGY

In the United States of America, it is estimated that 3.1-3.6 newborns per 1000 will develop CP (Christensen et al., 2014). In 2009, the gender ratio of children affected with CP is greater for males than females with a ratio of 1.4:1. Also, CP is the most common motor disability in childhood, affecting approximately 1 of 303 eight-year-old children in the US. Furthermore, this motor disability significantly has been shown to impact the health system and economy of industrialized countries; in the US, the lifetime-estimated-cost of children with CP is approximately 1 million dollars (CDC, 2010).

CLASSIFICATION OF CEREBRAL PALSY

Cerebral palsy is a pediatric disorder of the development of movement and posture, causing activity limitations attributed to non-progressive disturbances of the fetal or infant brain, peri- or post-natally, that may also affect sensation, perception, cognition, communication, and behavior. Motor control during reaching, grasping, and walking are disturbed by spasticity, dyskinesia, hyper- and/or hyporreflexia, excessive co-activation of agonist/antagonist muscles, retained developmental neuromotor reactions, and secondary musculoskeletal malformations, together with paresis and defective motor programing. Weakness and hypoextensibility of the muscles are due not only to inadequate recruitment of motor units, but also to changes in mechanical stresses (myotendinous unit and fascia) and hormonal factors (Richards & Malouin, 2013). Frequently, the brain insult is associated to other neurological problems, like epilepsy, that can aggravate the clinical picture and functional ability of the patient with CP. The cerebral lesion is not always well localized and it is usually heterogeneous, resulting in diverse symptomatology, signs and complex functional repercussions.

CP can be functionally classified into different types depending on the clinical picture and motor presentation of the patient. There are three basic forms of CP, in which spasticity, a well-recognized clinical sign, and topography of the motor disorder is used in the classification: unilateral, hemiplegia/hemiparesis and bilateral, subdivided into spastic diplegia/diparesis or quadriplegia/tetraplegia. Functionally, these subtypes can be in turn classified as: mild, moderate and severe, depending on the level of motor dysfunction.

The description of the clinical features included in this section will focus on the principal subtypes manifested in moderate and severe cases of CP (The description of symptoms and signs have been principally obtained from Krageloh-Mann & Bax (2009), "Diseases of the Nervous System in Childhood, Chapter 7: Cerebral Palsy").

Mild Type of Bilateral Spastic CP: Spastic Diplegia

Spastic diplegia is the most common type of bilateral spastic CP in which lower extremities are more involved than the arms. There are two main subtypes: Diplegia and Ataxic Diplegia. Some researchers also classify spastic diplegia into: three-limb dominated type (triplegia) and dyskinetic spastic type (Hagberg and Hagberg, 1993).

The pathognomonic clinical sign in spastic diplegia is increased muscle tone in the lower limbs. When these patients are held vertically against gravity, the legs are reflexively extended and adducted (scissored position). During infancy, some of these patients demonstrate hypotonia (extremely accentuated on occasion), lethargy[15] and feeding difficulties. After this period of hypotonia, the dystonic features appear in which involuntary motion of limbs associated with increased muscle tone takes place when the child's position is altered. In this dystonic phase, there is a flexion of hips and knees, and in the standing position legs are internally rotated. During walking, if present, the gait is on tiptoes with semiflexion of hips and knees as well. With regard to the upper limbs, they can be variably affected; though manipulative skills are less impaired than locomotion.

---

[15] **Lethargy:** State of weakness and lack of energy with slowness and torpidity.

Severe Type of Bilateral Spastic CP: Spastic Quadriplegia

Tetraplegia or Quadriplegia is the most severe case of CP and it is less prevalent than spastic diplegia. This subtype of CP is characterized by motor dysfunction of upper and lower limbs. The upper extremities can be the most commonly affected, or the four limbs could have similar degrees of involvement. Furthermore, children with tetraplegia usually present mental retardation and microcephaly[16].

Severe forms of quadriplegia commonly occur in infants born at term. As clinical features these patients present with important dystonia of the face, trunk and hands. There is a significant delay in gross motor development in association with bilateral spasticity, pseudobulbar paralysis[17], absence of speech and dysarthria. These clinical features severely limit the patient with quadriplegia. They are not able to walk independently by the age of 5 years and present important contractures in equinus position, hip adduction and knee flexion. In addition, cognitive impairments and visual problems, even blindness, are found in this CP subtype. Finally, quadriplegic types should be distinguished from dyskinetic-spastic cases in which the dystonic and athetotic components are more accentuated.

---

[16] **Microcephaly:** Reduction of head size.

[17] **Pseudobulbar palsy:** It is defined as an injury of corticobulbar axons that innervate the cranial nuclei IX-XII. It occurs as consequence of upper motor neuron impairment.

Unilateral Spastic CP: Hemiplegia, Hemiparesis or Congenital Infantile Hemiplegia

Spastic hemiplegia is the most common form of CP. In the case of congenital hemiparesis, the neural injury is acquired before the end of the neonatal stage (28 days). In this subtype of CP, the level of involvement of the leg or arm can be different, with leg involvement being more common in pre-term infants and arm involvement in infants born at term. Also, there is no facial palsy in unilateral spastic CP, different from the forms acquired in the postnatal period. In addition, a mild involvement of the lower VII cranial nerve is possible.

The two principal clinical characteristics of spastic unilateral CP are: spasticity and paresis. Also, weakness is very typical in the distal parts of the limbs; associated reactions[18] are frequently found during voluntary or reflex behaviors (sneezing or yawing) (Bhakta, O'Connor, & Cozens, 2008). The first manifestations of this subtype of CP are around 4-5 months. One of the principal observations is that infants with hemiplegia reach for toys with the same upper extremity, which is the less impaired arm. This is accompanied by pathological flexion of elbow and hand fisting. During the act of prehension, these patients display excessive abduction of the arm, wrist flexion and metacarpal hyperextension. Sometimes, the ability to grasp and pinch is not developed due

---

[18] **Associated Reactions:** They are defined as reflexive synergistic contraction of a neuromuscular group in flexion or extension (less frequent occurance). These reactions are very frequent in hemiplegia, in the paretic upper limb, when the subject uses the non-paretic member.

to neural damage or biomechanical constraints, or both. The lower limb is also involved in hemiplegia. Also, there is a greater growth of the anatomical structures in the less-involved hemibody than in the hemiparetic side.

Among the main principal signs, we should point out: spasticity, hyperreflexia in the tendons of the paretic side and positive Babinski[19] and Rossolimo[20] signs. Visual deficits like reduced stereopsis or visual acuity can also be found.

Dyskinetic CP: Dystonic and Choreoathetotic Forms

This form of CP is defined by fluctuating muscle tone and involuntary, uncontrolled, recurring and stereotyped movements with predominant primitive reflexes. The essential motor problem in dystonic-dyskinetic groups is the inability to organize, plan and execute motor actions. Also, they present significant incoordination of automatic muscle responses and postural maintenance.

During development hypotonia and poor tone regulation of trunk muscles is found, delaying the acquisition of other gross motor functions like sitting, standing or walking. Fixed contractures are infrequent, but hip dislocations can be found. There are usually twisting movements of distal limbs, feet and hands. The involvement of bucco-pharyngo-laryngeal muscles commonly disrupts the

---

[19] **Babinski sign:** It is an abnormal response after pyramidal injury of the hallux towards extension when the plantar area is stimulated with a blunt instrument.

[20] **Rossolimo sign:** It is a Babinski-like response that occurs in pyramidal lesions. The percussion of the tips of the toes generates an excessive flexion.

ability to swallow and speak. This last function is aggravated in some cases that have hearing loss.

A) Dystonic Form

In these cases of CP, abrupt shifts of muscle tone are observed, principally in trunk muscle extensors. These fluctuations in muscle tone are elicited through head motion and intentional limb movements, or strong emotional responses. Automatic twisted and stereotyped postural patterns are also present. Dystonic postures are explained by sustained tonic contractions and slow writhing postures that result in forceful movements (different from hyperkinesia). They can also present spasticity and primitive reflexes like the asymmetrical tonic neck reflex.

B) Choreoathetotic Form

This CP type is characterized by hyperkinesia, fluctuating tone and hypotonia. Attending to the etymology of the word, “chorea” means rapid, jerky and fragmented movements and “athetosis” means slow changing contorting movements.

Pure neurological dyskinetic disorders are not associated with pyramidal signs such as hyperreflexia or clonus; whereas in dyskinetic CP, these signs can be present. Dyskinesia, added to dysregulation of this reflexive muscle tone, can aggravate the ability to control movement in these subtypes of CP. In this regard clonus has been inversely correlated to the stretch reflex threshold of some muscles, such as elbow flexors (Levin, 1996).

Ataxic CP: Nonprogressive Cerebellar Ataxia

Patients with this form of CP have problems in recruiting muscles in an orderly fashion and in regulating joint amplitude. One typical sign is trunk ataxia, which leads to continuous perturbations of balance. In upper limbs, subjects with ataxic CP present dysmetria, overshooting or undershooting final targets, and low intentional tremor while carrying out goal-oriented tasks. In addition, generalized low muscle tone can be found in these patients. Additional cognitive impairments can be present. And finally, as functional problems, postural control and tone regulation can be extremely impaired in some ataxic cases (Krageloh-Mann & Bax, 2009).

DEFINITION AND PATHOGENESIS

The sensorimotor disorder in CP is the pathognomonic sign and for that reason it is usually considered as an upper motor neuron syndrome[21]. Nonetheless, the brain lesion is usually more complex and involves other cerebral regions that aggravate its clinical picture. CP is defined as an encephalopathy in which ante-, peri-, and postnatal factors can be involved in the origins of this pathological entity. Congenital malformations are rarely identified. CP is most often the result of environmental factors, which might

---

[21] **Upper motor neuron syndrome:** Pathological entity produced by a lesion of the descending motor pathways at any point of their trajectory.

interact with genetic vulnerabilities, and could be severe enough to cause the destructive injuries visible with standard imaging (i.e., ultrasonographic study or MRI). This injury predominantly occurs in the white matter in preterm infants and in the gray matter and the brainstem nuclei in full-term newborns. Moreover, these lesions act on an immature brain and may alter the normal series of consecutive developmental events. Biochemical alterations that result in cell apoptosis and cell loss are also present. They are typically observed in hypoxic-ischemic as well as in inflammatory neural conditions, such as: excessive production of pro-inflammatory cytokines, oxidative stress, maternal growth factor deprivation, extracellular matrix modifications and excessive release of glutamate that in turn trigger excitotoxic cascades (Marret, Vanhulle, & Laquerriere, 2013).

CLINICAL SYMPTOMS AND SIGNS

The clinical picture of patients diagnosed with CP during development is diverse and complex since it is characterized by neurological disruption of brain areas as well as neuronal tracts in addition to pathological changes of the osteoarticular and muscular systems.

Weakness is always present in some degree across the different sub-types of CP, in which there is always lack of force production in voluntary muscle contractions to a certain degree. This is mainly observed in the distal areas and it is principally due to loss of corticospinal drive. In the specific case of a dysfunction of hand movements, it would be mainly explained by a disruption of the corticomotoneuronal system[22]. Nonetheless, other systems like the rubrospinal funiculus, indirect corticomotoneuronal tracts and intrinsic spinal proprioceptive networks of upper cervical segments innervated by coticofugal fibers are importantly involved in hand shaping and finger positioning. Consequently, a loss of dexterity can also be observed with the lesion of either neural tracts or cerebral areas that control them (Burke, Wissel, & Donnan, 2013; Newton et al., 2006; Sasaki et al., 2004)

In CP there is a dysregulation in the inhibition of muscle tone and antigravitatory muscle groups. These groups are stabilizer muscles for the postural framework, which is activated prior to executing voluntary movements. This feedforward mode of control is also required for inhibiting pathological agonist-antagonist co-activations (Dan, Bouillot, Bengoetxea, Boyd, & Cheron, 2001). Exacerbated muscle co-contractions associated with decreased muscle selectivity during voluntary movements is also very common in spastic presentations of CP. When patients activate agonist muscles there is an undesirable antagonistic contraction that affects the movement direction and efficiency of the motor commands. This effect can be accentuated by disrupted spinal mechanisms, such as reciprocal innervation (see spasticity section). In the

---

[22] **Corticomotoneuronal system:** Direct corticospinal fibers from primary motor cortex (Brodmann area 4) to the lateral area of the motor neuron pool. These fibers innervate distal muscles involved in dexterity movements.

same way, there is a deficit of coordination in the muscle sequences of movements, like reaching and grasping. These are called *synkinetic movements* and they are due to disrupted collateral pathways to the lateral corticospinal tract, like reticulospinal and tectospinal fibers. These collaterals plus the peripheral medullary afferents converge in metameric propriospinal interneurons. In reaching for instance, there is a dysregulation of the cervical C3-C4 propriospinal system, which regulates cervical motoneuron pools that in turn control and coordinate different muscle synergies required for optimizing the limb movements with respect to a goal (Burke et al., 2013; Canedo, 1997; Lemon, 2008).

Abnormal posture is another concomitant impairment frequently observed in patients diagnosed with CP. The effects of abnormal posture are more accurately identified during voluntary actions. Research on hemiplegic animal models with different cerebral lesions in size and locations have shown that postural defects are also dependent upon descending non-corticospinal pathways that are very sensitive to postural changes. As an example, the abnormal posture in these animal preparations were principally related to the motion of head with respect to the trunk and space, in addition to active cervical extension (Burke et al., 2013; Denny-Brown, 1966).

Visual deficits are found in 7%-19% of children with CP (Guzzeta, et al. 2001; Himmelmann, 2006). Within these visual motor impairments we can point out: visual acuity deficits, strabismus, oculomotor problems (alteration of the III, IV and VI cranial nerves), reduced visual fields (e.g. types of anopsias and hemianopsias) and cortical blindness (impaired visual detection of objects in the visual field). Deficits of the visual system, anterior part (eyes and optic nerves up to the optic chiasm) and posterior part (optic tracts, lateral geniculate nuclei, optic radiations and occipital cortex), cause postural alterations. Among the most common visual dysfunctions in CP, we could point out homonymous hemianopia[23]. Subjects with this defect are accompanied by postural adjustments like torticollis[24] with or without secondary compensations of the upper body depending on the site and complexity of the neural insult (Porro, van der Linden, van Nieuwenhuizen, & Wittebol-Post, 2005; Prayson & Hannahoe, 2004).

Other processes like visuospatial processing, essential for posture and control of reach-to-grasp actions can be affected by an injury of cortical or white matter related to parietal-temporal-occipital association regions. In this regard, new imaging techniques are showing that white matter disruption is associated with functional outcomes. Specifically, the injury of the microstructure of the diverging reciprocal thalamo-cortical axons that interconnect basal ganglia,

---

[23] **Hemianopia or hemianopsia:** Reduced or complete blindness in half visual field of one or two eyes. There are two types: 1) homonymous, in which the same side of the visual field is lost in the two eyes and 2) heteronymous, which is the loss of half of the visual field on different sides in both eyes. This last category is subdivided into: binasal (nasal visual field) and bitemporal (lateral visual field).

[24] **Torticollis:** Abnormal positioning of the head over the shoulders in which the sagittal, frontal and transversal planes of motion can be affected.

thalamus and sensory-motor brain areas (precentral, postcentral and paracentral lobules) for planning and executing motor actions are associated with reduced sensorimotor function, motor learning and executive functions (Henry, Pannek, Boyd, & Rose, 2013). Additionally, recent research in hemiplegic subjects has demonstrated that the lack of intracortical inhibitory processes of sensorimotor cortices and interhemispheric inhibition from the ipsilesional to the contralateral hemisphere through transcallosal fibers is related to impoverished upper limb control (Mackey, Stinear, Stott, & Byblow, 2014).

Research and clinical evidence also indicates that proprioception is affected in CP at the CNS level. Children may have problems detecting passive joint movements and sensing the position of anatomical segments in different postures (*kinesthesia*). Thus, the analytical and global neural processing of the different anatomical segments during passive and/or active movements can consequently alter the ability to maintain the motor plan regarding posture and upper limb movements (Langan, Kern, Hurvitz, & Brown, 2014; Pihko et al., 2014). Another relevant neurological aspect related to proprioception and vision in movement composition is the formation of different postural frames of reference. The egocentric frame of reference detects the position of different parts of the body in relation to each other, while the allocentric frame of reference relates the body position with respect to other objects in the external environment. The latter condition is extremely important in the sensory experience and perception of self-motion. This neural property is affected in children with CP due to long periods of immobility and lack of self-produced motor activity (Anderson et al., 2014; Galati, Pelle, Berthoz, & Committeri, 2010; Pitzalis et al., 2013).

NEUROMUSCULAR DISORDER IN CEREBRAL PALSY: CENTRAL AND PERIPHERAL NERVOUS SYSTEM

Spasticity can be simply defined as a velocity-dependent increase in muscle tone accompanied by tendon jerk hyperreflexia. This increase is due to both a reduced threshold and an increased gain of the muscle stretch response (Gracies, 2001; Malhotra, Pandyan, Day, Jones, & Hermens, 2009).

Although spasticity is a consequence of the CNS damage, complex neurophysiological changes, facilitation and inhibition, reside at the level of the spinal reflex circuitries. Most of these adaptive/disruptive changes can be observed in cerebrovascular injuries as well. The activity of spinal motor neurons is self-regulated by a special class of inhibitory interneurons, Renshaw cells[25]. Motor neurons create a recurrent inhibitory circuit sending collaterals to this type of inhibitory interneurons. Then, neural activity of alpha motoneurons will reduce and stabilize their own depolarization rate through Renshaw interneurons. This inhibition will also reduce the electrical activity of other synergist motor neurons and Ia inhibitory interneurons of antagonistic muscles.

---

[25] **Renshaw cells:** Interneurons located in the spinal gray matter that regulate the recurrent inhibition of alpha motoneurons via its own collateral axons.

Additionally, Renshaw cells are also controlled via descending cortical axons and the level of neural activity of this recurrent inhibition is increased in the resting state in neuromotor impairments like CP and stroke (Burke et al., 2013; Pearson & Gordon, 2013).

The group Ib fiber can act on excitatory interneurons causing excitation of alpha motoneurons. In healthy conditions, this reflexive pathway takes place during automatic motion. However, these fibers can also act on Ib inhibitory interneurons[26] and contrarily inhibit spinal motoneuron activity, mainly in the resting state. In neuromotor disorders, some evidence pinpoints a possible hyperexcitability of the Ib axon-group during inactivity that in fact could justify the tendon jerks and clonus typically associated with spasticity (Burke et al., 2013; Pearson & Gordon, 2013).

Considering the disruption of these pathological reflexes from a more functional perspective, children with CP have to deal with spastic paresis in volitional movements. CP is defined as a syndrome that causes limb deformities and motor limitations that will consequently affect functional performance and daily living activities. This spastic paresis includes: stretch-sensitive paresis, soft tissue contracture and muscle overactivity (Bayle & Gracies, 2014).

---

[26] **Ib inhibitory interneurons or nonreciprocal group I inhibition:** Spinal inhibitory interneurons receiving inputs from tendon organ, muscle spindles, joint and cutaneous receptors in addition to descending pathways.

As cited in Bayle & Gracies (2014) "the term s*tretch-sensitive paresis* is the inability to recruit motor units in an agonist effort when a contractured, spastic antagonist is stretched. This usually occurs in the less contractured muscle of two muscles around a joint". *Contracture* consists of a shortening of muscle length due to a decrease in the number of sarcomeres in series along the myofibrils, accompanied by an increase in the resistance to passive stretch. The muscle structure, and the rest of soft tissue, including tendons, ligaments, joint capsules, dermis, vessels and nerves are then adapted to this new imposed length. There is also reduced muscle compliance[27], which is probably attributable to remodeling of muscle connective tissue. Consequent to this lack of muscle fiber extensibility, the range of joint motion is considerably reduced. Furthermore, these plastic changes affect the contractile properties of the muscle, such as slow-to-fast changes of originally slow muscle fibers (Bayle & Gracies, 2014; O'Dwyer, Ada, & Neilson, 1996; P. Williams & Goldspink, 1978). This phenomenon is the main cause of bone deformities during growth, partial or complete subluxation, like hip dysplasia or coxofemoral dislocations and articular disfigurements (Bayle & Gracies, 2014; Burke et al., 2013; Spiegel & Flynn, 2006).

Spastic muscle overactivity occurs when intraspinal reorganization is activated due to denervated neurons of the ventral horn of the spinal cord. Then, new rudimentary sprouts and connections of descending motor tracts grow

---

[27] **Muscle Compliance:** Degree of deformity and distension that a muscle can undergo.

within the spinal cord. Secondarily to this effect, the brainstem and corticospinal descending funiculus are highly activated, even in the resting state, due to dishinibition of frontal or transcallosal fibers. At different levels of the spinal cord, interneurons also suffer from abnormal sprouting and synapses that generate a continuous hyperexcitability state. This status leads to overall muscle overactivity that can be present in spastic forms of CP, like spastic dystonia and spastic co-contraction (Bayle & Gracies, 2014; Gracies, 2001). *Spastic dystonia* is represented by a chronic tonic muscle activity in the resting state. It is spontaneous and is not triggered by any concrete factor. Functionally, spastic dystonia can exacerbate limb and postural deformities (Bayle & Gracies, 2014; Denny-Brown, 1966). *Spastic co-contraction* is characterized by an excessive level of antagonistic muscle activity during voluntary agonistic muscle activation. This sign is extremely disabling for controlling the motor action and it can be facilitated by increased recurrent inhibition (Bayle & Gracies, 2014; Gracies, 2005).

In spite of the extensive literature on spasticity, this clinical sign is not considered as the core element in the motor dysfunction presented in CP. Contrarily, the degree of hypertonia and hyperreflexia are understood as secondary mechanisms derived from the disruption of the CNS. This maladaptation of the CNS provides some degree of flexibility during motor activity in the majority of cases with CP (Bayle & Gracies, 2014; Burke et al., 2013). Thus, the major concern in this neurological entity would be to identify the causes that exacerbate muscle tone and uncontrolled reflexes, such as problems with movement planning and coordination, head stabilization and postural control.

In conclusion, CP is a relatively common neuromotor disorder of multifactorial etiology in which the motor disorder is the most characteristic sign. The motor dysfunction will be determined by the site of brain lesion, extent of neural damage and subtype of CP. The damage of cortical and sub-cortical centers will affect the ability to organize, coordinate and execute movements. In addition to the cerebral damage, there will be a severe impairment of reflexive pathways at the metameric level that will affect the automatic control and organization of intentional movements. Knowledge about pathogenesis and clinical features in CP is crucial in the design of experiments since the motor disabilities of each of the different subgroups will be extremely diverse.

NORMAL AND ABNORMAL DEVELOPMENT AND POSTURAL DYSFUNCTION IN CEREBRAL PALSY

Development of sitting is considered one of the most important phases in the development of motor function. With the onset of the ability to position the head with respect to the trunk, at around 3 months, and acquisition of independent balance in the vertical plane, at approximately 7-8 month of age, new egocentric and allocentric frames of reference are generated between the growing corporal structures of the body and the external environment. In the visual system, the new orientation of the ocular globes in vertical sitting would allow the infant to receive the visual stream of information in the horizontal plane. Similarly, in the vestibular system, the three semicircular canals for detecting head angular motion are orthogonal with respect to each other; and the utriculum and saculum constitute a perpendicular plane for detecting horizontal and vertical linear motions of the head. Additionally, in sitting, self-triggered and external postural perturbations occur over a decreased base of support compared to previous lying positions. This new postural interaction between the infant and the ecological context will require more advanced neural processing and sophisticated sensorimotor patterns of activity to attain upper extremity goals during sitting.

In the most severe cases of CP, the heterogeneous brain lesion/s will result in a wide spectrum of sensory, motor and muscular impairments that will delay or even eliminate the acquisition of sitting. Additionally, the different subtypes of CP can display diverse postural dysfunctions. For instance, hemiplegic subjects present balance constraints in standing. These impairments are associated with an increased passive degree of stiffness and severe lack of stretch reflexes of leg muscles against external perturbations. These hemiplegic cases demonstrate infrequent and disorganized temporal patterns of muscle activation between gastrocnemius and hamstrings muscles. On the other hand, ataxic subtypes present an important deficit of sensory integration, muscle timing and postural muscle organization with consequent problems of muscle recruitment in standing balance (Woollacott, Assaiante, & Amblard, 1996).

Moderate and severe forms of CP can present profound deficits, or even complete absence, of the basic level of postural control[28]. Children with CP classified as GMFCS-level V (see chapter VII: Clinical Assessments), are unable to automatically regulate the specific neuromuscular patterns of the trunk; this in turn impairs the ability to acquire vertical sitting. These children have tremendous difficulties in maintaining the control of the head and trunk against gravity in the vertical plane and thus require adaptive equipment for improving posture and upper extremity functions. On the other hand, cases of CP categorized as GMFCS level IV present some difficulties in consistently generating these specific postural adjustments in the sitting position. Subjects with CP often require adaptive seating in order to improve motor performance of posture and reaching skills, although the functional disability is less evident than in children categorized as GMFCS level V (Hadders-algra, Brogren, Katz-salamon, & Forssberg, 1999; van der Heide & Hadders-Algra, 2005; van der Heide et al., 2004). In addition, children with CP, mainly moderate and severe cases, display deficits in the recruitment order of antagonistic muscles, temporal

---

[28] **Basic or First Level of Postural Control:** This level consists of direction specific postural adjustments in which the muscles antagonists to the movement are activated.

organization of muscle sequences and modulation of muscle amplitude (second level of postural control[29]). Research using external perturbations in sitting and standing paradigms has shown that children with CP present differences in recruitment order, increased onset latencies of muscle activation and a higher degree of antagonistic muscle participation in postural control than healthy peers (Eva Brogren, Hadders-Algra, & Forssberg, 1996; Nashner, Shumway-Cook, & Marin, 1983).

Research on sitting control while performing reaches has demonstrated that children with CP with normal muscle tone demonstrate variable muscular activity in reaching. In addition, CP cases associated with hypotonia of paraspinal muscles show weak postural activity; whereas CP children with hypertonia display an excessive activation of postural muscles while reaching. Yet, in moderate to severe CP, the major disruption occurs at the second level of neuromuscular control: amplitude and timing of muscular patterns specific to the context and motor tasks. Children with CP present severe problems to modulate EMG amplitude and the temporal sequence of postural muscle contractions in comparison to typically developing children.

With regard to this latter point, children with CP, principally with mild or moderate dysfunction, tend to generate cranial-caudal temporal sequences for

---

[29] **Second Level of Postural Control:** This level of postural control is more advanced since it requires from a dynamic and adaptable regulation of the muscle patterns involved in the motor task.

postural control. This top-down recruitment is characterized by a fast activation of cervical muscles followed by a slower muscle activation of thoracic and lumbar segments. Also, contrary to their responses to externally perturbed balance, subjects with CP interestingly do not display exacerbated antagonistic co-activation of paravertebral muscles. The use of this recruitment order could be either a result of the neurological damage or a functional strategy used to deal with task-specific circumstances, in which head maintenance would be a priority function (Hadders-Algra et al., 1999; Pozzo, Berthoz, & Lefort, 1990; van der Heide & Hadders-Algra, 2005; van der Heide et al., 2004).

NORMAL AND ABNORMAL DEVELOPMENT AND DEFICITS OF UPPER LIMB CONTROL IN CEREBRAL PALSY IN REACHING TASKS

In typical development during unimanual reaches, the arm progressively acquires a smooth trajectory in reaching tasks. The trajectory becomes straighter and faster due to a decreased number of sub-movement corrections, or *movement units* (MU), along the arm path (von Hofsten, 1991). At early stages, around 3-7 months, the typical number of MUs while reaching is between 3 and 7. However, reaches start to adopt an adult-like trajectory with 1 MU around the age of 12.

In adolescence and adult life, the velocity profile of mature reaches should be bell-shaped, with only one acceleration and one deceleration phase during arm transport (Jeannerod, 1984; von Hofsten, 1991). Additionally, the duration time of the first MU, called *transport movement unit*, is lengthened and it results in a greater coverage of the arm trajectory while reaching for an object (Brogren, Hadders-Algra, & Forssberg, 1998; Fallang, Saugstad, & Hadders-Algra, 2000; von Hofsten, 1991).

In children with CP, without considering the postural influence, the number of MUs as well as the time duration of the first transport MU is increased in reaching for both the most and less affected upper limbs. The ability to produce smooth reaches is related to the degree of muscle spasticity of the upper extremity and also to the goal of the reaching task (Chang, Wu, Wu, & Su, 2005; van der Heide, Fock, Otten, Stremmelaar, & Hadders-Algra, 2005). In sitting, van der Heide et al (2005) concluded that subjects with CP aged 2-11 years frequently display reaching movements with the least affected arm characterized by more than one MU compared to age-matched controls. In the specific case of bilateral spastic CP, the reaches were more affected than those performed by children with spastic unilateral CP, showing less straight reaching trajectories and shorter transport MUs. These features of the arm trajectory were opposite to the reaching configuration observed in typically developed matched peers (van der Heide et al., 2005).

In reaching, the neuro-modulation of myoelectrical activity at the second level of muscular control (amplitude and timing of muscular patterns specific to context and tasks) would be mandatory for controlling simultaneously posture, upper limb and hand movements. This level of neural control allows adaptation and updating of the kinematics and kinetic parameters of upper limb and initial/compensatory posture of head, trunk and pelvis during the reaching movement (van der Heide & Hadders-Algra, 2005).

The neuromuscular control of posture and reaching is more complex when the trunk is involved due to greater number of DOF provided by the upper body (e.g. head, trunk and upper extremity) (Bernstein, 1967; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). The CNS should then adjust and coordinate the redundant amount of DOF provided by the arm and body for adapting the pre-planned motor command of the arm and controlling equilibrium. In this way, the end goal would be preserved (Archambault, Pigeon, Feldman, & Levin, 1999; Ma & Feldman, 1995). Due to the higher degree of motor complexity in reaches involving the trunk, the maturation of arm and trunk kinematics, understood as a decrease in movement or trajectory variability, emerges later in childhood instead of infancy. Some kinematic parameters such as endpoint trajectories, joint excursions and timing of arm and trunk involvement and inter-joint coordination are progressively acquired and mastered at the age of 3 years and beyond. More specifically, reaching trajectory straightness and smoothness in children attain maturation, or an adult-like level, at the age of 6 years when the target is at a distance of the subject arm’s length and 8 years when the object is beyond this length. Nonetheless, inter-joint coordination variability is still present at the age of 11 years while reaching for an object at both distances in healthy children (Schneiberg et al., 2002).

We should point out that all these principles apply when the CNS is healthy and the degree of difficulty, numbers of planes involved in the movement, target position and movement velocity, and also instructions remain constant during controlled experimentation. However, we would expect greater variability of motor performance in ecological contexts and in patients with lesions of the CNS, as is observed in moderate-severe cases of CP (Fitts, 1954; Utley & Sugden, 1998).

THEORETICAL FRAMEWORK: UNDERLYING TRUNK CONTROL

ANATOMICAL FEATURES OF THE TRUNK

The vertebral column is composed of four main vertebral segments: cervical (lordosis), thoracic (kyphosis), lumbar (lordosis) and sacroccocygeal (sacrum with 5 fussed sacral vertebrae and coccyx). The vertebral units and joints of each of these segments are characterized by specific anatomical and biomechanical features that require complex neuromuscular control. Thus, the optimal control of the vertebral column will be an essential element in the control of posture and upper/lower extremities mobility. The morphology and structure of the vertebral column evolves during ontogeny and with the progressive acquisition of complex motor milestones against gravity: head control, roll, sit, crawl, stand and walk among other high-order functions.

Anatomical and anthropometric parameters of the spinal cord are not constant throughout the life-span. For instance, in normal motor development the lumbar segment is concave in its anterior side at birth and it acquires its physiological lordosis at the age of 10 (Kapandji, 2008). Aging-related body deterioration and mainly pathological conditions due to metabolic, infectious, vascular or neurogenic factors also cause important morpho-physiological changes in both spinal cord and vertebral column, such as reductions in inter-vertebral spaces, disrupted disc mobility, osteoporotic microfractures, radiculopathies and spinal deformities (hyperkyphosis/lordosis and scoliosis). In CP, spinal deformities are frequent and perturb the biomechanical framework that serves postural stability and mobility (Chan & Miller, 2013; Del Grande, Maus, & Carrino, 2012; Saito, Ebara, Ohotsuka, Kumeta, & Takaoka, 1998).

BIOMECHANICAL AND MOTOR CONTROL ASPECTS FOR MODELING THE TRUNK AS A MULTISEGMENTED STRUCTURE

Considering the vertebral column as a non-dissociable unit, from sacrum to the base of the cranium, the trunk would be biomechanically considered as a pseudo ball-and-socket joint with three main DOF: flexion-extension, lateral flexion and axial rotation. The flexion-extension would take place around the sagittal plane with a complete range of motion of 250°. The lateral flexion around the frontal plane would be 75-85°. Lastly, the trunk rotation would occur around the transversal plane with a total range of motion of 90° (Kapandji, 2008).

However, this is not a realistic anatomical and biomechanical perspective in the case of the vertebral column. There are 25 sub-vertebral units in total: occipito-cervical, cervical (7), thoracic (12) and lumbar (5) (without considering the sacroccoygeal joint). These sub-vertebral units are in turn grouped into three main segmental regions of the trunk that will contribute very differently to the global range of trunk motion (Tables 1, 2 & 3).

Panjabi et al (1976) described a biomechanical model of the spine using cadavers in order to study the degree of vertebral motion and stability in response to controlled external intersegmental forces. These forces simulated the activity of deep muscle layers close to the rotational axis of the vertebral column: rotatores, multifidus and interspinalis.

This study concluded that the neuromuscular control of the muscles that comprise this profound spinal layer would be characterized by a faster level of activation in postural control due to their short length (shorter reaction time) (Panjabi, Abumi, Duranceau, & Oxland, 1976). In this regard, a study in muscle tone regulation through vertebral rotations (± 10°/s) around the axial plane of the spinal column hypothesized that the CNS could generate an intermediate level of muscle tone so that back muscle activity would increase (shortening of fibers) or decrease (lengthening of fibers), maintaining posture during external perturbations and volitional upper limb movements (Gurfinkel et al., 2006).

Table 1: Segmental Flexion-Extension of Trunk Motion

	Range of Motion	
Segmental Region of the Trunk	Flexion (°)	Extension (°)
Lumbar Spine	60	20
Thoracic Spine	45	40
Cervical Spine	40	60

Table 2: Segmental Lateral Flexion of Trunk Motion

	Range of Motion (°)
Segmental Region of the Trunk	Lateroflexion (°)
Lumbar Spine	20
Thoracic Spine	20
Cervical Spine	35-45

Table 3: Segmental Rotation of Trunk Motion

	Range of Motion (°)
Segmental Region of the Trunk	Rotation (°)
Lumbar Spine	5
Thoracic Spine	35
Cervical Spine	45-50

Tables 1, 2 & 3 represent the range of motion of the principal segment of the vertebral column in three planes of motion. Note that each of the main trunk regions has 3 DOF (Obtained from Kapandji, 2008).

On the other hand, the superficial and long paravertebral muscles counterbalance external postural loads and control spinal posture and spinal movements (Kapandji, 2008; Panjabi et al., 1976).

Even though the studies presented in this dissertation use surface EMG of superficial muscles, we need to be aware of the aforementioned contributions of the profound muscles to trunk stability. Spastic bilateral presentations and dystonic cases of CP manifest dysregulation of these spinal deep muscles aside from the lack of control of more superficial paraspinal muscles (Krageloh-Mann & Bax, 2009; van der Heide & Hadders-Algra, 2005).

As stated in relation to the degrees of freedom problem, goal-oriented movements can be performed in multiple ways and following diverse motor paths in order to achieve the same goal. In this manner, there will be multiple suitable solutions to solve a motor problem in goal-oriented tasks (Bernstein, 1967). In the study of reach-to-grasp movements in combination with posture, the number of DOF and the range of motion to control challenges the neuromuscular system with regard to motor planning, motor performance and online motor corrections. For this purpose, the explicit numbers of DOF of the anatomical segments and the adequate implicit range of motion has to be learned by the infant and practiced in goal oriented tasks across diversified contexts throughout the life span (Bernstein, 1967; Shumway-Cook & Woollacott, 2011).

In a biomechanical sense, the anatomical position of the muscle usually defines its goal. However, most of the anterior and posterior trunk muscles are multifunctional and a muscle's symmetrical or asymmetrical contraction will depend upon the postural demands of the motor task. In this way, motor units of muscle branches of the trunk can be selectively controlled by the somatic nervous system. The intricate neuromuscular control of trunk muscles has been extensively investigated. As an example, psoas major can generate flexor or extensor trunk torques depending upon the orientation of its muscle fibers. Furthermore, the CNS presents a sophisticated discrete control of specific myofibers of these multifascicular trunk muscles the during anticipatory muscle adjustments elicited by arm movements (Gandevia, Hudson, Gorman, Butler, & De Troyer, 2006; Park, Tsao, Cresswella, & Hodges, 2014).

All the evidence mentioned above, bolsters the proposed multisegmental viewpoint of trunk control. In sensorimotor disorders, the trunk should not be assumed to be a single and non-dissociable structure, especially during infancy and childhood. In the moderate and severe cases of CP with limited independent self-produced mobility, diminished motor experience in diverse ecological contexts, neuromuscular dysfunction, persistence of postural reflexes and musculoskeletal malformations such as hyperkyphosis, scoliosis and coxofemoral dislocations will critically limit the ability to control and coordinate the segments of the trunk as a unique structure across development, as opposed to what is seen in healthy individuals (Chan & Miller, 2013; Kapandji, 2008; Rosenbaum et al., 2002; Scheck et al., 2012; van der Heide & Hadders-Algra, 2005).

MULTISEGMENTED BIOMECHANICAL MODEL FOR INVESTIGATING REACHING & POSTURAL CONTROL IN CEREBRAL PALSY

In healthy individuals, in most of trunk movements, the trunk can be considered a single structure, since the anatomical segments are accurately coordinated in temporal and spatial coordinates. Nonetheless, in CP there are evident deficits for planning and executing automatic trunk postural responses of epaxial and hypaxial muscles[30], controlled through long descending motor tracts[31] that act bilaterally on motor interneurons, propriospinal interneurons and motor neurons, functionally associated with the upper limb motor program (Martin, 2005; Rizzolatti & Kalaska, 2013; Shinoda et al., 2006). Due to the profound deficit for controlling the wide range of DOF provided by the upper body (trunk, head and arm) in children with CP, the trunk cannot be controlled as a whole unit. Then, why would we not reduce the number of vertebral segments involved in postural movements to facilitate the neuro-modulatory

---

[30] **Hypaxial muscles** refer to the ventral muscles of thorax innervated by the ventral rami of the ventral root; whereas **epaxial muscles** correspond to those dorsal muscles of the back innervated by the dorsal rami of the ventral root. Epaxial muscles are in turn categorized into: mutifidus, semiespinalis, longissimus and iliocostalis groups of neck and back.

[31] **Long descending motor tracts:** In this dissertation, this group of tracts is subdivided into lateral (corticospinal and rubrospinal funiculi) and medial (vestibulospinal, reticulospinal, tectospinal, interstitiospinal and fastigiospinal).

control and coordination of the DOF within the trunk deficit, and indirectly improve reaching proficiency?

In order to study this multisegmental concept of trunk control from a functional perspective, myoelectrical and biomechanical techniques can be used in the analysis of posture and arm movements in CP. The results of such analyses could then be utilized for understanding and describing the sensorimotor consequences of the original CNS damage on postural and upper limb control. The principal theoretical assumptions and the biomechanical model applied in this dissertation are summarized in Figure 1.

As we can observe in figure 1, middle panel, the trunk can be sub-divided into different anatomo-functional segments and considered as a core element to be controlled as part of the central set of posture in the sitting position, mainly in neurological conditions (Butler, 1998; Cordo & Nashner, 1982). According to the aforementioned information and this theoretical concept, the number of sub-vertebral units could be simplified if we group them into the three main segments that compose the vertebral column: cervical, thoracic and lumbar.

In this experimental paradigm the vertebral column acts as different lever arms of the system, which is placed over the fixation point at which the trunk is constrained through a firm external support at three levels of the trunk: axillae (cervical segment), mid-rib (cervical and thoracic segments) and pelvic (cervical, thoracic and lumbar segments).

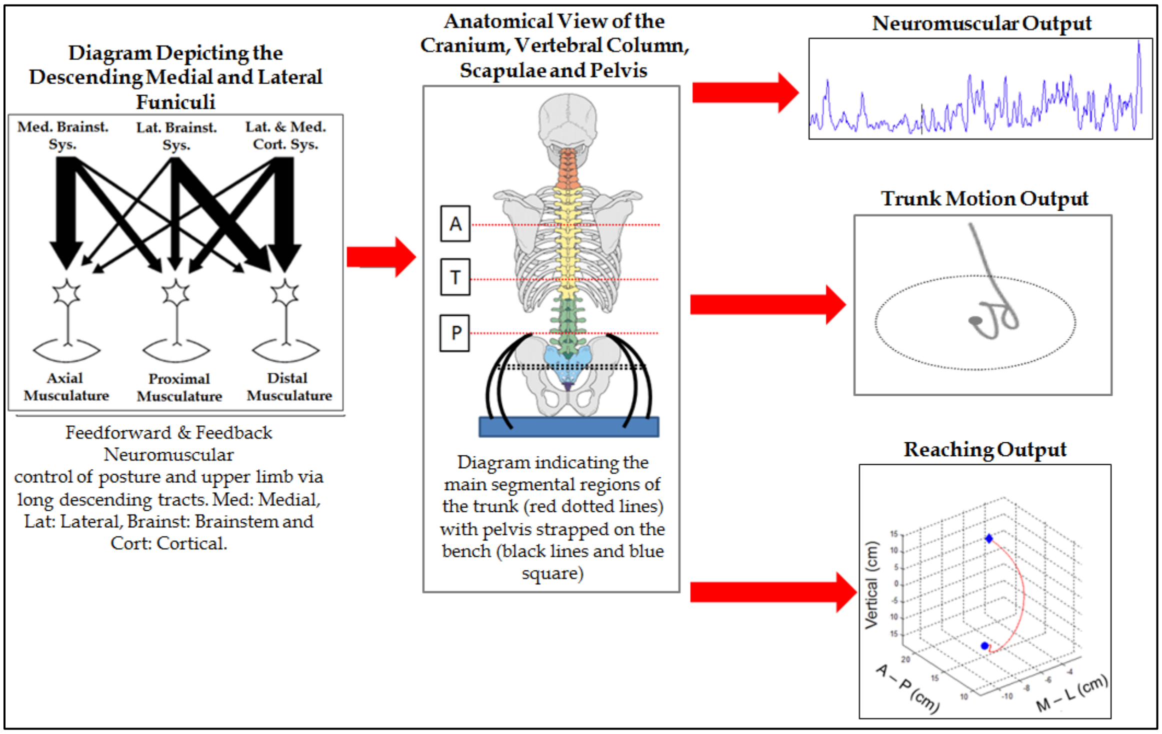


Figure 1. Methodological Approach for Studying Segmental Trunk Control in Postural Sitting and Reaching. Left Panel: Neural control of posture and volitional movements for generating outputs appropriate to the motor task and surrounding ecological context. Middle Panel: Core skeletal system that must be controlled and coordinated with head and upper limb during voluntary reaching. Right Panel: Motor outcomes determined by the muscular activity (EMG) and movement trajectory depending on the final goal of the task.

At the different levels of support the biomechanical parameters would be different. For example, the configuration of the passive osteo-ligamentous structures, height of the lever arm and range of motion. Also, the level of neuromuscular complexity would differ depending on the number of sub-vertebral units to coordinate. Therefore, the constraint of the biomechanical DOF of the trunk would change the position of the center of mass of the trunk and head, and also how the movement of these segments would need to be maintained against gravity and associated with arm movements. From a biomechanistic viewpoint, this group of observations could be monitored in a simple linked-segment model representing the vertebral column over the pelvis in vertical sitting (Figure 2).

This biomechanical subdivision of the trunk can be utilized in research for investigating not only posture in CP but how postural dysfunction influences upper limb control during reaching as well (Fig. 1 & 2). Because of the close functional relationship between motor control of posture and reaching, a plausible improvement or decrement of upper limb control would result from the decrease or increase of vertebral segments to control. Thus, it is viable to hypothesize that those subjects with severe damage of parieto-frontal areas with important problems in reaching-grasping organization and execution would require further assistance for controlling those DOF of the trunk.

RATIONALE, RESEARCH QUESTIONS AND HYPOTHESES

STATEMENT OF THE PROBLEM

The presented dissertation is a three-fold project in which we examine the contributions of trunk control to reaching proficiency in 1) healthy individuals and 2) children diagnosed with CP with moderate and severe motor dysfunction according to the GMFCS scale.

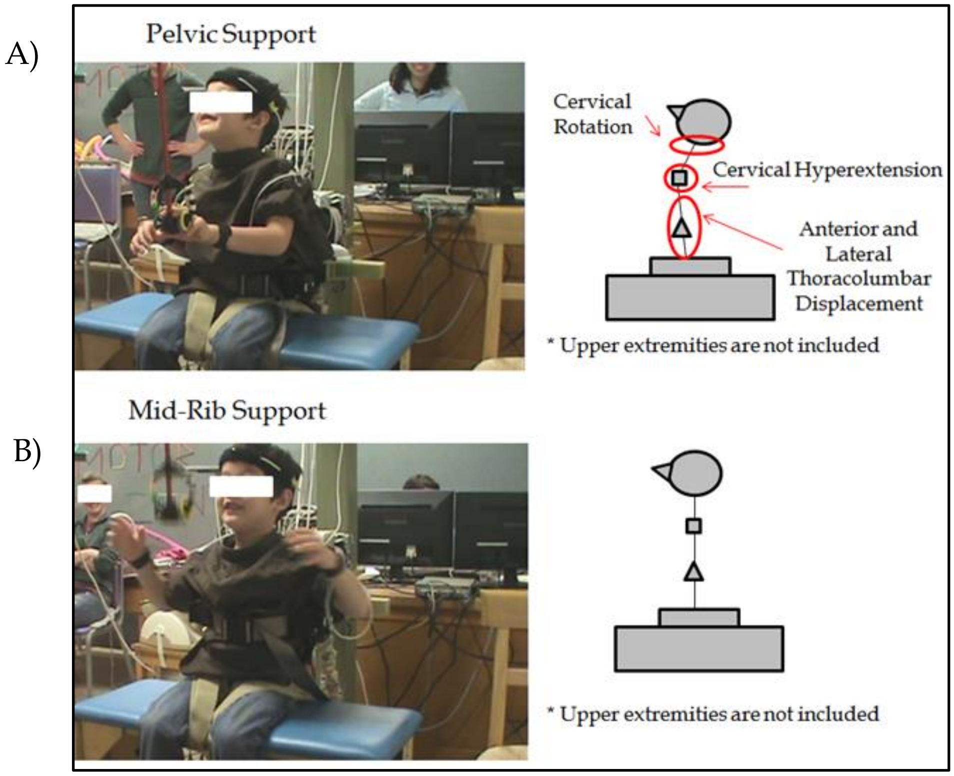


Figure 2. Simplified Linked-Segment Model & Biomechanical Effect of the External Trunk Support on Postural Sitting. Pediatric subject diagnosed with CP. The left side is a photograph captured during data collection and the right side represents the simplified biomechanical model investigated. A) Example of the biomechanical disruption typically found in children with CP and trunk dysfunction in the experimental paradigm investigated. B) This other picture represents the three-dimensional improved alignment of head-trunk when the external trunk support was raised only one level, to the mid-rib position.

In the series of experiments addressed in this dissertation, the trunk is modeled as a dynamic multisegmental structure in which the multifascicular trunk muscles have specific control over the sub-vertebral units that compose the vertebral column.

In motor learning and control, the DOF and range of motion provided by the number of anatomical segments and articulations involved in a movement must be controlled and coordinated in order to accomplish the goal of the motor task (Bernstein, 1967). In the human body, the upper extremities are typically carrying out voluntary movements, with the final goal of orienting hand and fingers to manipulate an object. The upper extremity is a complex articular system linked by specific joints that offer a high range of DOF in order to provide the high variability required in arm movements (using the upper extremities for eating or drinking, for instance). The inclusion of other anatomical segments, like head or trunk, increases the number of DOF and range of motion to control. Thus, postural preparation and stability is required for the dynamic control of the arm and hand.

In healthy conditions, we could assume that control of the head and trunk segments is embedded in the control of the upper limb. More specifically, the trunk would be assumed to work as a complete functional unit controlled by coordinated muscular synergies and adapted to the constraints of the motor task and environment. Nonetheless, in neuromotor disorders like CP, the vertebral column should not be considered as a non-dissociable system. In this pathological condition and principally in the most severe cases, there is a substantial disruption of those automatic postural adjustments that accompany upper limb movements. Children with CP would not even be capable of executing and coordinating these postural reactions in the sitting position.

In research, the design and investigation of the experimental protocol on a mature adult population is desirable and highly recommended in order to determine the “gold standard” for task performance. In this case, young adults with no musculoskeletal or neurological problems were selected as the population of reference for testing and developing the impact of the external support on postural stability and arm control during a reach-to-grasp task. The experiment was designed to test the experimental protocol, as well as to contribute to the understanding of normal head-trunk and arm control during sitting, as a comparison to that seen during reaching in children with CP. We aimed to determine if an external trunk support at pelvic and mid-rib levels would influence the control of posture and arm movements during reaching in healthy young adults.

In moderate and severe cases of CP (GMFCS: III-V), there is a typical disability in coordinating the voluntary control of upper extremities and posture that is evident in seated reaches. In fact, some of these children with CP (GMFCS IV-V) are not capable of keeping independent balance in the sitting position. In these children the head and trunk postural control is critically damaged and this affects planning and execution of precise motor skills, such as reaching and grasping. In addition, their low score on clinical assessments including the

GMFM, QUEST and SATCo, documents their poor functional status and justifies the necessity for investigating the extent to which higher levels of postural support would lead to improved upper extremity control in seated reaching. The next three studies are described in Chapters III-V and include un-published, co-authored material. Jaya Rachwani, Sandra L. Saavedra, Wayne Manselle and Marjorie Woollacott are co-authors.

FIRST AIM: THE IMPACT OF SEGMENTAL TRUNK SUPPORT ON REACHING AND POSTURE IN HEALTHY ADULTS WHILE SITTING

The principal goal of this study was to establish a gold standard methodology and experimental protocol involving postural and arm control during reaching in healthy young adults. We tested how an external trunk support at pelvic and mid-rib levels impacted the kinematic and EMG profiles of head-trunk and arm in adult individuals with non-pathological conditions. The following set of main research questions was addressed:

1). Does the external level of trunk support [Mid-Rib/Pelvic] change the kinematic profiles of the head and/or trunk [Angular Displacement/Angular Orientation] during a reaching task?

2). Does the external level of support [Mid-Rib/Pelvic] impact the accuracy of the reach [Movement Time/Peak Velocity/Percentage of Reaching Trajectory at which Maximum Velocity was Acquired/ Straightness Score/Movement Units/Normalized Jerk Score] in a reaching task?

3) Are there differences in arm-trunk coupling [Arm-Trunk Coupling Index in the A-P plane of the reach] when changing the constraint of the trunk with the external support [Mid-Rib/Pelvic]?

4) Could the trunk constraint [Mid-Rib/Pelvic] induce kinematic or neuromuscular adaptation [Motor Adaptability] of postural or reaching control?

5). Does the external level of support [Mid-Rib/Pelvic] modulate the rate of muscle activation of arm and/or trunk [Muscle Activation Rate]? If this is the case, would this muscle activation rate occur prior to the reaching onset [Anticipatory postural stage (APA)] or during the reach [Compensatory postural stage (CPA)]?

6). Are there any changes in the amplitude [iEMG] of the trunk and/or arm muscles during baseline, APA or CPA stages depending on the provided level of trunk support [Mid-Rib/Pelvic]?

7). Are there different EMG temporal sequences in the activation of trunk/arm muscles [Onset/Offsets of Muscle Responses] depending upon the trunk support [Mid-Rib/Pelvic]?

8) Would the synergistic control of ipsilateral/contralateral trunk muscles differ [Percentage of Complete/Coupled/Isolated paraspinal pattern] depending on the external level of trunk support provided [Mid-Rib/Pelvic]?

SECOND AIM: THE IMPACT OF SEGMENTAL TRUNK SUPPORT ON POSTURE AND REACHING IN CHILDREN WITH MODERATE AND SEVERE CEREBRAL PALSY I: A KINEMATIC STUDY

In this part of the project, subjects with CP were grouped according to their level of postural impairment. We studied how the motor control of head-trunk and arm was modulated with regard to the level of the trunk at which the external support was provided. The following research questions were addressed:

1) Is the deficit of intrinsic trunk control of children with CP [Mild/Moderate/Severe] correlated to their gross motor functional ability [GMFM] and to their gross motor functional classification system [GMFCS]?

2) Does the level of external support [Axillae/Thoracic/Pelvic] depending on the intrinsic trunk control of the subject with CP [Mild/Moderate/Severe] improve, or contrarily, reduce the quality of arm movements [Movement Time/Path Length/MU/Straightness Score] during a reaching task?

3) Could the level of external support [Axillae/Mid-RIb/Pelvic] improve the motor control of head [Head Angular Displacement/Head Angular Orientation] and/or trunk [Trunk Angular Displacement] during the reaching task in children with different levels of intrinsic trunk control [Mild/Moderate/Severe]?

THIRD AIM: THE IMAPCT OF SEGMENTAL TRUNK SUPPORT ON REACHING AND POSTURE IN CHILDREN WITH MODERATE AND SEVERE CEREBRAL PALSY II: AN ELECTROMYOGRAPHIC STUDY.

In this part of the project, the electromyographic profiles of arms and trunk muscles during the reaching task were the focus of the research. The neuromuscular control of arm and paraspinal muscles prior to and during the reaching task was investigated. Additionally, the biomechanical effect on trunk position during the reaching task was investigated as a complementary analysis of EMG profiles. For this purpose, the research questions related to temporal-spatial and synergistic parameters using surface EMG were:

1) Do we observe anticipatory or compensatory postural control of head or trunk [activation rate of APA and CPA] in the seated reaching task depending upon the level of external trunk support [Axillae/Mid-RIb/Pelvic] and level of intrinsic trunk control in children with CP [Mild/Moderate/Severe]?

2) Is there any modulation of the amplitude of arm and/or head-trunk muscle responses [iEMG] in APA and/or CPA stages during the reach depending on the external level of support provided [Axillae/Thoracic/Pelvic] in subjects with CP with different levels of intrinsic trunk control [Mild/Moderate/Severe]?

3) Could different external levels of trunk support [Axillae/Mid-Rib/Pelvic] modulate the temporal patterns of arm and paraspinal muscle activations [Onsets/Offsets/Latencies of muscle responses]? Do they take place in the APA

or CPA stage depending on the level of support [Axillae/Mid-Rib/Pelvic] and level of intrinsic level of trunk control [Mild/Moderate/Severe]?

4) In terms of postural control, would an external level of trunk support [Axillae/Mid-Rib/Pelvic] affect the synergistic paraspinal patterns [Percentage of Complete/Coupled/Isolated paraspinal patterns] depending upon the intrinsic control of the trunk of the child with CP [Mild/Moderate/Severe]?

5) Could external trunk support [Axillae/Mid-Rib/Pelvic] affect the recruitment order of back muscles [Percentage of Craniocaudal/Caudocranial synergistic patterns] with regard to the intrinsic control of the trunk of the child with CP [Mild/Moderate/Severe]?

CHAPTER II

GENERAL METHODS & EXPERIMENTAL PROCEDURE

INFORMED CONSENT

The Institutional Review Board (IRB) for Protection of Human Subjects formally approved the studies and protocols that constitute this dissertation (Chapters III -V). Also, the IRB requirements for dealing with special populations as research participants were completed by the laboratory personnel before any data collection. The inclusion criteria for the study with adults were: 1) adults aged 20-30 years, and 2) no neurological or orthopedic impairments. The inclusion criteria of the studies with children were: 1) children aged 2–15 years; 2) diagnosis of mild, moderate or severe CP; 3) inability to walk independently (GMFCS III, IV and V) and 4) severe spinal deformities, scoliosis > 40° and kyphosis > 45°. The experimental protocol was performed on one day for healthy adults and two different days for children in order to perform the clinical assessment and kinematic/EMG analyses, with no more than one week between sessions. Additionally, families who lived outside Eugene and Springfield (OR) were reimbursed for hotel stay and trip mileage. The experimental protocol was explained to the subjects/parents and occasionally the child, if the age and cognitive level allowed it. Then, the written consent was signed before proceeding to the data collection.

MOVEMENT KINEMATICS

Kinematics can be generally defined as the analysis of movements in terms of space, angles, velocity and higher derivatives; kinematics is different from kinetics that deals with the causes of motion, considering mass, inertia and stiffness for calculating joint torques and forces (Winter, 2005; Wolpert et al., 1995). In the set of experiments performed, kinematics analysis in Cartesian coordinates was applied in order to describe the motion of head, trunk and arm during the reaching task in the sitting position in young adult subjects and children with CP.

The kinematic analysis was carried with the miniBIRD® system (Ascension company technology. Burlington, Vermont). It is a six degrees-of-freedom measuring system that tracks and calculates the position and orientation of electromagnetic sensors with respect to a transmitter. The motion of the sensors can be registered at 30-144 measurements per second within a distance of ± 30 inches from the transmitter. The data position and orientation of the sensors is obtained by the pulsed DC magnetic fields produced by the miniBIRD® that are received by the tracking sensors. The magnetic field information is then made available to the host computer. The magnetic transducers can detect different positions and orientation of the sensors due to the properties and interaction between stationary electric charges (electric field) and moving electric charges (currents) of the generated electromagnetic field. In the set of experiments performed for this dissertation, four miniBIRD® units were interconnected and setup with a Fast Bird Bus (FBB) to form what is called a Flock of Birds (FOB). This configuration allowed the use of 4 different sensors associated with a unique common transmitter (miniBIRD™ installation and operation system, 2000).

The kinematic convention for describing the motion of head, trunk and arm was adapted to the default axis-configuration of X, Y and Z axes programmed by default in the electromagnetic device. Once the reference axes were established, the right-handed convention was used for addressing the directionality of angular motion in which a positive direction follows a counterclockwise course (Figure 3).

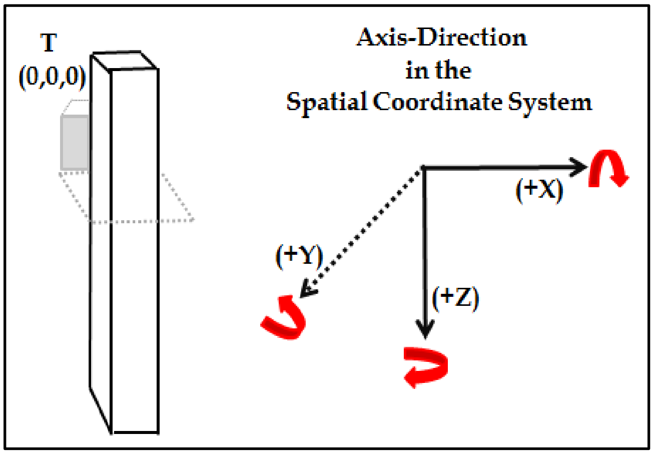


Figure 3. Diagram of the Magnetic Tracking Device Flock of BIRDs and Global Reference System. Axis-coordinates provided by the flock of miniBIRDs according to the right-handed convention and Euler's model. The motion of the segments around the axes would be X: flexion (+) / extension (-), Y: right lateral flexion (+) / left lateral flexion (-), and Z: left rotation (+) / right rotation (-). T: Transmitter with coordinates (X:0, Y:0, Z:0).

SENSOR CONFIGURATION AND DATA COLLECTION OF ANATOMICAL REFERENCES

Four magnetic sensors were used to track the motion of head, trunk and upper extremities. The head sensor was placed on the center of the forehead, following the midline that crosses the nasion. The sensor for detecting the trunk motion was placed over the prominent spinous process of C7. And the sensors for detecting arm movements were located on the radial styloid processes of both arms.

We estimated the position of the virtual center of the head (VCH) for calculating head kinematics with respect to the trunk. For this purpose, the right and left tragus were digitized together simultaneously with the data position of the forehead sensor. We calculated the midpoint between left and right tragus. Then, we computed again the midpoint distance between forehead sensor and mid-point between the right and left tragus and thus obtaining the VCH.

In the two-dimensional kinematics applied in the adult study (chapter III), the estimation of the virtual center of the trunk (VCT) was calculated by digitizing the anatomical position of the sternal notch and then calculating the midpoint between this point and the sensor placed over the spinous process of C7.

In the three-dimensional kinematic approach applied in the study of children with CP (chapters IV), the VCT was defined as half the distance of the vector created by the sternal notch-C7 midpoint to the intersection point between the anteroposterior and transversal virtual axes, or center of trunk support (CTS). These anteroposterior and transversal axes were obtained by digitizing the anterior, posterior and lateral points of the thorax immediately over the external trunk support provided. More specifically, the anterior and posterior trunk points coincided with: sternal manubrium and T3-T4 at axillae level; middle anterior area of the sternum and T7–T8 at mid-rib level; and, umbilicus and midpoint between posterior superior iliac spines/base of sacrum at pelvic level.

Lastly, the origin of all the kinematics was re-referenced to the center of the external trunk support (CTS) at each of the analyzed levels: axillae, mid-rib and pelvic. An important methodological aspect to point out is that the CTS does not correspond to the base of support; which by definition corresponds to the area of the bench in contact with the buttocks and posterior side of the two thighs while sitting

The two-dimensional analysis of arm, head and trunk movements is described in detail and depicted in chapter III.

COMPUTATION OF TRACKING AND ANATOMICAL REFERENCE SYSTEMS IN THREE-DIMENSIONAL KINEMATICS

In chapters IV and V, we evaluated head and trunk movements with three-dimensional angular kinematics. The first step was to define two Cartesian coordinate systems that corresponded to the anatomical coordinate system (ACS) of Head and Trunk (ACS_{Head} and ACS_{Trunk}). The concept of rigid body formation was assumed and Cardan angle's approach (X Y' Z'') was applied in the computation of the joint coordinate systems (JCS) of the cervical and trunk segments. The distal ACS was fixated on the head (moving segment) and the other one was placed on the trunk (fixed segment). Then, a third system was placed between these two body-fixed-references and acted as a "floating" system. This last mobile reference system has been proposed to be aligned with the longitudinal axis of the moving segment (Kono et al., 2002; Wu et al., 2005).

The ACS_{Head} and ACS_{Trunk} were obtained by collecting the data position of three non-collinear anatomical references selected and digitized during the static trial at each level of support provided (Figures 4 & 5); in which head and trunk were maximally aligned with respect to each other. For this purpose, the concepts of unit vectors[32] and rotational matrices[33] were applied in the computation of the ACS_{Head} and ACS_{Trunk}.

The origin of the ACS_{Head} was located at the position of the virtual center of the head (VCH, see above: *Computation of Anatomical and Biomechanical References)* and calculated as follows:

---

[32] **Unit Vector ($\bar{u}$):** A unit vector is defined as a vector of unit length along one of the axes of a coordinate system, where $|\vec{e}A| = 1$.

[33] **Rotational Matrices:** Matrices applied to compute two- or three-dimensional rotations in the Eucledian space. The arbitrary rotation around X, Y and Z axes are commutative and thus the order in which matrices are multiplied will have an effect on the definition of the axis rotations.

Computation of the unit vectors ($\bar{u}$) along the x-, y- and z-components for the configuration of the ACS_{Head:}

$$\bar{\boldsymbol{i}}\ \textbf{vector} = \frac{Left\ Tragus - VCH}{|Let\ Tragus - VCH|}$$

$$\bar{\boldsymbol{k}}\ \textbf{vector} = \frac{(Left\ Tragus - VCH) \times (Forehead - VCH)}{|(Left\ Tragus - VCH) \times (Forehead - VCH)}$$

$$\bar{\boldsymbol{j}}\ \textbf{vector} = \bar{k} \times \bar{i}$$

Where $\lvert vector \rvert$ = *Indicates the magnitude of the vector, defined as* $\sqrt{x^2 + y^2 + z^2}$

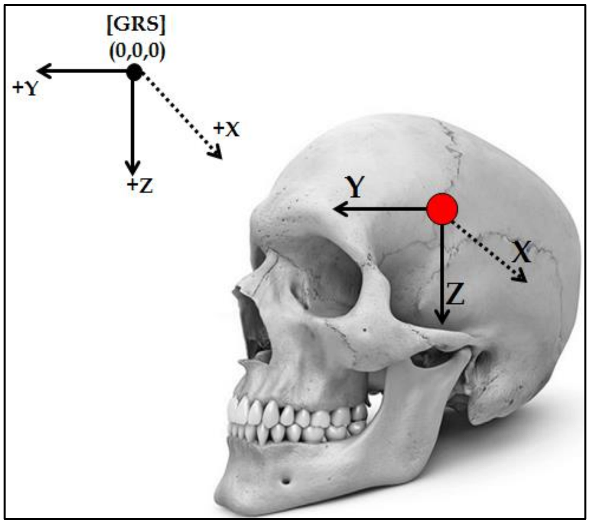


Figure 4. Configuration of the Anatomical Coordinate System of the Head. The red circle indicated the approximate location of the virtual center of point of head (VCH). GRS shows the positive disposition of the global axis. Y-axis points forward; X-axis points left and Z-axis points downward. Figure obtained and modified from: http://www.3dscience.com/3D_Models/Human_Anatomy/Skeletal/Human_Skull.php

In the case of the trunk, the origin of the ACS$_{\text{Trunk}}$ was placed over the position of the VCT (see above three-dimensional analysis of the trunk*: Computation of Anatomical and Biomechanical References*). Then, the ACS$_{\text{Trunk}}$ was configured with respect to the CTS and calculated as follows:

Regarding the computation of the unit vectors ($\overline{u}$) for the ACS$_{\text{Trunk}}$ with origin in VCT (Half way between midpoint of the vector C7-SN and CTS):

$$\boldsymbol{\overline{j}\, vector} = \frac{Sternal\ Notch - VCT}{|Sternal\ Notch - VCT|}$$

* We keep the location of the VCT in the z-coordinates so that the $\overline{j}\ vector$ has its origin at the VCT.

An additional vertical vector pointing downwards along the z-axis was calculated for obtaining the unit vector $\overline{i}$ (pointing left along the x-axis):

$$\vec{V} vertical = CTS - VCT$$

Once we calculated this supplementary vertical vector pointing downwards to the center of the trunk support, $\overline{i}\ and\ \overline{k}$ vectors were computed:

$$\boldsymbol{\overline{i}\, vector} = \frac{(Sternal\ Notch - VCT) \times (\vec{V} vertical)}{\left|(Sternal\ Notch - VCT) \times (\vec{V} vertical)\right|}$$

$$\boldsymbol{\overline{k}\, vector} = \ \overline{i} \times \overline{j}$$

Where $|vector|$ = *Indicates the magnitude of the vector, defined as* $\sqrt{x^2 + y^2 + z^2}$

According to the *International Society of Biomechanics* (ISB), in the analysis of three-dimensional angular kinematics, the distal segment, head, should be referenced to the proximal one, the trunk. An exception can be made in the case of the trunk; this can alternatively be referenced with respect to the global reference frame (Figure 6). Therefore, in the experimental paradigm proposed, the head is referenced to the trunk and trunk to the GRS in order to calculate the motion of both segments during the reaching task (Wu et al., 2005).

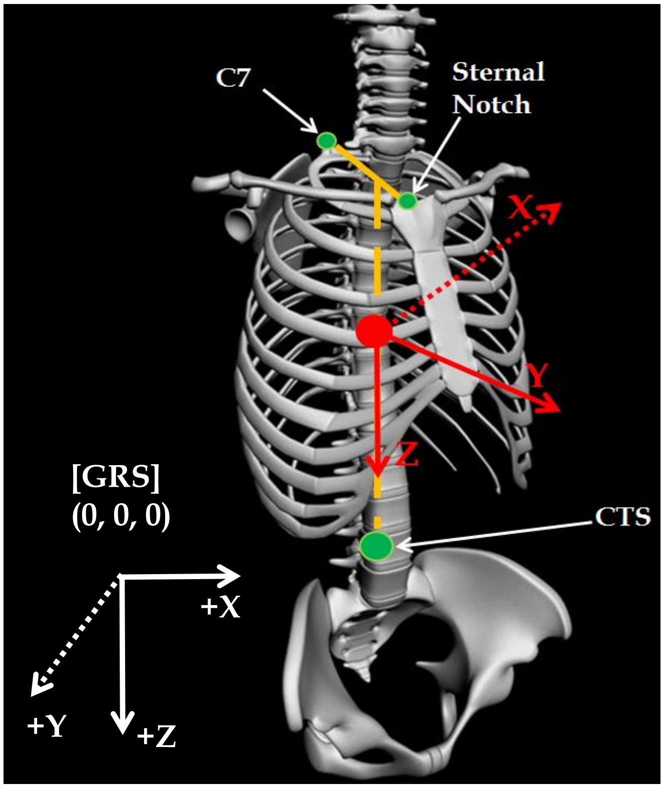
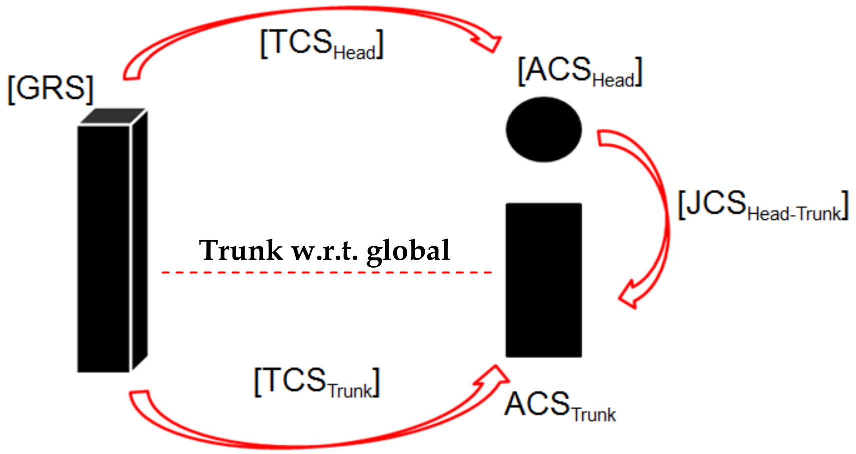


Figure 5. Configuration of the Anatomical Coordinate System of the Trunk. CTS: center of trunk support, represented as the intersection between the anteroposterior and lateral axes **.** Red Circle: Virtual center of the trunk (VCT). Figure obtained and modified from: http://www.turbosquid.com/3d-models/maya-thorax-bones-anatomy/641400

Cardan's angle computation is sequence dependent and thus requires selecting the most appropriate order of angles for describing the postural orientation and motion of head and trunk along the x-, y and z- axes.

A)



B) $[\mathrm{JCS}_{\mathrm{Head\text{-}Trunk}}] = [\mathrm{ACS}_{\mathrm{Head}}]^{-1} * [\mathrm{TCS}_{\mathrm{Head}}]^{-1} * [\mathrm{TCS}_{\mathrm{Trunk}}] * [\mathrm{ACS}_{\mathrm{Trunk}}]$

C) $[\mathrm{JCS}_{\mathrm{Trunk\text{-}GRS}}] = [\mathrm{TCS}_{\mathrm{Trunk}}]^{-1} * [\mathrm{ACS}_{\mathrm{Trunk}}]$

Figure 6. Diagram Representing the Computation of Angular Kinematics of Head with Respect Trunk and Trunk with Respect to Global. This figure shows the biomechanical sequence for calculating the angular displacement of head and trunk (A). Also, the final mathematical equations for calculating the head with respect to trunk (B) and Trunk with respect to Global Reference System (C) are included. [Head ACS] = Anatomical coordinate system of the head; [Trunk $_{\mathrm{ACS}}$] = Anatomical Coordinate System of the Trunk; [JCS $_{\mathrm{Head\text{-}Trunk}}$] = Joint Coordinate System of Head with respect to Trunk; and [JCS $_{\mathrm{Trunk\text{-}GRS}}$] = Joint Coordinate System of Trunk with respect to Global.

For this purpose, we decided to apply as the angular sequence X, Y′ Z′′ that corresponded to gamma (γ), beta (β) and alpha (α), respectively. In the selected set of angles, the movements were described as flexion (+) and extension (-), around the x-component (Pitch: horizontal axis); right (+) and left (-) lateral flexion, by the y-component (Roll: anteroposterior axis); and right (+) and left (-) rotations around the z-component (Yaw: vertical axis).

The matrix for the computation provided by the Magnetic Tracking system, flock of MINIBirds is:

$$\begin{bmatrix} \cos Y * \cos Z & \cos Y * \sin Z & -\sin Y \\ -\cos X * \sin Z + \sin X * \sin Y * \cos Z & \cos X * \cos Z + \sin X * \sin Y * \sin Z & \sin X * \cos Y \\ \sin X * \sin Z + \cos X * \sin Y * \cos Z & -\sin X * \cos Z + \cos X * \sin Y * \sin Z & \cos X * \cos Y \end{bmatrix}$$

From this matrix, the angles γ, β and α were obtained by calculating the function (Atan2) in the next set of matrix elements:

$$\gamma = Atan2\ (\frac{R_{23}}{R_{33}})$$

$$\beta = Atan2\ (\frac{(R_{13} * \cos \gamma)}{(R_{33} * -1)})$$

$$\alpha = Atan2\ (\frac{R_{12}}{R_{11}})$$

KINEMATIC FILTERING

The biomechanical analysis of movement is associated with inherent sources of error. These are mainly derived from the simultaneous use of two systems of data collection (e.g. electromyography and electromagnetic sensors), skin motion artifact and assumption of rigid body dynamics[34] (Robertson,

---

[34] **Rigid Body Dynamics:** Theoretical approach in biomechanics in which body segments are considered to be non-deformable by external forces and with fixed inertial properties.

Cladwell, Hamill, Kamen, & Saunders, 2004). Additionally, in most cases of CP, the disruption of corticopontine and corticospinal pathways as well as damage of basal nuclei and thalamus typically result in spastic, dystonic and athetoid movements (Krageloh-Mann & Bax, 2009). Therefore, in the set of experiments presented in chapters IV and V, the postural and reaching movements are expected to be segmented and characterized by irregular trajectories and abrupt changes in the velocity and acceleration profiles. Added to the perturbation of motion due to the nature of the neuropathology, the mathematical computation of the first and second derivatives of the position data of the body landmarks will require an adequate filtering process (D'Amico & Ferrigno, 1992). The digital algorithm-filter applied for smoothing kinematic outcomes was a zero-lag 4thorder low-pass Butterworth filter with a cutoff frequency of 6Hz. Among the main features in the selection of this digital recursive filter we could point out the absence of ripple effect in the pass-band of the kinematic signal; which results in a maximally undisrupted flat signal. The zero-lag feature was used to avoid possible delays secondarily induced by the 4th order filter (Winter, 2005).

MYOELECTRICAL ANALYSIS

Surface electromyography (EMG) describes the differential voltage potential established between two superficial electrodes placed over the belly of the muscle of interest, when the muscle fibers are depolarized and contracted.

EMG signal conveys information about the degree of muscle contraction (force), frequency bandwidth of muscle fibers (frequency spectrum) and muscle onsets/offsets (timing parameters) required in the motor task (de Luca, 1997; Robertson et al., 2004).

Trunk and arm muscle activity were recorded using a 16-channel surface electromyography system (MA300, Motion Lab Systems, Baton Rouge, LA). In the studies with adults and children with CP, the EMG was collected as a digitized discrete time-varying signal at a sample rate of 1000Hz per channel, with 10 channels in the adult study and 13 channels in the CP study. In addition, one voltage-dependent trigger channel was used for synchronizing the beginning and end of reaching trials.

With regard to the EMG sensor configuration, the interspace between detection surfaces has been shown to affect the amplitude and frequency spectrum and bandwidth of the EMG signal detected. Also, the anatomical characteristics of the area below the surface electrode for registering muscle activity can influence the quality and fidelity of the signal (de Luca, 1997). According to this, the surface electrodes were placed perpendicular to the length of the fibers over the center of the belly muscle, avoiding the muscle tendon, and with electrode inter-distance no greater than 1.5 cm (de Luca, 1997).

The selection of the frequency bandwidth across EMG channels was developed by studying the EMG activity across channels in 50% of the subjects.

For this purpose, the signal of each muscle was visualized in its frequency domain and the power of the signal spectrum was studied by applying a Welch's power spectral density estimate with MatLab software (The MathWorks, Inc., Boston, MA).

An additional study of the possible electromagnetic interference induced by the Magnetic Tracking System was applied. This analysis showed a specific electromagnetic artifact at the frequency of 84Hz. Thus, a notch filter with a narrow bandwidth frequency (2Hz) was applied at the frequency of 84Hz and its harmonics along the EMG muscle signal in order to remove the electromagnetic interference induced by the Magnetic Tracking System.

Since we were collecting myoelectrical activity of paraspinal muscles, the cardiac signal can be an artifact during the EMG data collection. For this reason, EMG data of healthy adults and children with CP underwent an extra stage for removing the cardiac QRS complex from raw EMG signal before moving into the filtering stages of muscle activity.

There have been different techniques and algorithms proposed for removing the heart beat from muscle channels and other electrical sources; however, in this dissertation, a modified version of the algorithm proposed by Aminian et al. (1988) has been applied (Aminian, Ruffieux, & Robert, 1988).

For the design of the heartbeat signal subtraction we used a customized program developed with MatLab software (The MathWorks, Inc., Boston, MA).

We designed a set of interactive visual and quantitative aids that read and plotted the cardiac signal so that the user could visually select the amplitude and polarity of the QRS complex. Once this amplitude was determined and reviewed, the algorithm searched for those EMG data points above the selected threshold with duration no longer than 7ms in the heart signal channel and then identifying the potential QRS artifact peaks in the complete heartbeat signal.

In the next stage of the algorithm, the amplitude of each cardiac QRS complex was averaged and if the peak amplitude was above 2.0 standard deviations (SD) of this average, it was discarded and not removed from the EMG muscle signal. Signals over 2.0SD were assumed to be related to other sources of noise: EMG electrodes or cables that hit or snagged between the subject's body and level of support during data collection, myoelectrical activity from the surrounding abdominal or pectoral muscles or electromagnetic noise.

After the selection of the adequate QRS complex, the mathematical algorithm searched for every potential QRS cardiac complex with the same duration and shape to the one identified in the cardiac EMG channel across each raw EMG muscle channel. This final stage of cardiac QRS removal from the muscle was re-evaluated, plotting three graphs that represented EMG activity of muscle and cardiac artifacts, cardiac signal and EMG muscle activity without cardiac signal (Aminian et al., 1988) (Figure 7).

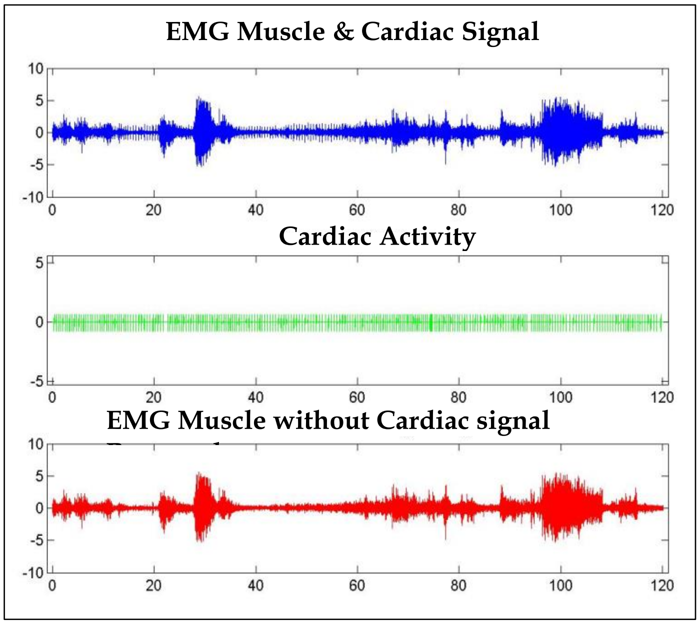


Figure 7. QRS Cardiac Complex Subtraction from EMG Muscle Activity. This graph depicts the visual aid used in the final stage of cardiac signal subtraction. Note that EMG cardiac and muscle signals have been visually compressed to match the variable time scale and amplitude. The upper panel depicts muscle and cardiac signal together, pinpointing the artifact induced by the electrical signal of the myocardium. The middle panel shows the extracted QRS waveform. And the lower panel shows the EMG muscle activity with no cardiac artifacts.

BEHAVIORAL ANALYSIS OF REACHING

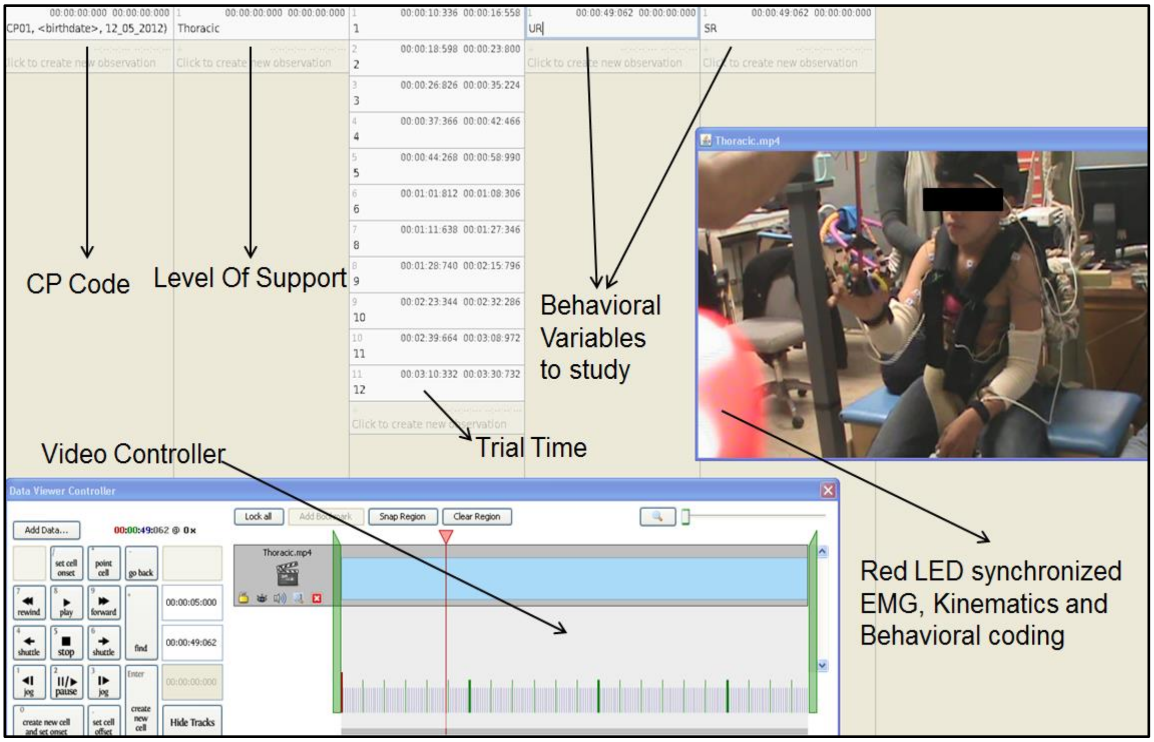
In our sample of children with CP, most of them manifested important cognitive deficits that made it impossible to instruct them to perform a specific behavioral type of reaching. Due to this reason, the subject could reach for the toy with one or two hands, once the object was vertically displayed in the midline. Once the reaches were identified as successful, in which the hand contacted the toy, a behavioral analysis was required to identify the nature of the reach. This reaching classification and typology are presented in table 4:

Table 4: Typology of Reach

Type of Reach	**Description of the Reach**
Unimanual	Only one arm is directed to the object for reaching without any use of the contralateral arm.
Bimanual	The left and right hands are used for reaching for the toy. The hand reaching first for the toy was identified and used for further analysis.
Coupling Bimanual	In this case, both arms are used for reaching as well; however, the time difference between the onsets of the two arms should be < 50ms (van Hof, van der Kamp, & Savelsbergh, 2002; von Hofsten, 1984). In these bilateral reaches, the only arm identified was: - The arm with earlier onset - The first hand to touch the toy

Note: This table displays the three types of reaches included in the behavioral analysis of each participant through visual inspection.

The behavioral analysis was carried with the help of Datavyu software (www.datavyu.org). This program permitted coding the type of level of trunk support, number of trials, arm side and typology of reaching (Figure 8).



[redacted]

Figure 8. Behavioral Analysis of Reaching with Datavyu Software. This illustration displays the user interface design of Datavyu software. It was used for identifying successful reaches and coding the typology of the reach. Notice the red light placed on the left corner of the camera field for synchronizing the beginning (light on) and end of the trial (light off) in synchronization with kinematics and EMG analyses.

CLINICAL ASSESSEMENTS: MOTOR DYSFUNCTION OF POSTURE AND ARM-HAND IN CEREBRAL PALSY

GROSS MOTOR FUNCTION MEASURE: GMFM

The gross motor function classification system (GMFM) is a validated clinical assessment used for measuring the gross motor ability of children diagnosed with different subtypes of CP (Russell, Rosenbaum, Wright, & Avery, 2013). This assessment consists of 5 principal dimensions:

- Dimension A: Lying and Rolling
- Dimension B: Sitting
- Dimension C: Crawling and Kneeling
- Dimension E: Standing
- Dimension D: Walking, Running and Jumping

Currently, there are two main versions of this motor assessment GMFM-88 and GMFM-66. The former is the original version and it includes 88 items, including some motor activities mentioned in the definition of motor ability by the World Health Organization, such as motor ability for moving the body and motor ability related to community participation and interaction. On the other hand, the GMFM-66 is a subset of motor items from the GMFM-88 that have been shown to be uni-dimensional and more related to the dimension assessed with the GMFM. In addition to these GMFM evaluations, other two simplified versions have been created: GMFM-66-Item sets (GMFM-66-IS) and GMFM-66 Basal & Ceiling (GMFM-66-B&C). The former is an algorithm of motor items that permits the tester to identify the dimension and subset of items that should be evaluated according to the motor limitation of the explicit subject; whereas the latter, as its name indicates, uses a basal/ceiling approach to identify such a subset of items.

Among the different versions of the GMFM, GMFM-66-IS was selected for gross motor evaluation of children with CP. The rationale in this decision was because it is in an experimental context and we were interested in determining the specific motor ability of each of the participants. Moreover, this version considerably reduces the amount of time invested in the clinical assessment, avoiding the possibility of fatigue of the child. This simplified method organizes the motor items of each dimension according to their difficulty. The hierarchy of the motor items depending upon the degree of difficulty is obtained through the Rasch analysis of the original GMFM-66. Rasch analysis is a theoretical approach that applies log-linear analysis[35] to ordinal test data for obtaining interval scores, estimating item difficulty and child's ability. This motor assessment in CP has been essential not only in clinical practice but also in research, since it allows us to classify patients with CP regardless of the heterogeneity and extension of the neurological injury. Then, groups with CP that present similar clinical pictures can be used for investigating clinical interventions, like surgeries, pharmacological treatments and rehabilitation programs, aside from research in physiological, biomechanical and motor impairments in this population (Farmer & Sabbagh, 2007; Heinena et al., 2010; Ketelaar M, Vermeer A, 1998; Russell, Rosenbaum, Wright, & Avery, 2013).

---

[35] **Log-linear analysis:** Statistical technique applied in hypothesis testing and model building in non-dependent variables. It examines the relationships between more than two categorical (nominal) variables, looking for the most parsimonious model that accounts for the variance of the observed frequencies.

GROSS MOTOR FUNCTION CLASSIFICATION SYSTEM: GMFCS

The Gross Motor Function Classification System, or GMFCS, was designed in McMaster University in Canada, in the Center for Childhood Disability Research (CanChild). As described in the web site CanChild "The Gross Motor Function Classification System (GMFCS) is a 5 level classification system that describes the gross motor function of children and youth with cerebral palsy on the basis of their self-initiated movement with particular emphasis on sitting, walking, and wheeled mobility. Distinctions between levels are based on functional abilities, the need for assistive technology, including hand-held mobility devices (walkers, crutches, or canes) or wheeled mobility, and to a much lesser extent, quality of movement". The GMFCS allows for a functional categorization of children diagnosed with different subtypes of CP. It focuses on the motor ability of the child at home, school and community contexts examining "what they do" rather than "what they are expected to do" in regards to their age or clinical profile.

The GMFCS is divided into 5 levels of functional categorization, level I–V, based on self-initiated movements emphasizing sitting, walking and hand-held mobility or wheeled mobility devices. Age is another key factor to consider in this classification system (Palisano, Rosenbaum, Bartlett, & Livingston, 2008; Palisano et al., 1997).

In this dissertation, the new version of the GMFCS expanded and revised (GMFCS-E&R version) was used. This version has been selected from the original since it covers the complete range of ages of the recruited participants. It is composed by the following categories:

- Before 2 years
- From 2 to 4 years
- From 4 to 6 years
- From 6 to 12 years
- From 12 to 18 years

Additionally, Rosenbaum and colleagues in 2002, published a paper correlating the GMFM and GMFCS and discussing the potential ability to predict the functional ability of CP subjects with GMFCS by using the score obtained in the GMFM-66 evaluation. This statistical relationship for predicting motor performance depending upon the GMFCS level is depicted in figure 9.

SEGMENTAL ASSESSMENT OF TRUNK CONTROL: SATCo

Different assessment tools have been designed for the evaluation of balance control in children with motor disorders, including the GMFM and the Chailey Levels of Ability. In these tests, trunk control is included as a subset of other gross/fine motor items and it is usually evaluated as body balance in different positions. More specific assessments for trunk control are the Slump test, Seated Postural Control Measure, Spinal Alignment and Range of Motion Measure.

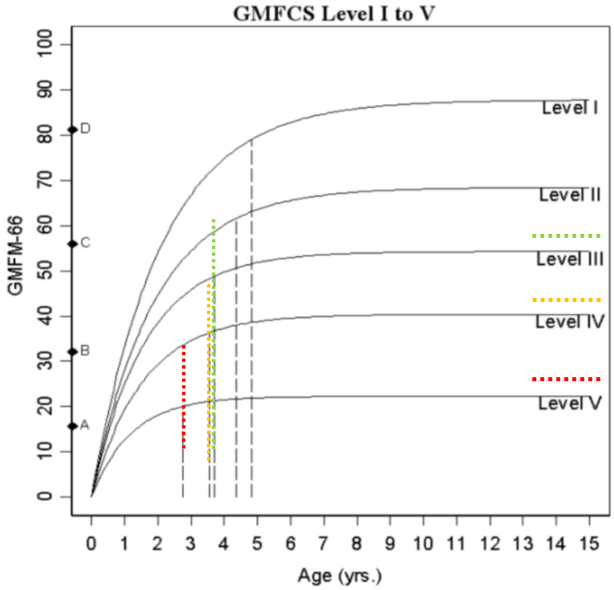


Figure 9. Predicted Gross Motor Potential in GMFCS according to Age and GMFM-66. Prediction of gross motor function measured as GMFCS level according to age and score obtained in GMFM-66 in a sample of children with CP. The curved lines indicate the average motor performance considering the GMFCS level (I-V). The dotted vertical lines indicate the expected 50% of children's age in years by which they would obtain 90% of their motor development. Notice how the maximum potential is obtained in early stages of life in GMFCS levels III, IV and V. Obtained and modified from (Rosenbaum et al., 2002).

Although all these tests are accurate in specific cases, they consider the trunk as a single unit, mainly provide a musculo-skeletal approach or only assess the static and active control of balance (Butler, Saavedra, Sofranac, Jarvis, & Woollacott, 2010).

The Segmental Assessment of Trunk Control, or SATCo, offers a novel biomechanical approach to assessing trunk balance, considering the analytical control of the different vertebral sub-units that compose the main regions of the vertebral column. Using this approach, SATCo evaluates the three principal dimensions of balance control in upright sitting in a population of children diagnosed with CP: static (the participant maintains steady state balance for at least 3 seconds), reactive (the experimenter nudges the participant in the anteroposterior and lateral planes over the level of support evaluated) and active (the participant rotates the head to left and right). This clinical assessment has two main evaluation requirements. The first one is that the pelvis is a key anatomical segment and it must be fixed over the bench where the test will be performed. And the second requirement is that all the vertebral segments below the level of support that fixes the analyzed trunk segment must remain immobile during the test. This last point is essential for providing specificity about the number of vertebral subunits that the patient with CP is able to control in the three dimensions (Butler, 1998) (Appendix).

QUALITY OF UPPER EXTREMITY SKILLS TEST: QUEST

The Quality of Upper Extremity Skills Test, or QUEST, consists of a 34-item criterion –referenced observation test. It is used for evaluating the voluntary and reflex mobility of the upper extremities in children diagnosed with motor impairments (DeMatteo et al., 1992). There are four domains to assess:

- Dissociated Movement: Examination of the arm, hand and fingers
- Grasp: This section examines grasping abilities with different arm positions. Evaluation of the voluntary movement of the fingers is determined by how the child grasps and holds objects.
- Weight Bearing: This area evaluates the ability to support the participant's weight in prone and sitting positions.
- Protective Extension: This part of the test assesses the reflexive and automatic responses of the child performed with upper extremities after a quick displacement of the center of gravity in the sitting position.

The original QUEST was developed for children aged 2-8 years old; however, it has been utilized in older children as well. Additionally, this clinical assessment has been demonstrated to be reliable in the evaluation of upper limb dysfunctions in CP (Thorley, Lannin, Cusick, Novak, & Boyd, 2012).

In this dissertation, the QUEST has been included as a complementary assessment for describing the motor impairment of the upper limb and arm reflexive movements of the participants with CP.

MANUAL ABILITY CLASSIFICATION SYSTEM: MACS

The Manual Ability Classification System, or MACS, determines the skill level of the child with CP during daily living activities. This clinical assessment describes the child's typical performance instead of the child's maximal capacity.

In this dissertation, the flow chart of the MACS was used to categorize the participant's manual ability. It considers the use of both hands for performing manual tasks, organization of movement, task accuracy and rate of success (Eliasson et al., 2006).

Children with moderate or severe CP very commonly show grasping disorders, including poor motor planning, hand and finger shaping during the transport phase, and motor execution, including distal neuromuscular coordination for smooth upper limb movements. In this dissertation, the MACS allowed us to obtain a more functional description of what the child with CP was able to do and at what level of difficulty.

ASHWORTH SCALE: SPASTICITY ASSESSMENT

Ashworth scale is a manual test and it is used to evaluate the degree of spasticity of the main muscle groups in upper and lower extremities, including: elbow flexors, wrist flexors, quadriceps, adductors, hamstrings and dorsiflexors.

In this test, the clinician mobilizes the anatomical segment being analyzed, exerting a movement that opposes the agonist contraction of the examined muscle group while firmly fixating the proximal segment. The examiner is required to exert the same force across the different tested muscles in order to obtain a reliable measure.

The Ashworth scale has been widely investigated with respect to diverse neuromotor disorders and it has been shown that this scale is an adequate reliable assessment for the clinical analysis of muscle tone of upper and lower extremities in CP.   Nonetheless, research has also pinpointed the fact that some muscles present better test-retest reliability than others. For instance, muscles like the hamstrings and coxofemoral adductors, with the knee flexed, display more inter-subject reliability than gastrocnemius or coxofermoral rotators (Mutlu, Livanelioglu, & Gunel, 2008; Yam & Leung, 2006).

Previous studies examining reaching in adults have modeled the trunk as a single unit, ignoring the fact that the spine is a multi-segmented column with anatomically distinct regions varying in function, range of motion and form. There is a lack of research exploring how specific segments of the trunk maintain stability during a reaching task while sitting, and the contributions of the trunk segments to reaching kinematics. Therefore, the aim of the following study was to determine if there would be a difference in postural and arm kinematics of healthy young adults in a seated reaching task, dependent on the level of external trunk support.

CHAPTER III

THE IMPACT OF SEGMENTAL TRUNK SUPPORT ON REACHING AND POSTURE WHILE SITTING IN HEALTHY ADULTS

This chapter contains un-published, co-authored material and thus, the explicit collaboration of each author should be highlighted. I performed the experimental design, data collection, data analyses, statistical analysis and writing of the manuscript. Jaya Rachwani collaborated in the experimental design, data collection and data analyses. Wayne Manselle contributed to the data analysis. Sandra L Saavedra participated in the experimental design, data interpretation and reviews. Marjorie Woollacott provided editorial assistance and collaborated in the experimental design and data interpretation.

INTRODUCTION

Posture has been extensively studied, but our conceptual understanding of how it is controlled is still evolving. Postural control is typically defined as the activation of steady state, anticipatory and compensatory automatic muscular reactions generated in order to maintain balance (Belen'kii et al. 1967; Massion 1992; Shumway-Cook and Woollacott 2011). Research related to postural control in healthy adults has been primarily investigated in standing paradigms; nonetheless, postural control is also required during other activities of daily living, such as reach-to-grasp movements while sitting. Efficient reaches require the interaction of highly specialized cortical areas and subcortical systems to effectively plan the movement while simultaneously preparing and maintaining stability of the trunk prior to and during the ongoing motion of the arm (Downing et al. 2001; Jacobs and Horak 2007; Rosenbaum et al. 2001; Schepens and Drew 2006; Zimmermann et al. 2012).

The impact of posture on the spatiotemporal control of reaching according to target location and distance can be investigated through the end-point kinematics of the arm-hand trajectory (Flanders et al. 1992; Leonard et al. 2009, 2011). Unobstructed reaches without postural constraints are characterized by stereotypical features: straight paths, single-peak bell-shaped velocities, and acceleration and velocity peaks scaled with amplitude (Atkeson & Hollerbach, 1985; Georgopoulus & Massey, 1988; Messier & Kalaska 1999). Research in healthy individuals has shown that these reaching kinematic patterns can be adapted to diverse postural configurations (Hua et al. 2013; Leonard et al. 2011). Specifically in the sitting position, research examining the influence of trunk movements while reaching has shown that most arm kinematics in adults are flexible and can be adapted, remaining invariant regardless of the degree of trunk involvement (Archambault et al. 1999: Ma & Feldman, 1995).

Moreover, research on reaching and pointing tasks in standing paradigms has demonstrated the required continuous coordination needed between arm movements and posture. This is due to the fact that reaching without accompanying postural adjustments can cause a disturbance of the center of mass of the body (Caronni et al. 2013; Gahéry and Massion 1981; Massion 1992). This is achieved by anticipating through feedforward control (anticipatory postural adjustments, or APAs) and/or counteracting through continuous sensory feedback (generating compensatory postural adjustments, or CPAs) (Belen'kii et al. 1967; Hall et al. 2010; Hodges et al. 1999; Massion 1992). APAs occur prior to the activation of the prime mover muscle, either biceps or anterior deltoid, in forward reaching (van der Fits et al. 1998). These APAs are known to be modulated by movement velocity, level of accuracy of the motor task and biomechanical features of the reach per se (Aruin and Latash, 1995; Bouisset 1991; Caronni et al. 2013; Cordo and Nashner 1982; van de Fits et al. 1998). Additionally, APAs are dynamic and flexible, and they are scaled in relation to the degree of both the expected forthcoming perturbations to equilibrium and familiarity with the external support conditions (Arutyunyan et al. 1969; Belen'kii et al. 1967; Hall et al. 2010). On the other hand, CPAs, including associated postural responses, are generated for controlling the COM of each body segment during imposed or self-triggered perturbations (Horak and Nashner 1986; Massion 1992; Santos et al. 2010). Additionally, the neural control of the trunk in reaching tasks includes the regulation of the paraspinal muscle tone prior to APAs (i.e., steady state balance) (Al-Falahe and Vallbo 1988; Gurfinkel et al. 2006). These postural patterns prior to and during arm movements have been widely described in the literature for different age populations in standing paradigms, by examining the activity of the bilateral dorsal and ventral muscle groups of the trunk (Girolami et al. 2010; Hodges et al. 1999; Hodges et al. 2000; Park et al. 2014; Van der Fits and Hadders-Algra 1998; Van der Fits et al. 1998). Nevertheless, activation characteristics of ipsilateral and contralateral paraspinal muscles at each segment of the trunk have not been examined in detail during a reaching task while sitting.

It has been proposed that trunk stability is a foundational element in the central set of posture for efficiently controlling the arm through these APAs and CPAs (Cordo and Nashner 1982). The trunk is a multi-segmented musculoskeletal system with anatomically distinct regions; yet its degrees of freedom (DOF) during a reach are simplified and controlled by muscular synergies elicited as functional units to coordinate and adjust the different muscles to produce the desired biomechanical output (Bernstein 1967; Ting and Macpherson 2005; Ting and McKay 2007; Tresch et al. 2002; Masani et al. 2009). Thus, the CNS, with the appropriate sensory input, can spatially and temporally organize these neuromuscular patterns to control the biomechanical redundancy provided by the vertebral articulations as well as the joints that control the arm during the reach (Bunderson et al. 2008; Latash 2010; Ma and Felman, 1995; Sohn et al. 2013; Ting and McKay 2007). In healthy adults, the optimization of neuromuscular responses of the trunk and neck can posturally support the performance and adaptability of the reaching task. This adaptability explains why healthy adults can smoothly dissociate or couple arm-trunk segments during reaching depending on the goal and/or environmental constraints of the task (Berret et al. 2009; Levin et al. 2002; Wang and Stelmach 2001). However, patients with neurological conditions, for instance stroke and cerebral palsy, manifest sensorimotor problems in planning and controlling the wide range of DOF that drives posture and reaching. This inability of movement control is accompanied by dysregulation of muscle tone and neuromuscular patterns that do not respond adequately to the postural demands of the reaching task (Roby-Brami et al. 2003; Shaikh et al. 2014; van der Heide et al. 2004).

A limitation inherent in the above-mentioned studies, in both healthy adults and neurologic populations, is their reliance on postural responses elicited during unsupported sitting conditions. Researchers have not looked at the contributions of individual trunk segments to posture and reaching and thus conclusions are based on the involvement of the trunk modeled as a non-dissociable and whole structure. While modeling the trunk as a single unit in healthy adults could be viable due to their motor adaptability, this assumption should not be taken for granted in neurological conditions in which trunk control is immature or compromised. For instance, we have reported previously that in typically developing infants, the contributions of distinct segments of the trunk can impact the motor performance of posture and reaching skills during the progressive top-down development of the trunk (Rachwani et al. 2013, Saavedra et al. 2012). Similar results on postural stability applying segmental trunk support have also been observed in children with cerebral palsy (Saavedra et al. 2010). Thus, the underlying purpose of the current study in healthy young adults was to analyze the biomechanical and electromyographic output of posture and arm, applying trunk support at distinct levels of the trunk. The knowledge obtained could then contribute to the creation of a potentially innovative approach for the rehabilitative assessment and treatment of the trunk in pathological conditions.

For this purpose, we applied external support at either the mid-rib or pelvic levels of the trunk during reaching in upright sitting. These two levels of trunk constraint would result in different numbers of DOF of the trunk to control during the reach. Thus, the pelvic support involved the contributions of lumbar, thoracic and cervical segments, and the mid-rib support involved the contributions of only thoracic and cervical segments. Electromyographic and kinematic profiles of arm and trunk posture during reaching were compared between levels of trunk support. The following research questions were addressed: 1) would the level of support modulate postural and arm kinematics?; 2) could a reduction/increase of trunk segments involved in the sitting position modulate the temporospatial EMG features of arm and ipsi- or contra-lateral paraspinal muscles?; 3) would there be any type of arm or head-trunk motor adaptation in terms of kinematics and electromyographic profiles across trials?; and 4) to what extent would the trunk participate in the reaching task depending upon the level of trunk support provided?

Assuming that healthy adults are able to optimize trunk movements and arm kinematics, regardless of the constraints on DOF provided by the external trunk support, we hypothesized that no kinematic changes of arm, head or trunk would be observed between support levels, as has been previously observed (Archambault et al. 1999; Levin et al. 2002; Ma & Feldman, 1995). In contrast to postural and arm kinematics, it was hypothesized that muscle activation patterns during baseline, APA and CPA stages would be modulated depending on the level of the external trunk support provided, in order to effectively respond to the requirements of the task across changing conditions. Lastly, given the unusual constraint of the trunk through the use of an external device, the kinematics and neuromuscular profiles of arm and posture were expected to undergo some degree of adaptation across reaches.

METHODS

SUBJECTS

A sample of 15 healthy young adults (6 males and 9 females) with a mean age of 26.5 years (+/- SD: 2.8 years) was recruited from the University of Oregon. In the recruited sample, 13 out of the 15 subjects were identified as right handed (defined as the dominant hand used in writing). All subjects were free from any neurological and/or orthopedic condition. Each participant was informed of experimental details and gave written consent prior to the session. All procedures were approved by the office for protection of human subjects at the University of Oregon.

EXPERIMENTAL SETUP AND PROCEDURES

Subjects were asked to sit on a tall bench made of wood and covered with vinyl (length: 82cm and width: 36cm), with feet off the floor, in order to eliminate postural strategies elicited by feet-ground contact. They were asked to reach and grasp a circular object (diameter: 8cm, edge circumference: 4.50cm) at a self-selected pace after the object was placed at midline at the height of the subject's sternal notch and at a distance corresponding to the length of the subject's arm in complete extension. The object was presented from above using a brace made of fiberglass that was placed over the head of the subject. A moving lock was attached to this device, allowing adjustments of the distance and height of the object with respect to the seated subject. This setup permitted a consistent presentation of the object along the vertical (height) and anteroposterior axes (arm's distance) across the different trials with pelvic and mid-rib levels of support.

The pelvis was firmly fixed to the bench with non-elastic straps made of heavy bonded thread to firmly block the pelvic movement. Two straps were placed over the top of the thighs and one strap surrounded the posterior-superior iliac spines (PSIS) so that the pelvis remained fixed in the vertical and horizontal planes over the bench throughout the experiment (*see Appendix of Butler et al, 2010 for more information about the strapping procedure*). A rigid posterior support made of fiberglass was placed behind the subject and had three main contact points to eliminate trunk movement below the level of support. Customized pads made of rigid foam were placed at the points of contact with the trunk for comfort: one point of contact was posterior and placed on the trunk segment to be fixated and two were lateral contacts adjustable to the width of the mid-ribs or pelvis. An additional anterior pad attached to a belt was used for regulating the level of tightness and trunk fixation (Figure 10). This trunk support was raised or lowered to allow evaluation of the trunk segments above the level of support provided: mid-rib support, below the inferior angle of the scapula (T7 – T8); and, pelvic support, surrounding the waist.

The initial level of support was randomly assigned across subjects in each session, to create a counter-balanced experimental design. Subjects started the reaching task from a resting position in which the arms were situated laterally along the side of the trunk and the hands placed over the thighs. A total of 15 reaches per level of support for each subject was collected. The reaching task was synchronized with the collection of kinematic data (sampling rate = 84 Hz) using magnetic tracking (Minibird system, Ascension Technology, Burlington, VT), with a 16-channel electromyography system (MA300, Motion Lab Systems, Baton Rouge, LA) (sampling rate = 1000 Hz), and with video data (sampling rate = 30 Hz).

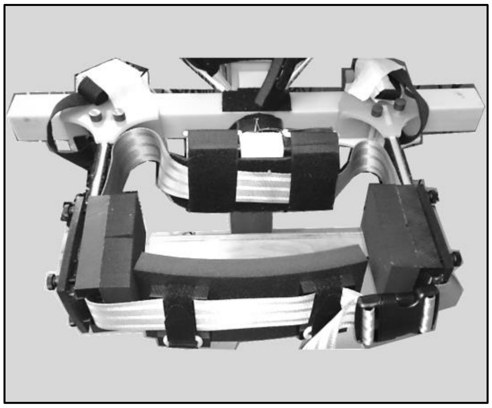


Figure 10. External Trunk Support Device Applied to Restrict the Trunk at Mid-Rib And Pelvic Support. Note the rigid foam pads placed at the posterior and lateral sides. An additional pad attached to the belt was used for regulating the level tightness of the trunk fixation.

KINEMATIC PROCEDURE

Magnetic tracking was used to record the position of the trunk, head and dominant arm in relation to the external support. One tracking sensor was placed on the surface of the styloid process of the radius, a second one on the C7 cervical process and the third one on the center of the forehead. Prior to the reaching task, digitized marker positions were collected for the left and right tragus, the medial/lateral and anterior/posterior locations of the external trunk support (padded contact points), and anterior aspect of the sternal notch. These digitized marker positions were used to estimate the location of the virtual center of the head and trunk (VCH and VCT, respectively) over the level of trunk fixation, and the center of the external trunk support provided. The VCH location was computed by first calculating the midpoint of the vector created between the two tragus markers (position in the frontal plane). The center between this point and the forehead sensor (position in the anteroposterior plane) was estimated as being the VCH. The VCT location was estimated as the midpoint between the sternal notch and C7. The center of the external support was calculated as the intersection point of the two vectors created by the anterior/posterior and medial/lateral markers of the external support; if the intersections did not coincide, we obtained the average of the two midpoints. Position data of the VCH, VCT and arm were referenced to the center of the external support.

ELECTROMYOGRAPHIC PROCEDURE: ARM & PARASPINAL MUSCLES

Electromyography (EMG) from 9 muscles was recorded via bipolar self-adhesive surface electrodes (Ag-AgCL) with poles placed 0.5 - 1.0cm apart. Muscles from the dorsal surface of the trunk were bilaterally sampled (ipsilateral: ipsi. and contralateral: contra.) at cervical segment, thoracic or mid-rib segment and lumbar segment. For the upper extremity, the muscles were unilaterally analyzed depending on the dominant arm of the subject. These muscles were: anterior deltoid (Ant. Delt), long head of biceps (Bic) and long head of triceps (Tric). An additional channel was utilized to detect the heart beat (HB) signal. The HB electrodes were placed over the 7th intercostal space, below pectoralis major, and over the sternal angle. EMG signals were pre-amplified (gain X 20) and band-pass filtered (10-375 Hz). The preamplifiers were attached in a custom harness made of light Velcro-sensitive neoprene that was placed over the subject's shoulders.

DATA REDUCTION AND ANALYSIS

Video Coding

All reaches were visually analyzed by using the computerized video-coding software Datavyu (http://www.datavyu.org/) before further evaluation of kinematic and EMG parameters. This visual analysis allowed us to discard those reaches in which the subject initiated the reach before the object was present in their visual field or when the object was still in motion. Also, this software allowed a pre-selection of the reach initiation, i.e., the time when arm transport started, and the reaching offset (R_{OFFSET}), i.e., when the hand contacted and grasped the object. A light emitting diode (LED) in the corner of the visual field of the camera and a voltage trigger were used to synchronize video, kinematic and EMG data during each trial. Additionally, the conformity of 80% of video coding measures related to reaching initiation and R_{OFFSET}, between two coders, was statistically compared (*see Results*). Once the reaching segment of each trial was defined through video analysis, the reaching initiation was reset as reaching onset (R_{ONSET}) according to the onset of the muscle selected as the prime mover, biceps or anterior deltoid (*see Electromyography*).

Kinematics

Kinematic data were filtered with a zero-lag fourth-order low-pass Butterworth filter with a cut-off frequency of 6Hz. We examined the following kinematic variables of the reach: movement time (MT), peak velocity, percentage of MT at which peak velocity of the reach occurred, the duration of the acceleration phase, straightness score, movement units (MUs) and normalized jerk score (NJS). Motor adaptation for NJS was also computed. Postural alignment and total angular displacement of the estimated VCH and VCT during a reach were examined. Lastly, arm-trunk coupling index was also computed.

MT was calculated as the time in seconds between R_{ONSET} and R_{OFFSET}. Peak velocity was computed as the maximum velocity obtained during the reach, measured in cm/s. The time at which the arm peaked during the reach was represented as a percentage of MT. The duration of the acceleration phase was defined as the interval, in seconds, from reaching onset to peak velocity. Straightness score was determined by measuring the straight distance from R_{ONSET} to R_{OFFSET}. This path is defined as the shortest distance to reach the target, and it is considered as the baseline path length with a value of 1. The extent of arm movement deviation from this trajectory was then determined as the proportion of the actual trajectory of the reach over this baseline path. Using this method, values greater than one meant a more deviant arm trajectory (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 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. Additionally, the normalized jerk score (NJS) was computed to determine the motor efficiency of the arm trajectory at each level of support according to the equation proposed by Chang et al (2005):

$$\text{NJS} = \sqrt{\frac{1}{2}} * \int (r''')^2 \, dt * (t^5/l^2)$$

Where r''' is the 3^{rd} derivative of position data, t is the movement time and l is the reaching path.

Postural alignment of head and trunk during the reach was calculated in degrees as the mean angular position of VCH with respect to the trunk (VCT) and VCT with respect to the center of the external trunk support, respectively, in the flexion (positive/greater values) and extension (negative/smaller values) planes between levels of supports (Figure 11). This variable was indicative of the most characteristic angular position of the head and trunk during the arm transport phase of the reach with respect to the vertical plane. In a similar manner, total angular displacement of the VCH and VCT were analyzed in the A-P and M-L planes as the absolute angular summation of head and trunk, respectively, during the reach.

The extent to which the trunk was involved in the reaching task was represented as the arm-trunk coupling index. It was computed as a percentage of the trunk path length with respect to the arm path length in the forward direction, in which a greater percentage would indicate a greater degree of arm-trunk coupling (Levin et al. 2002).

Motor adaptation for NJS at each level of support was computed by comparing repetitions (average of the 1st two reaches and the last two reaches) of each subject (Hall et al. 2010). Using this approach, increased values in the last reaches would indicate a reduced efficiency in arm control across reaches at the specific level that was constrained.

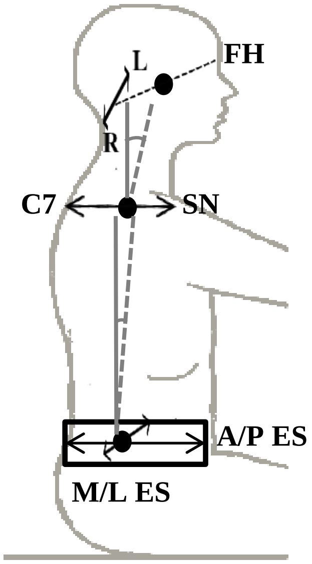


Figure 11. Marker Setup of Postural Kinematics. Black circles (●) represent the estimated locations of the virtual centers of head and trunk (VCH and VCT, respectively), and intersection point of the external trunk support. Head angular position was calculated with respect to VCT. Trunk angular position was calculated with respect to the intersection point of the external support (ES). FH = forehead sensor, C7 = C7 sensor, R = right tragus digitized marker, L = left tragus digitized marker, SN = sternal notch digitized marker, A/P =

Electromyography

The EMG signals were analyzed offline with customized software developed using MATLAB (The MathWorks, Inc., Boston, MA). A Welch's power analysis of the raw EMG signal was used to detect if electromagnetic interference was present and then removed with an 84Hz notch filter together with its higher harmonics.

The reaching task was subdivided into: baseline (200ms prior to the APA stage), APA stage (300ms prior to the R_{ONSET}), and CPA stage (variable movement time of the arm displacement during the reach) (Bigongiari et al. 2011). Reaches that did not have 500ms of EMG signal prior to the R_{ONSET} were rejected from further analysis. The EMG signal of these three pre-defined stages of each muscle's activity during the reach was normalized to its maximum peak amplitude and between levels of trunk support. The same protocol used by Leonard et al. (2011) was applied as a filtering procedure: high pass filter at 35Hz, demean, rectification and a second-order Butterworth filter at a cut off frequency of 10Hz. In addition to this process, a customized algorithm was used to identify and subtract the cardiac QRS waves from each muscle channel before signal filtering.

For the purpose of re-referencing the reaching initiation to the prime mover onset, a visual aid developed with MATLAB was used. This visual aid plotted the velocity profile of the reach, the EMG signal, a line defining 2.5SD above average of EMG baseline activity, and suggested EMG onsets and offsets calculated with an implemented automatic algorithm (Kamen and Gabriel 2010). The EMG onsets and offsets were reviewed by the user, and either approved or corrected. The user was blinded to the level of external support being analyzed.

The prime mover was selected by identifying the earliest EMG onsets between biceps and anterior deltoid. Once they were identified, the percentage of prime mover activation for both muscles was calculated with respect to the total number of reaches. The percentage activation across trials for the arm and paraspinal muscles in APA and CPA stages was also computed based on the total number of reaches.

EMG amplitude of each muscle was calculated using a trapezoidal integration (Kamen and Gabriel 2010) of the normalized EMG signal, with respect to the maximum peak amplitude ($EMG_{\%NORM}$), at each stage of the reach: APA and CPA. Applying this same principle, the integrated EMG of the baseline activity of the paraspinal muscles was calculated. This variable was indicative of the level of the paraspinal muscle tone prior to the APA stage and reaching initiation.

Muscle onsets were identified for arm and for paraspinal muscles in the CPA stage. In order to study the temporal organization of postural adjustments, we first calculated the percentage of time the paraspinal muscles of ipsi- and contra-lateral sides were activated as a synergy within the same reach, named as percentage of trials with “complete pattern”. Then, the number of trials in which they were activated within an interval of less than 40 ms was considered as the muscle co-activation rate (van der Heide et al. 2001).

Lastly, neuromuscular adaptability, in terms of changes in integrated EMG across trials during the CPA stage, was calculated by comparing the average $EMG_{\%NORM}$ of the last two reaches from the averaged $EMG_{\%NORM}$ of the first two reaches for each subject.

STATISTICAL ANALYSIS

Statistical analysis was performed with SPSS version 22 computer package (SPSS Inc., Chicago, USA). We first explored the assumptions of normal distribution of the kinematic and EMG data observing the linearity obtained in the Q - Q probability plots and results from the Kolmogorov-Smirnov test. However, non-normal distributions of kinematic and EMG variables was observed. Thus, we decided to apply a non-parametric approach with the Wilcoxon signed-rank test for related samples to analyze the impact of the mid-rib and pelvic supports on kinematics and EMG of the arm, head and trunk. An alpha level ≤ 0.05 was set as significant.

RESULTS

A total number of 292 reaches contained the pre-defined temporal window of 500ms prior to the reaching onset and were included for further kinematic and EMG analysis.

VIDEO CODING RELIABILITY TEST

A two-way mixed model Intraclass Correlation Coefficient (ICC) test was over 0.9 for reaching onset ($F = 1783.9$, $P < 0.01$) and reaching offset, ($F = 1783.9$, $P < 0.01$).

KINEMATICS

The typical trajectory and velocity profiles of the arm transport observed with pelvic and mid-rib supports are shown in Figures 12 and 13, respectively. The arm trajectory followed similar patterns with both levels of external support and arm kinematics was shown to be invariant (Table 5).

With regard to postural kinematics, head position in the A/P plane and head angular displacement in the M/L planes were significantly different between levels of trunk support. Nonetheless, the functional improvement in head position and displacement was not considered relevant in terms of postural control because of the small size of the change ($< 1^{\circ}$) (Table 5).

Arm-Trunk Coupling

The degree of trunk involvement during a reach did not show differences between levels of external trunk support (table 5). All subjects were able to reach while the trunk remained in vertical position and without significant trunk displacements.

Motor Adaptability of Arm Trajectory

There were significant changes across trials in the smoothness of the reaching trajectory, measured as NJS, depending on the level of trunk support provided. With pelvic support, the change in smoothness of the arm trajectory was not significantly different across reaches; whereas with mid-rib support, reaches became smoother across trials (initial reaches: $Mdn = 68.3$; last reaches: $Mdn = 59.2$, $Z = -2.33$, $P < 0.05$).

ELECTROMYOGRAPHY

Reaching was primarily initiated by the biceps muscle, which was identified as the prime mover irrespective of the level of support (~65%). Within the arm muscles, biceps activation was generally followed by anterior deltoid (~70ms after prime mover activation) and triceps (~140ms after prime mover activation).

EMG variables related to muscle activity and timing of arm muscles showed no differences between levels of external trunk support. On the contrary, specific neuro-modulation of paraspinal activity was observed depending on the level of trunk support provided. The typical EMG profiles of trunk muscles during the reaching task with pelvic and mid-rib supports are depicted in Figure 18.

Table 5: Arm and Postural Kinematics

	Pelvic *Mdn* (IQR)	Mid-Rib *Mdn* (IQR)	*P*
Arm kinematics:			
Movement time (s)	0.9 (0.8 – 1.0)	0.9 (0.8 – 1.0)	0.19
Peak Velocity (cm/s)	100.8 (92.2 – 117.3)	108.4 (93.5 –126.5)	0.39
% MT Peak velocity	65.4 (63.9 – 74.1)	66.2 (60.8 – 75.7)	0.69
Duration of acceleration phase (s)	0.6 (0.6 – 0.7)	0.6 (0.6 – 0.6)	0.16
Straightness score	1.1 (1.0 – 1.1)	1.1 (1.0 – 1.1)	0.53
Movement units	1.0 (1.0 – 1.0)	1.0 (1.0 – 1.0)	0.22
Normalized jerk score	67.4 (52.1 – 96.4)	67.5 (43.6 – 76.9)	0.91
Postural kinematics:			
A/P Head angle position (°)	10.5 (8.0 – 15.9)	9.4 (6.8 – 12.2)	**0.01**
A/P Head total displacement (°)	1.6 (1.3 – 2.0)	1.5 (1.1 – 1.8)	0.19
M/L Head total displacement (°)	1.5 (1.1 – 2.0)	1.0 (0.8 – 1.6)	**0.04**
A/P Trunk angle position (°)	2.6 (-0.7 – 3.9)	3.0 (-0.8 – 6.2)	0.61
A/P Trunk total displacement (°)	0.5 (0.3 – 1.0)	0.5 (0.4 – 0.6)	0.61
M/L Trunk total displacement (°)	0.3 (0.2 – 0.7)	0.4 (0.3 – 0.6)	0.16
Trunk coupling (%)	10.6 (5.8 – 13.9)	8.8 (6.3 – 10.6)	0.78

Note:% MT Peak Velocity = percentage of reach time at which peak velocity occurred; Mdn = median; IQR = interquartile range. Bold values indicate statistical signficance, $P \leq 0.05$. Note that the statistical significance for M/L head total displacement was not considered because a difference of 0.5° is not within the range of measurement precision of the magnetic tracking system.

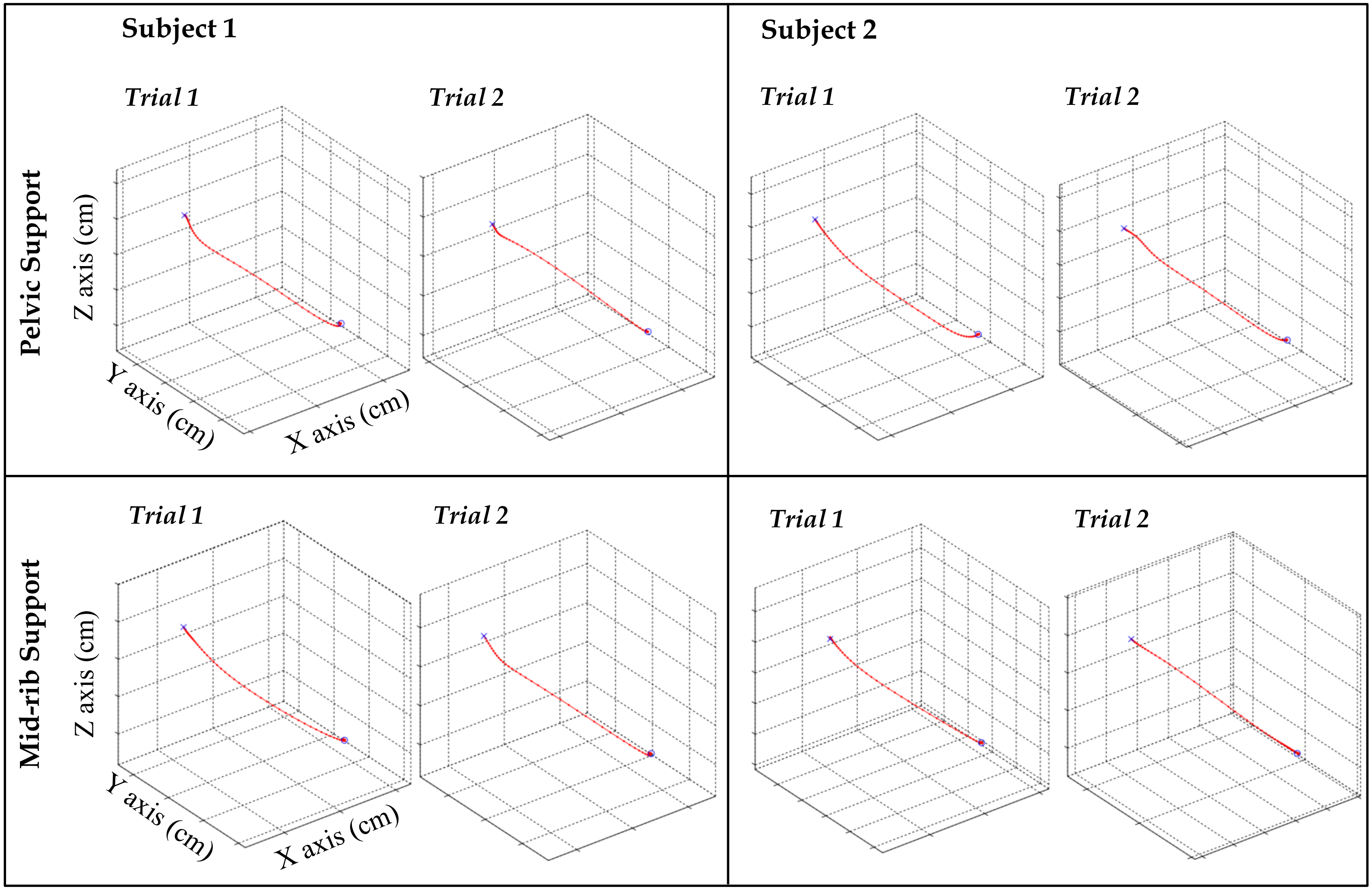


Figure 12. Three Dimensional Representation of Arm Paths between Levels of Trunk Support across Trials. Note the straight and linear trajectory observed between supports and across trials. The external level of trunk support did not modulate reaching trajectory. O =R_{ONSET}, X =R_{OFFSET}.

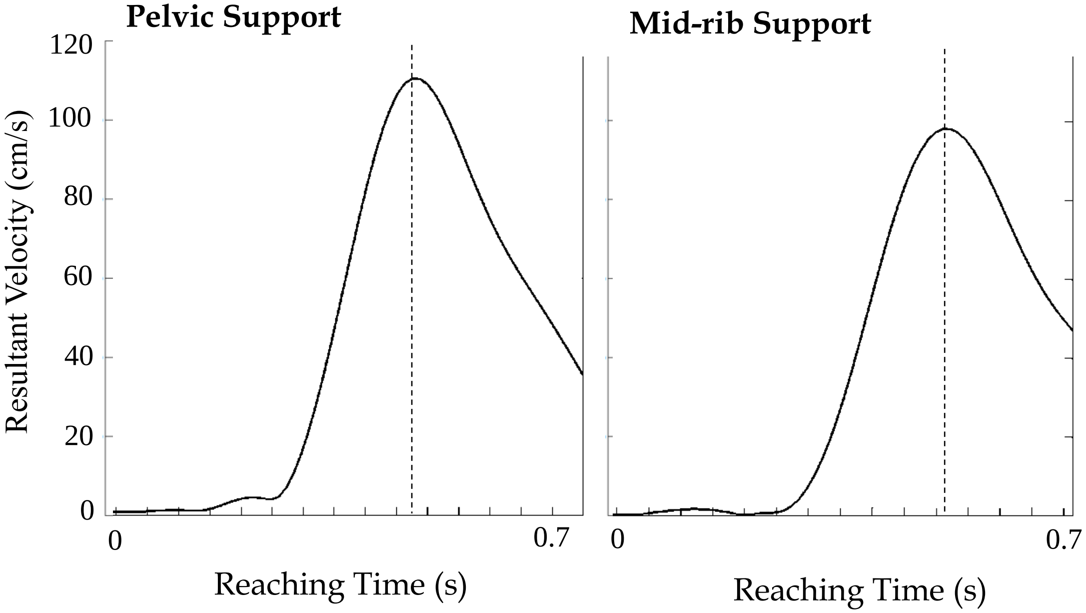


Figure 13. Representation of the Typical Reaching Velocity Profile between Levels of Trunk Support. Data obtained from one subject. Note the bell-shaped velocity profile, with 1 MU and how the time in which peak velocity occurred (approximately 65% of the reaching time) remained invariable between levels of external support.

Activation Rate of Paraspinal Muscles

Even though all paraspinal muscles showed anticipatory responses, the ipsilateral cervical muscle was the only one that demonstrated an increased rate of APAs when the trunk support was raised from pelvic to mid-rib support ($Z = -1.91$, $P \leq 0.05$) (Figure 14a).

With respect to the CPA stage, ipsilateral thoracic muscles demonstrated a decreased activation rate with mid-rib compared to pelvic support ($Z = -1.99$, $P < 0.05$). Similarly, the lumbar muscles were activated less frequently with the higher support at mid-rib level compared to pelvic level, (ipsilateral lumbar: $Z = -2.04$, $P < 0.05$; and contralateral lumbar: $Z = -2.32$, $P < 0.05$) (Figure 14b).

Electromyographic Amplitude of Paraspinal Muscles

Results did not demonstrate changes in the EMG amplitude of the ipsi- or contralateral cervical and lumbar muscles between levels of trunk support during either stage of postural adjustment, APA or CPA. Only the ipsilateral thoracic muscle exhibited a decreased EMG amplitude during the CPA stage of the reach with mid-rib support as opposed to pelvic support ($Z = -2.15$, $P < 0.05$) (Figure 15).

Electromyographic Baseline Activity of Paraspinal Muscles

Results from EMG baseline activity of the paraspinal muscles between levels of trunk support can be seen in Figure 16. With mid-rib support, the group of subjects had increased EMG baseline activity of the ipsi- and contra-lateral lumbar muscle (ipsilateral lumbar muscle baseline activity: $Z = -3.23$, $P < 0.01$; and contralateral lumbar muscle baseline activity: $Z = -3.18$, $P < 0.01$).

Neuromuscular and Temporal Electromyographic Patterns of Paraspinal Muscles

With mid-rib support, when the ipsilateral cervical muscle did not show an EMG burst in the APA stage, this muscle demonstrated a reduced onset latency in the CPA stage compared to the onset delay observed with pelvic support (${Z} = -1.91$, $P \leq 0.05$). A similar effect was observed in the contralateral thoracic muscle, showing an earlier muscle activation with mid-rib compared to pelvic support ($Z = -2.93$, $P < 0.01$) (Figure 17).

No differences were observed between levels of support in the number of trials in which a complete pattern of either ipsi- or contra-lateral paraspinal muscles was activated. However, when testing the rate of complete paraspinal muscle pattern between the ipsi- and contra-lateral sides, results showed a higher rate of synergistic activation of the ipsilateral side with both levels of support (pelvic: $Z = -2.13$, $P < 0.05$; mid-rib: $Z = -2.45$, $P < 0.05$) (Table 6).

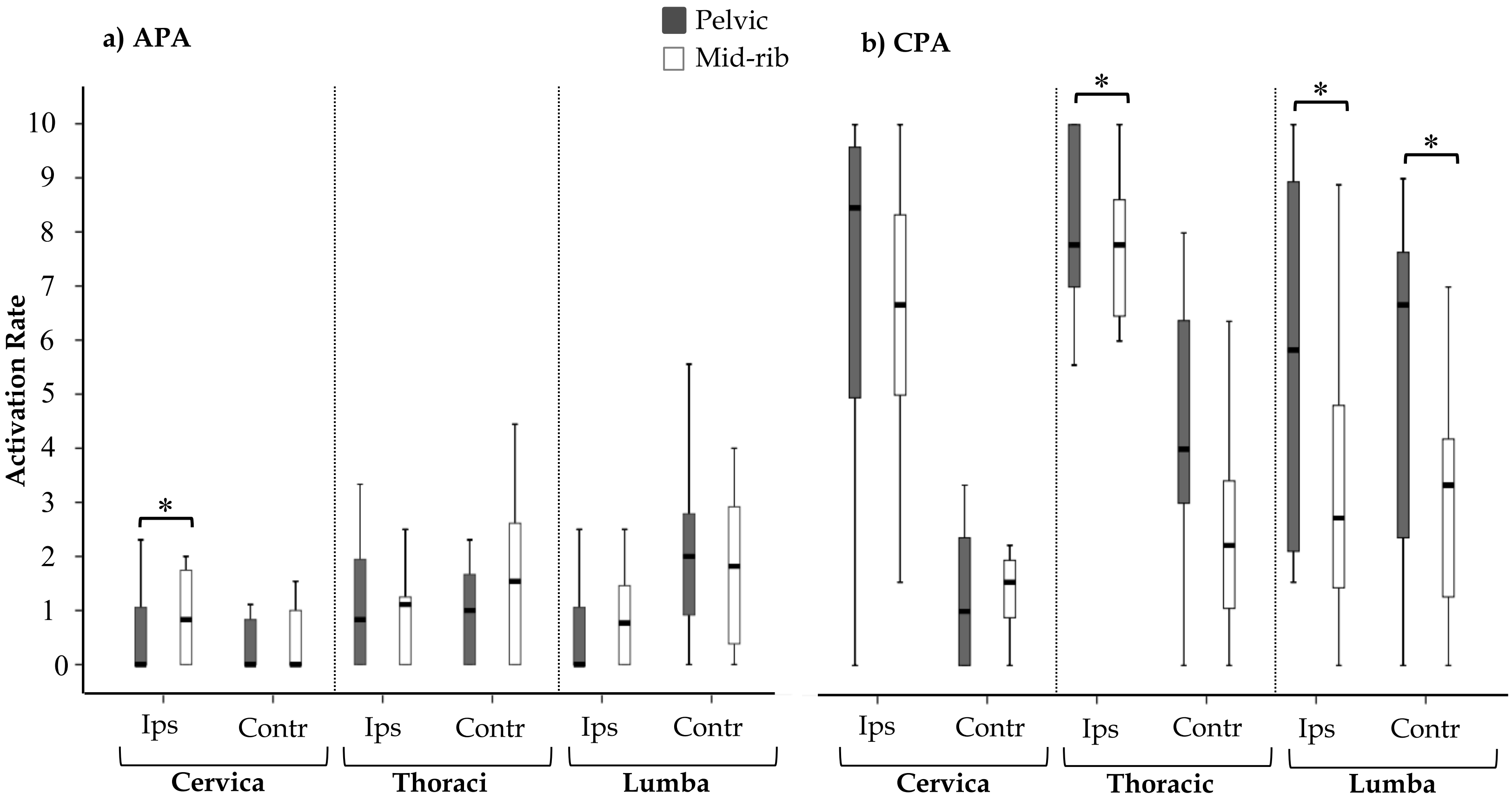


Figure 14. Activation Rate of Paraspinal Muscle During APA and CPA Stages of the Reach The data are presented by ranges (vertical lines) and median values (thick horizontal lines). a) The ipsilateral cervical was the only muscle in showing a significant increase in the activation rate during the anticipatory postural stage with mid-rib support. b) During the compensatory stage, there was a significant increase in the activation rate of ipsilateral thoracic and ipsi- and contra-lateral lumbar muscles with pelvic support. Ipsi. = Ipsilateral and Contra. = Contralateral. * indicates statistical significance between mid-rib and pelvic supports, $p \leq 0.05$.

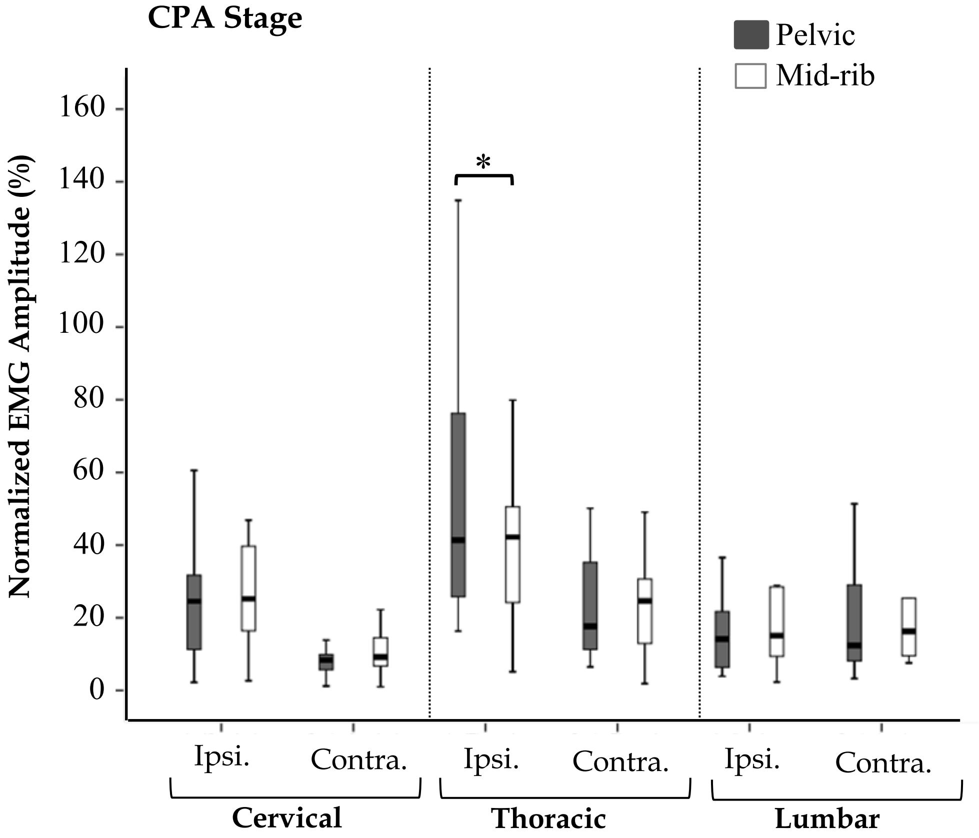


Figure 15. EMG Amplitude of Paraspinal Muscles During CPA Stage. The data are presented by ranges (vertical lines) and median values (thick horizontal lines). Note that the ipsilateral side of the thoracic muscle was the only paraspinal muscle displaying increased amplitude with pelvic support during the CPA stage of the reach. Ipsi. = Ipsilateral and Contra. = Contralateral. * indicates statistical significance of EMG amplitude during CPA stage between mid-rib and pelvic support, $p < 0.05$.

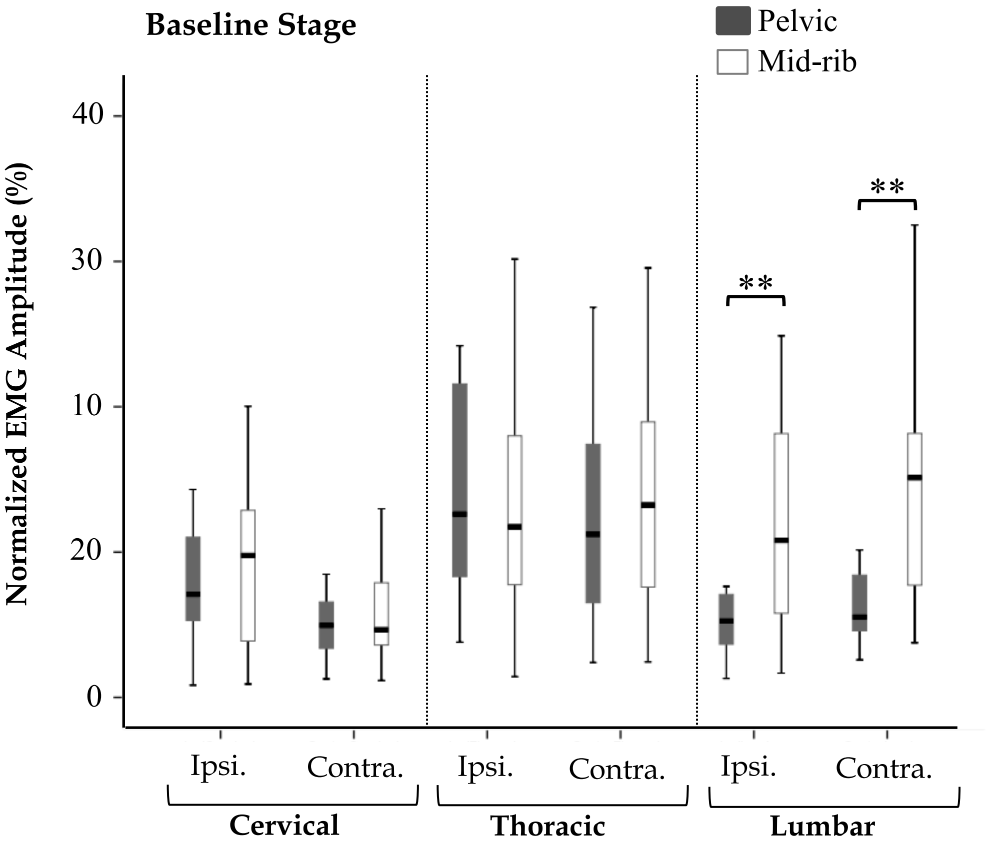


Figure 16. EMG Baseline Activity of Paraspinal Muscles between Levels of Trunk Support. The data are presented by ranges (vertical lines) and median values (thick horizontal lines). The ipsi- and contra-lateral lumbar muscles demonstrated significant increment of baseline activity when subjects were provided with mid-rib support. Ipsi. = Ipsilateral and Contra. = Contralateral. ** indicates significant difference of baseline muscle activity between mid-rib and pelvic support, $p < 0.01$.

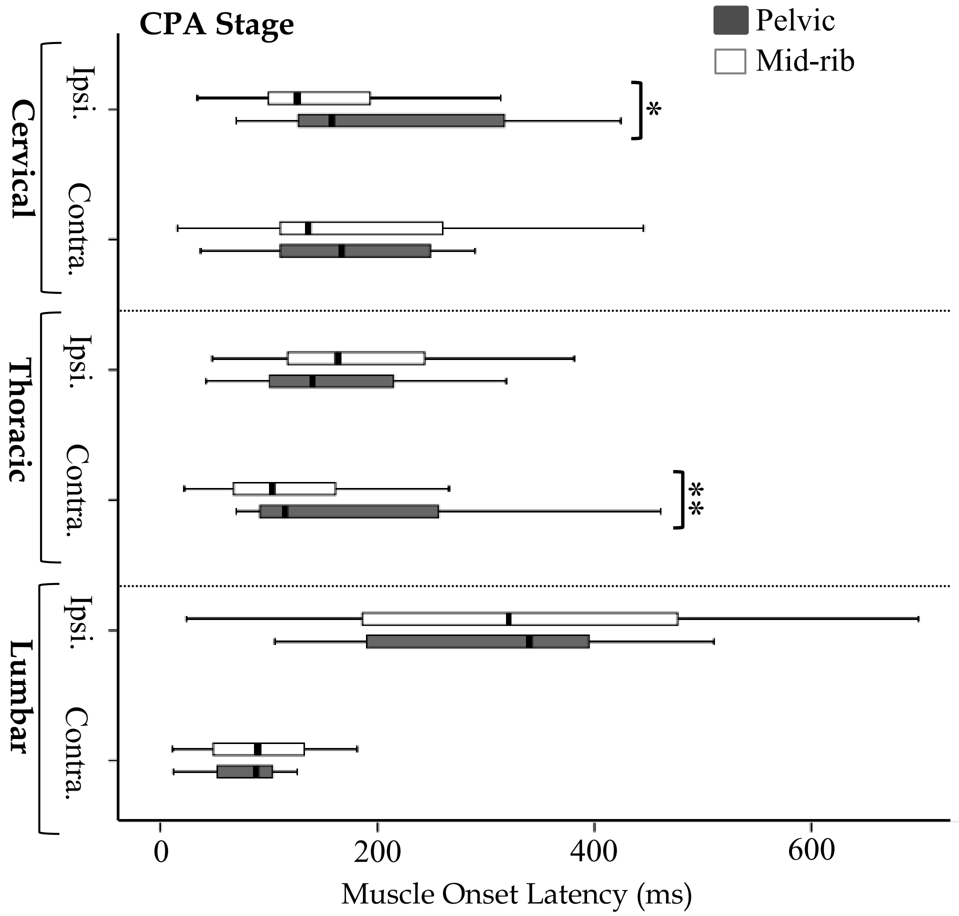


Figure 17. Activation Latency of Paraspinal Muscles during CPA Stage. The data are presented by ranges (horizontal lines) and median values (thick vertical lines). Notice an earlier EMG onset activation of the ipsilateral cervical and contralateral thoracic muscles with mid-rib support during the CPA stage of the reach. Ipsi. = Ipsilateral and Contra. = Contralateral. * indicates significant difference of EMG onset latency between mid-rib and pelvic support, $p \leq 0.05$ and ** $p < 0.01$.

No significant differences between levels of support were observed for co-activation rate of ipsilateral or contralateral paraspinal muscles. Trunk muscles displayed a low rate of co-activation rate.

Table 6: Rate of Synergistic Pattern

Support	% Synergistic Pattern		*P*
	Ipsilateral Side *Mdn* (IQR)	Contralateral Side *Mdn* (IQR)	
Pelvic	40.0 (10.0 – 75.0)	9.1 (0.0 – 20.0)	**0.03**
Mid-rib	25.0 (15.4 – 40.0)	0.0 (0.0 – 22.2)	**0.01**

Note: Mdn = median; IQR = interquartile range. Bold values indicate statistical signficance, p ≤ 0.05.

Neuromuscular Adaptability

Subjects did not display adaptability of muscle amplitudes across reaches with either pelvic or mid-rib support.

In summary, the motion of the arm was accompanied by different paraspinal EMG profiles during the baseline, APA and CPA stages of the reaching task when comparing mid-rib and pelvic levels of trunk support (Figure 18). Results obtained from the paraspinal muscles of the cervical, thoracic and lumbar segments between the two external levels of trunk supports suggest distinct control of ipsi- and contra-lateral muscles during the reach. Between levels of support, the ipsilateral cervical was the only muscle to show changes in

APA activation rate, showing an increase at mid-rib level (Figure 14a). When not activated in the APA stage, this muscle showed an early activation in the CPA stage with mid-rib support, similar to what happened with the contralateral thoracic muscle (Figure 17). Furthermore, with mid-rib support, EMG baseline activity was bilaterally augmented for the lumbar muscles (Figure 16). In contrast, with pelvic support, there was 1) an increase of the activation rate and muscle amplitude of the ipsi-lateral thoracic muscle during the CPA stage; and 2) an increased activation rate of the ipsi- and contra-lateral lumbar muscles in the CPA stage (Fig. 14b and 15).

DISCUSSION

The purpose of this study was to investigate the effect of constraining the trunk with pelvic and mid-rib levels of external support, on postural (trunk)/arm kinematics and EMG profiles of healthy adults during seated reaching. As expected, subjects displayed invariant trunk and arm kinematic profiles, regardless of the trunk constraints. However, arm trajectories were affected and underwent motor adaptation across sequential trials of external trunk support at mid-rib level. In reference to EMG activity, neuromuscular effects were found between levels of trunk support which could contribute to the invariance observed in kinematics. At odds with what one might expect, external mid-rib support increased the baseline activity of muscles located at the lumbar region (below the level of support). Changes in activation patterns during APA and CPA stages were also shown to be significantly different between levels of external trunk support.

KINEMATICS OF POSTURE AND UPPER EXTREMITY

Previous research in our lab has demonstrated that when trunk control is immature or compromised, providing specific external support at mid-rib levels results in an increase in head/trunk stability and subsequent improvement of the quality of the reach compared to pelvic levels of support (Rachwani et al. 2013; Saavedra et al. 2010). In healthy adults, despite the change in DOF of the trunk between levels of support, the performance and trajectory of the reach remained similar, indicating that the trunk is well controlled and coordinated in the overall goal of transporting the hand to the target (Archambault et al. 1999; Hua et al. 2013).

Moreover, results indicate that the level of trunk support did not influence the degree of trunk involvement during reaching. This evidence points out that in healthy adults the trunk does not display a greater involvement while reaching for an object despite the increase of DOF of the trunk with pelvic support. This observation is in line with the results of Levin et al. (2002), who showed that even in unsupported seated conditions healthy adults do not recruit the trunk when reaching objects located within arm’s length.

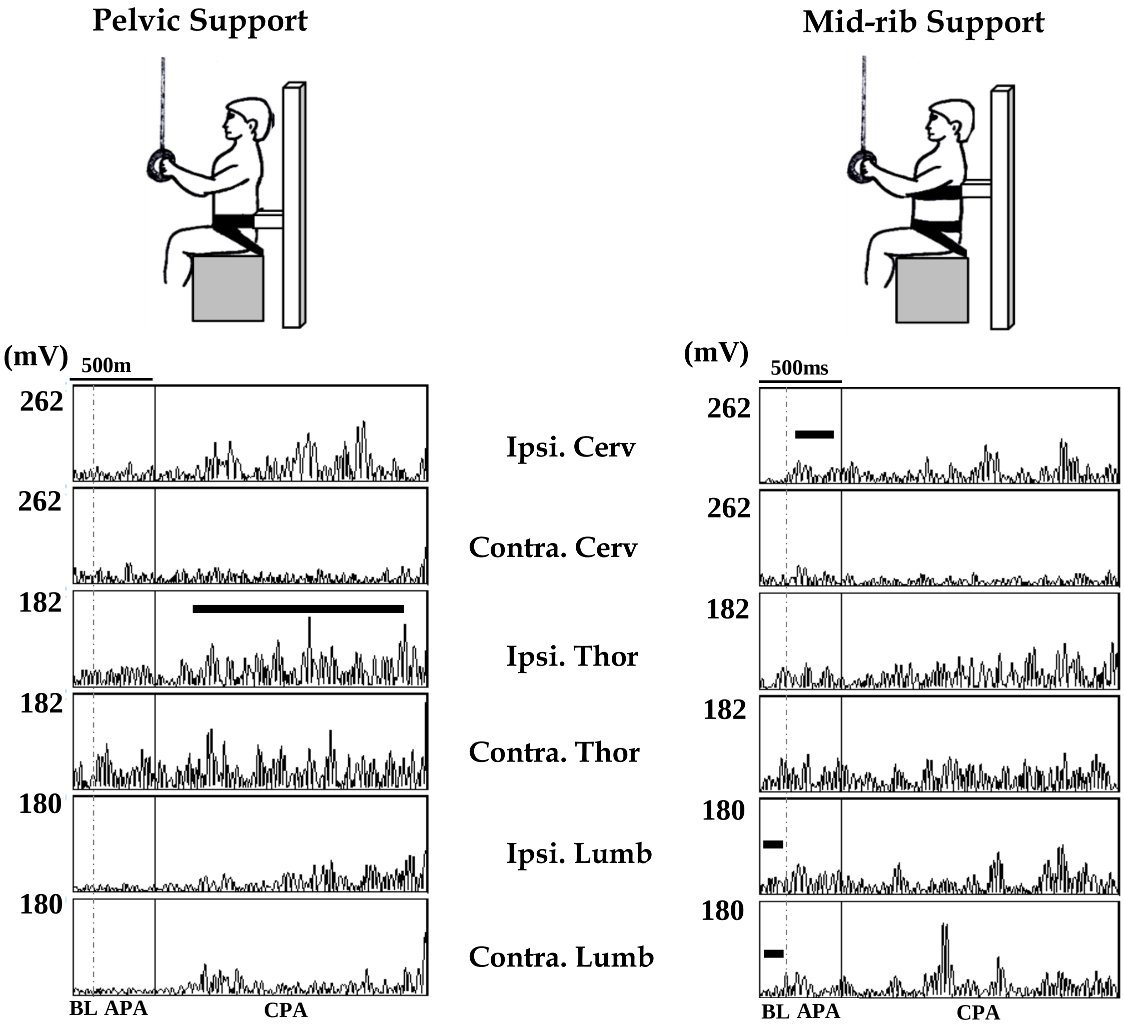


Figure 18. EMG Profiles of Paraspinal Muscles between Levels of Trunk Support. The two images in the upper part of the panel indicate the two levels of trunk support examined. EMG of each muscle has been normalized to its maximum peak amplitude across reaches and levels of support for each subject. The dotted line represents the time limit between baseline (BL) (200ms) and APA stage (300ms). The solid line marks the R_{ONSET} (prime mover activation). Black horizontal lines highlight: i) APA activity of ipsilateral cervical with mid-rib support, ii) increased EMG amplitude of ipsilateral thoracic in CPA stage with pelvic support and, iii) increased bilateral EMG baseline activity of lumbar muscles with mid-rib support.

Instead, the involvement of the trunk is observed in individuals with hemiparesis or cerebral palsy, in an attempt to compensate for deficits in the range of motion and control of joints of the upper limb. Nonetheless, inter-joint arm coordination is known to improve with complete restriction of these compensatory trunk movements (Schneiberg et al. 2010; Woodbury et al. 2009).

Future studies are recommended to determine if improvements in postural stability, endpoint kinematics and arm-trunk coupling in patients with trunk dysfunctions are specific to unstable regions of the trunk and thus, if use of specific levels of trunk support can help therapists design more effective treatment programs for improving sitting balance and reaching control.

ELECTROMYOGRAPHIC PATTERNS OF POSTURE

Results from the current study revealed that EMG patterns of the paraspinal muscles, prior to and after reaching onset, were differently adjusted depending on the level of trunk support provided. However, arm muscle activity was similar between pelvic and mid-rib support.

In relation to postural adjustments prior to reaching, results indicate that anticipatory postural activity is infrequent but present in the neck muscles, as it has previously been observed in seated healthy adults performing self-paced reaching tasks (van der Heide et al. 2003). However, we show that its frequency can be increased when changing the support from pelvic to mid-rib level of the trunk, which could probably explain the subtle increase in head verticality that was observed with more restriction of the trunk at mid-rib level. Aruin et al. (1998) found that APAs were significantly attenuated in highly unstable standing conditions, implying that APAs can be inactive in situations when destabilization of the posture becomes larger.

Previous studies have shown decreased amplitude in postural muscles during a reach as the amount of bodily support increases (Cordo and Nashner, 1982; van der Fits et al. 1998). Data from the current study confirm these results, because with mid-rib support, subjects exhibited a lower muscle activation rate of the thoracic and lumbar muscles in addition to decreased EMG amplitude of the ipsilateral thoracic muscle during the compensatory stage of the reach. Therefore, it is possible that with pelvic support there would be increased postural demands as a result of the greater number of DOF and increased range of trunk motion to control. Moreover, the invariant trunk posture while reaching with mid-rib support could be justified by the enhanced baseline lumbar activity obtained with an external support at mid-rib level.

The level of support did not impact the rate of synergistic activation. Nonetheless, subjects demonstrated a higher number of trials in which they activated the ipsilateral synergistic pattern irrespective of the level of support provided. This observation could imply a certain inherent preference by the neuromuscular system for the use of the ipsilateral side in the stabilization of trunk disturbances derived from the vertical and forward displacement of the arm while reaching. Lastly, there was a general tendency of the paraspinal muscles to demonstrate earlier muscle onset activation during the CPA stage with mid-rib support. This could be due in part to a restriction of the number of trunk segments to control and thus the execution of a quicker muscle response mediated by feedback mechanisms after reaching initiation (Santos et al. 2012). This is an important aspect of control to consider in neurological conditions. People with stroke and cerebellar disorders display deficits, including onset delays and synchronization of trunk muscles that consequently affect the temporal recruitment order that contributes to effective posture during activities of daily living (Bruttini et al. 2014; Dickstein et al. 2004; Diedrichsen et al. 2005; Winzeler-Merçay and Mudie, 2002).

Future studies could analyze the dynamic constraints of the trunk and arm. In this analysis we should include inertia and muscle forces, while controlling for the number of DOF of the trunk with an external support during seated reaches.

CONCLUSIONS

As expected, posture and arm kinematics remained invariant regardless of the constraints on the trunk created by giving segmental support at pelvic or mid-rib levels to healthy individuals during seated reaching. Nonetheless, the level of support was associated with explicit neuro-modulatory effects of the paraspinal muscles. EMG patterns of ipsi- and contra-lateral sides of trunk muscles revealed that feedforward control of cervical muscles, bilateral baseline lumbar activity and timing-modulation of compensatory postural adjustments can be improved with mid-rib compared to pelvic support. Contrarily, with pelvic support, paraspinal muscle frequency and amplitudes increased during reaching. The fact that providing external trunk support can modulate postural EMG activity in healthy adults, suggests that this might also be an effective way of improving postural control in patients with trunk control deficits, during neuro-rehabilitation. More specifically, its use could be investigated for improving sitting balance and reaching in persons with pathologies that are characterized by lack of anticipatory muscle control, dysregulation of back muscle tone and reaching deficits, such as stroke and cerebral palsy.

BRIDGING THE FIRST AND SECOND STUDY

In the previous study in young healthy adults, we observed that trunk constraint via an external support at mid-rib or pelvic levels did not influence trunk or reaching kinematics. This kinematic invariance between levels of support would be explained by the explicit neuromuscular responses of paraspinal muscles, specific to the external support provided.

As mentioned before, the neural structures and networks within the central and peripheral nervous systems that control reaching and posture are compromised in children with CP. The cerebral damage results in inadequate motor control of the redundant DOF provided by the upper body during seated reaching. In contrast to adults with no musculoskeletal or neurological problems, children with CP who had moderate and severe trunk impairments were hypothesized to show poor reaching kinematics at low levels of trunk support and to show significant kinematic improvements with more restriction of the trunk.

Chapter IV describes a study involving children diagnosed with CP, who performed a reaching task during sitting with distinct levels of trunk control. The study examined the kinematic profiles of reach movements of the arm and postural control, including movements of the head and trunk.

CHAPTER IV

THE IMPACT OF SEGMENTAL TRUNK SUPPORT ON POSTURE AND REACHING IN CHILDREN WITH MODERATE AND SEVERE CEREBRAL PALSY I: A KINEMATIC STUDY

This chapter contains un-published, co-authored material and thus, the explicit collaboration of each author should be highlighted. I performed the experimental design, data collection, data analyses, statistical analysis and writing of the manuscript. Jaya Rachwani collaborated in the experimental design, data collection and data analyses. Sandra L Saavedra participated in the experimental design, data interpretation and reviews. Marjorie Woollacott provided editorial assistance and collaborated in the experimental design and data interpretation.

INTRODUCTION

Cerebral palsy (CP) is a non-progressive and heterogeneous neurological condition of multifactorial etiology often associated with cognitive-attentional and visuomotor impairments. However, motor dysfunction is considered as the characteristic sign in CP due to frequent problems in learning, planning and coordinating posture and voluntary movements (Malouin et al., 2013; Krageloh-Mann & Bax, 2009). The resulting functional disability is more evident in children classified as III, and especially IV-V, according to the Gross Motor Function Classification System (GMFCS) (Rosenbaum et al., 2002).

Postural control is a fundamental requirement for reaching and grasping (Shumway-Cook & Woollacott 1985; Touwen, 1976). Even though both motor behaviors emerge early in infancy, the optimal control of posture and reaching develops progressively during childhood because of the many degrees of freedom (DOF) to be controlled in the upper body and the coordination required between the trunk, arm and head (Schneiberg et al., 2002; von Hofsten, 1984). In moderate and severe cases of CP, however, these fundamental motor milestones are delayed or never acquired due to brain damage and white matter disruption (Sheck et al., 2012; van der Heide et al., 2004).

Research investigating postural control in children with CP has demonstrated that applying pelvic support in sitting, with or without inclination, can improve postural stability and reaching performance (McNamara & Casey, 2007; Myhr & von Wendt, 1991). Most importantly, stabilization of the pelvis or trunk improves head stability, visual field orientation and control of distal segments, as well (Cheng, Lien, & Yu, 2013; Saavedra, van Donkeelar, & Woollacott, 2012). Thus, the origin of profound postural deficits with consequent reduction of reaching performance is in part due to inadequate trunk control (Butler, 1998).

The trunk is a dynamic structure in which the vertebral subunits are controlled as segments through synergistic patterns of ventral and dorsal vertebral muscles. In this manner the head and different trunk segments are coordinated with the upper limb during reaching (Park et al., 2014; Pozzo et al., 1990). The Segmental Assessment of Trunk Control (SATCo) evaluates trunk stability in static, reactive and active dimensions of balance at 7 different trunk segments: from the head through the hips (Butler et al., 2010). Other assessment tools, such as the GMFM, Seated Postural Control Measure (SPCM) or the Spinal Alignment and Range of Motion Measure (SAROMM), examine balance using a model in which the trunk acts as a single unit. While these clinical tests are reliable and effective in assessing limited aspects of functional balance while sitting, they do not give a detailed assessment of segmental trunk control in sitting (Butler et al., 2010).

Therefore, this research aimed to investigate how external support at different trunk levels influences posture and reaching proficiency in children with CP in relation to their segmental level of trunk control, measured with the SATCo. It was hypothesized that participants in the mild group would have similar postural and reaching patterns regardless of the external level of trunk support, given their intrinsic control of all trunk regions. However, participants in the moderate group would benefit from the use of axillae and mid-rib support, displaying improved postural and reaching kinematics compared to pelvic support, due to their deficits in lumbar control. Lastly, participants in the severe group would perform better with external support at the axillae since they only had partial cervical control.

METHODS

PARTICIPANTS

Seventeen children diagnosed with CP (12 males & 5 females), mean age, 6 years, 6 months, participated in the study (clinical details represented in Table 7). CP subtype and diagnosis of participants were confirmed by medical records. Participants were recruited throughout Oregon (USA), and research was conducted at the University of Oregon. All procedures were approved by the Institutional Review Board for protection of human subjects.

Children with severe structural vertebral deformities, scoliosis > 40° and kyphosis > 45° were excluded from the experiment. The functional disability of each participant was assessed with the GMFCS and gross motor ability with the GMFM-66-Item-Set and calculated with the GMAE-2 Gross Motor Ability Estimator (CanChild: Center for Childhood Disability Research. McMaster University, Canada). The ability to reach, grasp and manipulate were tested with the QUEST and MACS. All participants were grouped according to their SATCo score into three categories: Severe (n=4: partial cervical control); Moderate (n =7: thoracic control) and Mild (n = 6: complete trunk control) (Table 8) (Butler et al., 2010).

EXPERIMENTAL SETUP

Participants sat on a tall bench, with feet off the floor, to exclude pathological postural synergies elicited by feet-ground contact. The pelvis was firmly fixed to the bench with non-elastic straps. A rigid U-shaped support was placed behind the subject and a belt was used for regulating the tightness of the anterior trunk fixation (Butler et al., 2010). This support was raised or lowered to allow evaluation of trunk segments above the support levels: axillae, surrounding armpits (T4 – T5); mid-rib, below the inferior angle of the scapula (T7 – T8); and pelvic, surrounding the waist (L3 - L5). To create a counter-balanced experimental design, the trunk supports were randomly assigned.

During the reaching test, a colorful circular ring was presented from above, and dropped to a point in front of the participant's sternum at arm's length. Participants were encouraged to reach and grasp it at a self-selected pace. The reaching task was video recorded (30 Hz) and synchronized with kinematic data collection (sampling rate: 84 Hz).

KINEMATIC PROCEDURE

Magnetic tracking (Minibird system, Ascension Technology, Burlington, VT) was used to collect head, trunk and arm position. Tracking sensors were placed bilaterally on the two radial styloid processes, on spinous process of 7th cervical vertebrae (C7) and on the forehead center. Digitized positions of anatomical references: left and right tragus, C7 and sternal notch were used to estimate the location of the virtual head center (VHC) and the trunk segment above the level of support (VTC). Position data from VHC, VTC and arm were referenced to the midpoint of the provided external trunk support. This marker setup was used to calculate the 3D angular kinematics of VHC and VTC using methodology proposed by Wu et al. (2005). The selected Cardan's angle sequence of rotations was: X (flexion (+) / extension (-)), Y' (right (+) / left (-) lateral flexion) and Z" (right (+) / left (-) rotations).

DATA ANALYSIS

VIDEO CODING

Reaches were visually analyzed using Datavyu computerized video-coding software (http://www.datavyu.org/) before further kinematic evaluation to pre-select reaching initiation and reaching offset (R_{OFFSET}), defined as hand contacting the object. Reaching initiation was then set as reaching onset (R_{ONSET}) using the velocity profile of the reach (see below). Inter-rater reliability of R_{ONSET} and R_{OFFSET} were validated by having two coders evaluate 50% of the data with a coefficient of agreement above 0.70.

Reaches were coded as unimanual or bimanual (the subject touched the object with both hands with less than 1000ms onset time difference). For bimanual reaches, only the dominant arm (defined as the first one contacting and manipulating the object) was used for analysis.

Table 7: Clinical Assessment

Subject & Age	Segmental Level of Trunk Instability	SATCo Group	GMFCS Level	Subtype of CP	GMFM-66 (Average ±SE)	Quest Score	MACS Score
1 (8y 2mos)	Pelvis	Mild	IV	Hypotonic Quadriplegia	47.9 (±1.1)	32.33	II
2 (6y 8mos)	Pelvis	Mild	III	Spastic Diplegia	51.1 (±1.2)	85.20	I
3 (5y 3mos)	Pelvis	Mild	IV	Spastic Diplegia	46.9 (±1.0)	76.01	II
4 (5y 3mos)	Hips	Mild	III	Spastic Diplegia	51.9 (±1.2)	94.15	II
5 (4y 3mos)	Head	Severe	V	Spastic Quadriplegia	20.5 (±2.2)	5.11	IV
6 (7y 9mos)	Axillae	Severe	V	Dyskinetic Quadriplegia	20.5 (±2.1)	12.53	IV
7 (2y 5mos)	Head	Severe	V	Hypotonic Quadriplegia	22.7 (±2.0)	2.22	V
8 (2y 1mos)	Over Below Ribs	Moderate	III	Dyskinetic Quadriplegia	45.6 (±1.0)	36.40	II
9 (3y 7mos)	Over Below Ribs	Moderate	IV	Dyskinetic Quadriplegia	30.0 (±1.9)	39.79	II
10 (2y 1mos)	Below Ribs	Moderate	IV	Spastic Quadriplegia	36.0 (±1.5)	28.71	IV
11 (15y 8mos)	Over Below Ribs	Moderate	IV	Dyskinetic Quadriplegia	50.1 (±1.2)	45.73	II
12 (6y 8mos)	Inferior Scapula	Moderate	IV	Spastic Quadriplegia	26.0 (±2.0)	10.46	V
13 (10y 1mos)	Inferior Scapula	Moderate	IV	Dykinetic Quadriplegia	41.6 (±1.1)	34.45	II
14 (7y 4mos)	Head	Severe	V	Hypotonic Quadriplegia	14.8 (±2.8)	10.00	V
15 (7y 4mos)	Below Ribs	Moderate	IV	Dykinetic Quadriplegia	26.0 (±2.0)	38.47	II
16 (15y 1mos)	Hips	Mild	III	Spastic Diplegia	52.6 (±1.2)	99.07	I
17 (2y 1mos)	Pelvis	Mild	IV	Spastic Quadriplegia	25.3 (±1.9)	55.02	I

Note: Segmental level of trunk instability indicates the anatomical region at which the participant lost postural stability according to the SATCo score. GMFM-66 was measured with the GMFM-66-Item-Set and calculated with the GMAE-2 Gross Motor Ability Estimator. The values represent the GMFM-66 score ± SE. The final average QUEST and MACS scores are included to describe the clinical abilities of each participant to control upper extremity and hand. Note that the sample of CP was mostly composed by quadriplegic forms of CP (13 cases), cases with both moderate-severe trunk dysfunction (11 cases) and low ability of reaching and grasping, QUEST <42 (11cases) and MACS> III (6 cases) respectively.

KINEMATICS

Kinematics was analyzed offline with MATLAB (MathWorks, Inc., Boston, MA) and data were filtered with zero-lag fourth-order low-pass Butterworth filter (cut-off frequency, 6Hz). Planar kinematics was used for analyzing the reaching variables: Movement Time (MT, the time between R_{ONSET} and R_{OFFSET}), and Arm Path Length (distance covered by the arm during the reach). Straightness score was determined by measuring the baseline arm trajectory as the straight line from R_{ONSET} to R_{OFFSET}, with value of 1; scores greater than 1 would indicate the extent that the arm trajectory deviated from this baseline (von Hofsten, 1984). A movement unit (MU) was defined as the portion of the arm movement between two velocity minima with a velocity peak greater than 2.3 cm/s (Grönqvist, Strand Brodd, & von Hofsten, 2011). The normalized jerk score (NJS) was also computed for describing the efficiency of upper limb control during reaching (Chang et al., 2005). This last variable described the acceleration profiles of the reach; which has been considered to be a more sensitive and accurate measure to analyze the degree of movement smoothness (Hoogan & Stenard, 2009).

Three-dimensional kinematics was used for analyzing angular displacement and orientation of the head (VHC) and trunk (VTC) during reaching, represented in degrees.

STATISTICS

Due to the clinical features of our sample, different numbers of reaches and possible missing data across levels of trunk support were expected. Thus, a two-level Generalized Linear Mixed Model was applied. The statistical package SPSS version 22.0 (SPSS Inc., Chicago, IL, USA) was used to analyze the relationship between reaching and postural outcomes across trunk support and group. As fixed effects, we entered Group categories (Mild, Moderate & Severe), level of trunk support (Axillae, Mid-rib and Pelvic) and their interaction into the model. As random effects, we had intercepts for participants and number of reaches within participants, accounting for by-subject variability and by-number of reaches-within-subject variability in overall reach outcomes. Visual inspection of residual plots did not reveal obvious deviations from homoscedasticity and normality. Post-Hoc pairwise comparisons were performed in case of significant interactions. The level of P was adjusted to the number of comparisons applying Bonferroni´s sequential procedure.

RESULTS

VALIDITY OF THE SATCo

Pearson’s correlation coefficients showed a significant moderate-strong correlation for SATCo score and GMFM-IS-66 ($r = 0.64$, $p < 0.01$).This significant correlation was also observed in SATCo Group and GMFCS ($r = 0.65$, $p < 0.01$).

KINEMATICS

A total of 439 reaches were analyzed. No significant differences were observed for the type of reach (unimanual vs. bimanual) between levels of support across groups. Thus, all unimanual and bimanual reaches were pooled for further kinematic analysis.

With pelvic support, only subjects in the moderate and mild groups were able to maintain balance. Subjects in the severe group fell backwards when provided with pelvic support. Therefore, only reaches performed with axillae and mid-rib supports were analyzed for this group.

Out of the three groups, the moderate and severe groups showed differences in reaching and postural kinematics depending upon the level of trunk support provided, while the mild group did not demonstrate any significant differences.

Reaching Kinematics

Arm trajectories of one moderate group participant and photographic images of the reaching task across the three levels of trunk support are depicted in Figure 19. Improvements in reaching kinematics were mainly observed with higher levels of trunk support in this group (Figure 20).

Participants with moderate CP demonstrated a significant reduction in MT with both axillae, 130ms ($p < 0.01$), and mid-rib, 137ms ($p < 0.01$), compared to pelvic support, 300ms. In addition, the path covered by the arm during the reach was significantly reduced at axillae 28.5cm ($p < 0.01$), and mid-rib levels, 33.9cm ($p < 0.01$) compared to pelvic support, 58.3cm. This difference in path length was also observed between axillae and mid-rib support ($p < 0.05$).

Major changes were also observed in the moderate group for arm trajectory smoothness. Straightness score improved when the trunk support was raised from pelvic, 2.45, to mid-rib, 1.90 ($p < 0.01$), and axillae levels, 1.99 ($p < 0.05$). The level of trunk support also impacted the number of MUs, displaying 3 MUs at axillae ($p < 0.01$), and mid-rib level (p < 0.01), compared to 5 MUs at pelvic level.

Additionally, significant changes in arm control efficiency were found in NJS across trunk supports in moderate and severe groups. Moderately affected participants displayed improved arm trajectories while reaching with axillae, 278 ($p < 0.01$), and mid-rib support, 340 (p < 0.01), compared to pelvic support, 799. However, the severe group demonstrated better control of the arm with mid-rib, 630, than with axillae support 1211 ($p < 0.05$).

Trunk Angular Displacement

The moderate group showed a significant reduction in angular trunk displacement. This effect was observed in the three axes of motion with axillae and mid-rib compared to pelvic support ($p < 0.01$) (Table 8).

In the severe group, the reach was associated with exacerbated lateral flexion of the trunk at mid-rib level, whereas lateral trunk motion was more restricted with axillae support ($p < 0.05$). Contrary to this, the rotational component of the trunk was significantly reduced with mid-rib support versus the expected reduction at axillae level ($p < 0.05$) (Table 8).

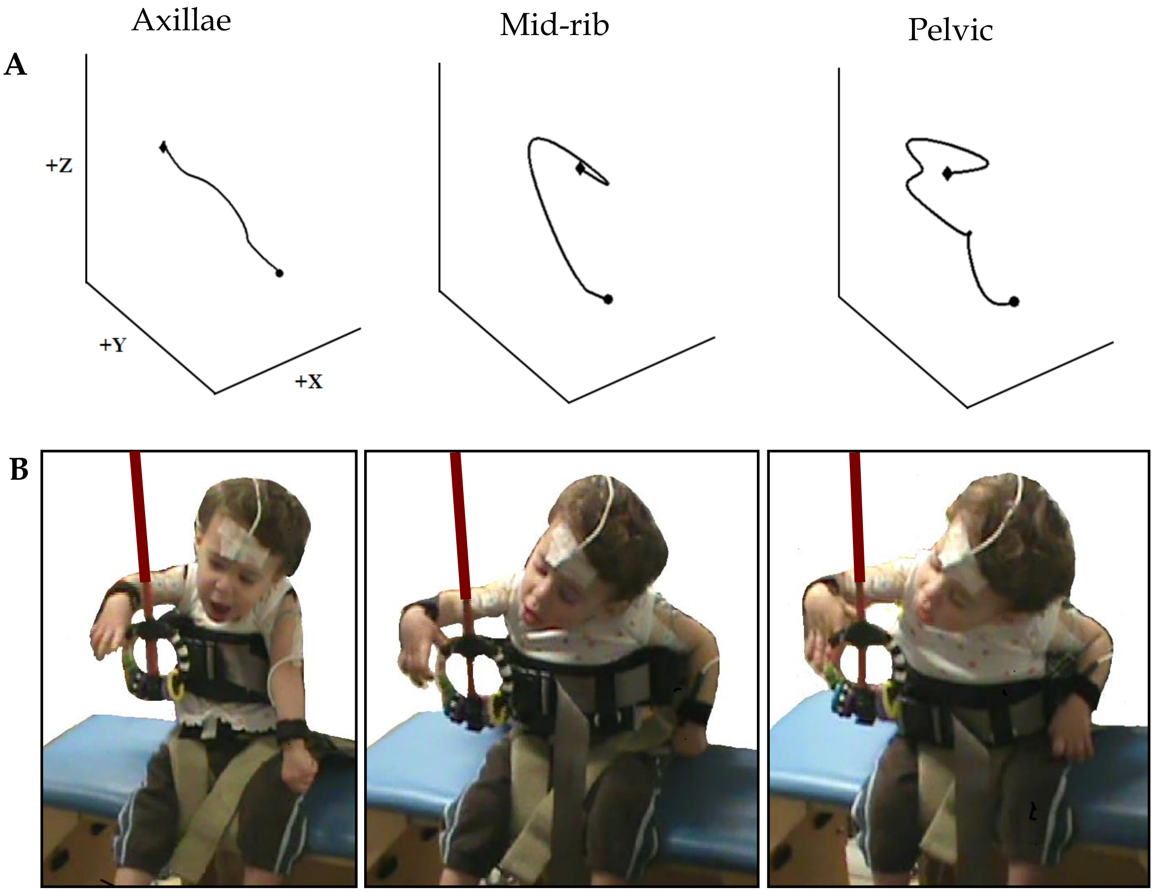


Figure 19. Reaching Performance across Levels of Trunk Support. Panel A depicts the three-dimensional representation of the arm path length of one participant with CP in the moderate group. Panel B shows the child reaching across the three different external trunk supports. Note the deviant trajectory of the arm when the level of trunk support was lowered from axillae to pelvic support. Circle shape indicates Reaching$_{\text{ONSET}}$ and diamond shape indicates

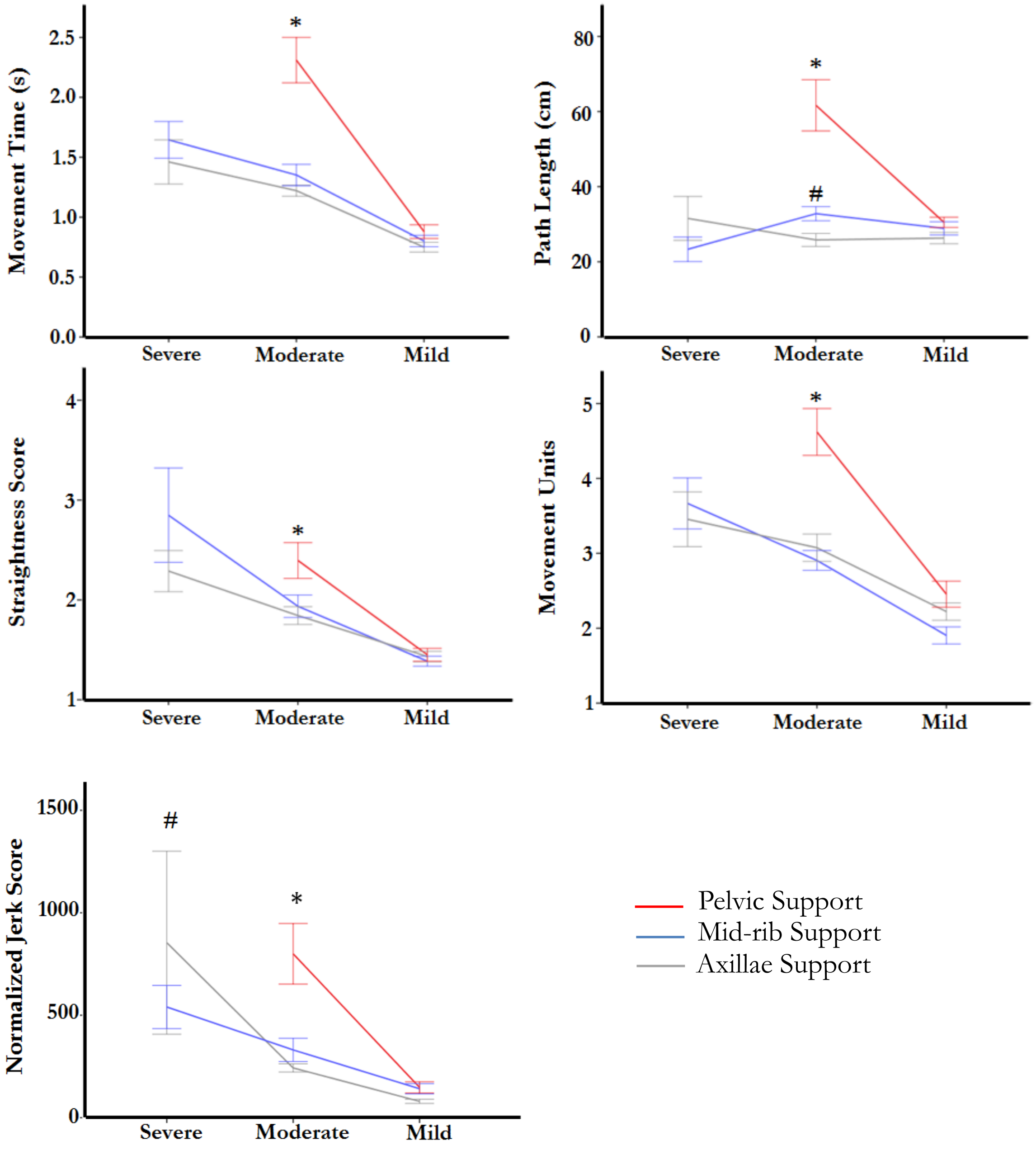


Figure 20. Reaching Kinematics across Levels of Trunk Support. Estimated means across groups for reaching kinematics with pelvic (red line), mid-rib (blue line) and axillae (grey line) supports. Error bars, ± 1 SE. * represents significant difference between pelvic vs. axillae and mid-rib support. # represents significant difference between axillae and mid-rib support.

Head Angular Displacement

In terms of head displacement, axillae and mid-rib support had a major effect in the moderate group along the three axes of motion (Table 8). Compared to pelvic support, angular head displacement while reaching was significantly reduced in flexion-extension ($p < 0.01$), lateroflexion ($p < 0.05$), and rotational axes ($p < 0.05$), with both axillae and mid-rib supports.

In the severe group, head angular displacement was significantly reduced only in the rotational axis with axillae compared to mid-rib support ($p < 0.05$) (Table 8).

Head Orientation

Inefficient trunk control had indirect effects on head during the reach only in participants in the severe group for the flexion-extension and lateroflexion planes of motion depending on the external trunk support provided (Table 8).

With mid-rib support, the position of the head was more extended and lateroflexed during reaching; however, raising the support to axillae level reoriented the head vertically in the flexion-extension ($p < 0.05$) and lateroflexion planes ($p < 0.05$).

Table 8: Postural Kinematics

Group	Level of External Trunk Support	Trunk Angular Displacement (*SEM*)	Head	
			Angular Displacement (*SEM*)	Orientation (*SEM*)
Severe (SATCo 0-2)	Axillae	F-E: 52.24(7.08) **Lat: 43.24(9.25)** **Rot: 52.00(6.72)**	F-E: 43.84(9.66) Lat: 60.12(14.81) **Rot: 44.15(7.73)**	**F-E: -0.89(491)** **Lat:-2.34(7.57)** Rot: -1.91(5.77)
	Mid-Rib	F-E: 48.56(6.78) **Lat: 64.17(8.93)** **Rot: 33.42(6.45)**	F-E: 57.29(9.36) Lat: 77.64(14.20) **Rot: 63.98(7.41)**	**F-E: 17.39(4.71)** **Lat:18.52(7.35)** Rot: 2.33(5.8)
Moderate (SATCo 3-5)	Axillae	**F-E: 8.70(3.79)** **Lat: 14.04(5.25)** **Rot:9.14(3.67)**	**F-E: 34.78(5.6)** **Lat: 51.12(7.89)** **Rot: 30.19(4.06)**	F-E: 0.66(2.65) Lat: -2.94(3.81) Rot: 3.98(3.30)
	Mid-Rib	**F-E: 11.81(4.07)** **Lat:12.11(6.17)** **Rot:10.79(3.91)**	**F-E: 31.37(5.87)** **Lat: 46.76(8.50)** **Rot: 28.89(4.40)**	F-E: 5.49(2.84) Lat: 3.35(4.24) Rot: 3.61 (3.46)
	Pelvic	**F-E: 41.48(4.31)** **Lat:39.29(5.79)** **Rot:38.93(4.13)**	**F-E: 71.50(6.11)** **Lat: 75.74(9.02)** **Rot:72.82(4.69)**	F-E: 0.34(3.00) Lat: 3.73(4.55) Rot: 2.41(3.62)
Mild (SATCo 6-7)	Axillae	F-E: 5.27(5.10) Lat: 10.21(6.84) Rot:5.44(4.88)	F-E: 11.66(7.22) Lat: 21.74(10.65) Rot: 12.63(5.53)	F-E: -0.51(3.55) Lat: -2.99(5.36) Rot: -3.64(4.28)
	Mid-Rib	F-E: 7.04(4.44) Lat: 11.71(6.17) Rot:6.82(4.30)	F-E: 11.78(6.59) Lat: 22.72(9.24) Rot: 11.25(4.76)	F-E: -2.65(3.11) Lat:-2.77(4.47) Rot: -2.04(3.87)
	Pelvic	F-E: 7.71(4.81) Lat: 16.54(6.54) Rot:7.36(4.62)	F-E: 11.47(6.93) Lat: 21.70(10.05) Rot: 10.19(5.21)	F-E: 0.74(3.36) Lat: 1.4(5.01) Rot: -1.98(4.10)

Note: Higher supports improved posture in moderate and severe groups. Bold characters: statistical significance. F-E: flexion-extension, Lat: lateroflexion and Rot: rotation. SEM: Standard error of the mean.

DISCUSSION

This study sought to investigate the impact of segmental trunk support on posture and reaching in children with CP, who were categorized according to their intrinsic level of trunk control. Results confirmed our hypothesis that improvements of the head, trunk and subsequent reaching proficiency would be observed with higher levels of trunk support in the moderate and severe groups. Children with complete trunk control (mild group) demonstrated similar behaviors, irrespective of the level of support. These data provide evidence that depending on the extent of intrinsic trunk control in children with CP, providing external support at specific levels has substantial effects on posture and reaching control during sitting.

Moderate participants were mainly classified as GMFCS levels IV with quadriplegic forms of CP and showed low reaching and manipulating skills, measured with the QUEST and MACS (Table 8). Despite noticeable motor impairments, reaching skills of the moderate group were significantly improved with higher levels of trunk support. Reaches that were performed with axillae and mid-rib levels of support showed decreased movement time and trajectory during the reach, in comparison to pelvic support. These improvements are indicative of a more mature reaching strategy (Jeannerod, 1988; van der Heide, 2005). In addition to this, reaching trajectories were more refined with external supports at higher levels, as indicated by the presence of less fragmented velocity profiles (MUs), straighter paths and more efficient control of arm transport (NJS).

Contrary to subjects in the mild group, differences observed in reaching kinematics in the moderate group could be explained by their ability to control cervical and thoracic segments but not the lumbar segment of the trunk. This observation is further supported with the postural kinematics results. Participants in the moderate group were able to stabilize their head and trunk in all planes of motion during a reach with axillae and mid-rib supports, contrary to the uncontrolled and exacerbated range of motion that was present with pelvic support. The fact that these differences were observed in the moderate, but not in the mild group, indicates that the region of intrinsic trunk control achieved is a main factor contributing to the differences found in postural and reaching kinematics. These data agree with research on infants that focused on the development of trunk control. Infants who had not acquired lumbar control demonstrated significant postural and reaching improvements with mid-rib in comparison to pelvic support (Rachwani et al., 2013). In contrast, infants with lumbar control, and thus, had the ability to sit independently (i.e. sit without arm support), did not show differences between levels of support. This suggests that the acquisition of lumbar control not only leads to an increased proficiency of posture and reaching skills but also influences the functional achievement of independent sitting. Similarly, in our sample, all children with mild trunk dysfunction were able to sit independently, whereas this ability was not present in participants in the moderate and severe groups.

Children in the severe group presented remarkable improvements in postural kinematics with higher levels of support. As expected, posture and reaching could not be analyzed with pelvic support since they were unable to maintain balance over the pelvis. Previous studies have already reported this problem, showing that children at GFMCS level V manifest profound postural dysfunction in head and trunk control and in counter-balancing active arm movements (Roby-Brami et al., 2003; van der Heide et al., 2004). However, when the support was provided at mid-rib or axillae levels, participants were able to maintain static trunk balance. Furthermore, with axillae in contrast to mid-rib support they demonstrated a more vertically aligned posture, with a reduction of head angular displacement during reaching. These findings suggest that external trunk support, mainly at axillae level, can provide static postural stability and reduce the range of head motion in severe cases of CP. However, regarding the angular displacement of the trunk, we obtained confounding results. With axillae support, the lateral flexion of the trunk was significantly reduced, while trunk rotation significantly increased. This might be related to the compensatory postural strategies that these children adopt for enabling reaching when the trunk is completely restrained.

Reaching performance in the severe group, measured as NJS, was also significantly impaired with axillae support. This reaching outcome was not expected; however, this support could have increased the accuracy demands of the reaching task since the trunk was completely restricted. It is possible that even though postural disturbance was ameliorated with the use of a higher support, children in the severe group required some degree of trunk mobility for reaching. In fact, an axillae support could eliminate the use of the trunk and arm as a coupled synergy, which has been typically observed as a compensatory strategy in neurological conditions that exhibit lack of control of DOF and inter-segmental coordination (Roby-Brami et al., 2003).

Therefore, in severe cases of CP with profound trunk deficits, the increase of trunk rotation and impoverished reaching proficiency with axillae support indicates that strict trunk constraints, or complete body stabilization, should not always be considered the optimal solution for biomechanical assistance in tasks involving head-trunk-arm movements.

Finally, we note that cognitive impairments and visuomotor deficits could have interfered in postural and reaching performance and thus could contribute to the reaching deficits observed in the study. Also, the results obtained in the group of children with severe trunk dysfunction should be interpreted with caution due to the small sample size recruited.

CLINICAL CONSIDERATIONS

An external trunk support at the level of balance impairment could be used for improving head, trunk and arm control during sitting, in children with CP that present postural limitations at thoracic-lumbar segments. A multi-segmented model in trunk control should be considered in both assessment and treatment of children with moderate-severe CP. Perhaps, it could also be included within evidence-based training protocols of upper limb function, such as Constraint-Induced Movement Therapy and Hand-Arm Bilateral Intensive Therapy (Gordon et al., 2011), since these are currently being applied mainly in mild cases of CP.

BRIDGING THE SECOND AND THIRD STUDY

The kinematic study in children with CP showed evidence that depending on the intrinsic control of the trunk, improvements in posture and reaching were observed with higher levels of support. However, this study did not provide information related to how the central nervous system of the different groups of children with CP controls trunk posture and arm reaching movements when provided with different levels of trunks support. Therefore, the following study in chapter V describes electromyographic recordings of trunk and arm muscles during the previously mentioned task.

In this population an expected improvement in neuromuscular control would be expected when reducing the postural demands with higher levels of external trunk support. As was hypothesized in the study of the kinematic profiles of posture and arm, we expected that the most substantial neuromuscular improvements during reaching would be observed in those subjects with incomplete segmental trunk control in sitting position and inadequate static, active and/or proactive trunk balance control (e.g. in our sample, children with CP associated to moderate and severe trunk dysfunctions).

CHAPTER V

THE IMPACT OF SEGMENTAL TRUNK SUPPORT ON POSTURE AND REACHING IN CHILDREN WITH MODERATE AND SEVERE CEREBRAL PALSY II: AN ELECTROMYOGRAPHIC STUDY

This chapter contains un-published, co-authored material and thus, the explicit collaboration of each author should be highlighted. I performed the experimental design, data collection, data analyses, statistical analysis and writing of the manuscript. Jaya Rachwani collaborated in the experimental design, data collection and data analyses. Sandra L Saavedra participated in the experimental design, data interpretation and reviews. Marjorie Woollacott provided editorial assistance and collaborated in the experimental design and data interpretation.

INTRODUCTION

One of the most challenging clinical features in cerebral palsy (CP) is postural dysfunction. The factors contributing to this problem are heterogeneous and can co-exist; these include lack of force generation, position or velocity-dependent reflexes, spasticity, dystonia, and dyskinesia (Krageloh-Mann & Bax, 2009; Van Doornik, Kukke, & Sanger, 2009). These postural deficits are further aggravated by inadequate ability to plan and coordinate movements due to injury to neocortex, sub-cortical centers and white matter (Scheck, Boyd, & Rose, 2012; Van der Heide et al., 2004). Specifically, children classified as GMFCS IV-V have impaired motor learning and reaching-grasping abilities; which are in turn accentuated by lack of postural control (Chang et al., 2005; Hanna et al., 2003; Palisano et al., 2007).

Posture control includes the ability to elicit compensatory (CPA) and anticipatory postural adjustments (APA). CPAs are responses to environmental disturbances or self-generated postural perturbations, like reaching, mainly controlled through continuous sensorimotor feedback (Massion, 1992; Santos, Kanekar, & Aruin, 2010). APAs, on the contrary, are more sophisticated postural responses based on feedforward mechanisms (von Hofsten & Woollacott, 1989). Non-refined APAs are observed in infancy; however, during childhood, sensorimotor experience, motor learning and inter-segmental coordination contribute to the refinement of both APAs and CPAs. During acquisition of postural adjustments, the trunk serves as a principal frame of reference for postural organization and orientation (Assaiante, Mallau, Viel, Jover, & Schmitz, 2005; Massion, 1992).

Children with CP display severe deficits in sitting control while reaching, including both basic levels of postural control (e.g. direction-specific recruitment) and fine-tuning modulation of muscle responses (e.g. amplitude, recruitment order and temporal activation) (Brogren & Hadders-Algra, 2008; Van der Heide, et al. 2004). In addition, as opposed to healthy children who display task-dependent postural responses, individuals with severe forms of CP manifest irregular and uncoordinated spatiotemporal patterns associated with pathological antigravity postural reactions (Boxum et al., 2014; Krageloh-Mann & Bax, 2009; Van der Heide et al., 2004). Nonetheless, task oriented training with trunk constraint has been linked to improvements of upper limb control and reduced compensatory trunk movements (Schneiberg, McKinley, Sveistrup, Gisel, Mayo, & Levin, 2010).

Previous studies on posture and reaching control have modeled the trunk as a single segment and therefore provided either full support or no support to the trunk during sitting. However, evidence indicates that the trunk should be approached as a multi-segmented structure with anatomically distinct regions that must be controlled through multi-articular muscles acting as synergistic functional units for adjusting the desired biomechanical output (Massion, 1992; Ting & Macpherson, 2005; Park et al, 2014). This level of neuro-anatomical complexity is well-controlled in healthy children but in moderate-severe CP, in which postural stability is compromised, a detailed examination of the contributions of segmental trunk regions to posture and reaching is mandatory.

We asked if the neuromuscular control of neck-trunk and arm muscles of children with moderate-severe CP could be improved during reaching when given optimal trunk support. Children were categorized according to their level of intrinsic trunk control (mild, moderate or severe), determined by the Segmental Assessment of Trunk Control (SATCo). The SATCo evaluates trunk stability at 7 different trunk segments: from head through the pelvis, and determines the level at which trunk instability occurs (Butler et al., 2010). Participants were given three levels of support (axillae, mid-rib and pelvic). Providing support at a level above the trunk-balance impairment decreases the exacerbated and uncontrolled position of the trunk, since it reduces the biomechanical effect of gravity on trunk control. Hence, we expected improvements in neuromuscular control of the arm and trunk during the reach with optimal support, including: 1) increased APA frequency, thus better stabilizing the trunk before the reach; 2) decreased CPA amplitudes, due to reduced instability during the reach; 3) reduced postural and reaching muscle onset latencies; and 4) improved neuromuscular organization. The neuromuscular effect with optimal support would be more prominent in children with trunk control deficits (severe and moderate groups); whereas children in the mild group, who have full trunk control, would not show changes across levels of support.

METHODS

PARTICIPANTS

The inclusion criteria and clinical description of the participants have been previously described elsewhere (see Chapter IV). All procedures were approved by the Institutional Review Board for protection of human subjects. Participants were grouped according to SATCo score into three categories: Severe (n=4: partial cervical control); Moderate (n =7: thoracic control) and Mild (n = 6: complete trunk control) (Table 9) (Butler et al., 2010).

EXPERIMENTAL PROCEDURE

During the reaching test, participants sat upright on a tall bench with pelvis firmly fixed with non-elastic straps and with an external device supporting the trunk at three different levels: axillae (T3 – T5), mid-rib (T7 – T8) and pelvic (L3 - L5). Participants were encouraged to reach a circular ring placed at midline at arm's length (Figure 21). The reaching task was video recorded (30 Hz) to visually analyze reach onsets and offsets using computerized video-coding software (http://www.datavyu.org/). This was synchronized with electromyographic (EMG) data collection.

EMG was recorded via bipolar self-adhesive surface electrodes placed 1-2 cm apart (MA300, Motion Lab Systems, Baton Rouge, LA). EMG signals were pre-amplified (gain X 20), band-pass filtered (10–375 Hz), amplified and sampled at 1000Hz. EMG signals were recorded bilaterally at cervical, thoracic and lumbar paraspinals, and anterior deltoid, triceps and biceps muscles. Additionally, heartbeat was recorded using electrodes placed over the 7th intercostal space, at the mid-axillary line, and over the sternal angle.

DATA ANALYSIS

A similar protocol used by Spencer and Thelen (2000) was applied for filtering EMG data: band-pass filter with cut-off frequencies at 20 and 160Hz, demean, full-wave rectification and BoxCar averaging with a window size of 7 data points in order to remove high-frequency components. A customized MATLAB program was used to identify and subtract the cardiac QRS-complex signal from the raw EMG signal before rectification and analysis.

EMG ANALYSIS

The normalization and identification of EMG phasic activity was calculated relative to baseline. For this purpose, EMG integrals of 10ms-bins were calculated across each muscle signal. A continuous five second-interval of the lowest level of activity for each muscle across support levels was identified and the 10ms-bin average during this baseline period was calculated. The average baseline bin was then used in the normalization of all bins within the muscle signal:

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

Muscle onsets and offsets were identified when 8 consecutive $EMG_{Norm.Integral}$ bins with a value greater or lower than 3 times the average baseline EMG-10ms-bin were detected, respectively. This value was based on the typical delay observed in normal postural responses (Horak, et al., 1997).

EMG analysis was structured into an APA stage, 500ms before reaching onset, and CPA stage (after reaching onset), which was variable depending on the reaching time. The rate of muscle activation was computed in APA and CPA stages. Only APAs activated within 500ms prior to reaching onset and deactivated at or after the reaching onset were considered. EMG amplitudes were calculated by adding the activated iEMG-10ms-bins in the CPA stage. Muscle recruitment pattern, craniocaudal or caudocranial, was analyzed when more than one paraspinal muscle was active. Lastly, muscle onsets and latencies, corresponding to the time-interval between reach initiation and muscle onsets during the CPA stage, were determined.

STATISTICS

A two-level Generalized Linear Mixed Model with the statistical package SPSS version 22.0 for Windows (SPSS Inc., Chicago, IL, USA) was applied. As fixed effects, we entered Group type (mild, moderate and severe), level of support (axillae, mid-rib and pelvic) and their interaction into the model. As random effects, we had intercepts for participants and for the number of reaches within participants, accounting for by-subject variability and by-number of reaches-within-subject variability in overall reach outcomes. Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity and normality. Post-Hoc pairwise comparisons were performed in case of significant interactions. The *P*-value was adjusted to the number of comparisons of the model applying Bonferroni´s sequential adjustment procedure.

RESULTS

A total of 394 reaches were analyzed. Participants in the severe group were unable to maintain balance when provided with pelvic support; therefore only axillae and mid-rib support conditions were analyzed for these participants.

PARASPINAL MUSCLES

Activation Rate: APAs & CPAs

Frequency of APA activity for the severe group was not included in the analysis due to practically non-existent occurrence. Moderate and mild groups showed no significant changes in activation rate across support levels.

CPA activation rate of paraspinal muscles remained invariable across support levels. However, mild participants manifested a greater tendency for thoracic and lumbar activation (52%) compared to moderate and severe participants (43%), who activated cervical muscles more frequently (57%) than mild participants (34%).

APA Activation Onset

As illustrated in Figure 22, mild participants showed APAs of cervical and thoracic muscles, closer to the reaching onset, compared to the moderate group, regardless of the support level (cervical: mild, -170ms, and moderate, -301ms, $p < 0.01$; thoracic: mild, -210ms, and moderate, -346ms, $p < 0.01$).

Temporal Organization & Recruitment Order of Postural Synergies

The activation of all three paraspinal muscles during a reach was seldom observed across groups. The participants mostly activated one muscle and occasionally two paraspinal muscles with diverse recruitment patterns.

Moderate and severe groups displayed caudocranial recruitment order of paraspinal muscles, irrespective of support (66% and 60% respectively). For the mild group, the directionality of recruitment patterns while reaching depended on the level of support (Figure 23). Craniocaudal order was more frequent with axillae support, whereas caudocranial recruitment increased with pelvic support (percentage of trials with craniocaudal order: axillae: 63%, mid-rib: 42 % and pelvic: 17%, $p < 0.01$).

CPA Latency

An interaction effect of group and support level was found in CPA latency of cervical and lumbar muscles for severely affected participants (Figure 24a). CPA onsets occurred earlier for both muscle types with mid-rib compared to axillae support (cervical: axillae, 725.07ms, mid-rib, 13.55ms, $p < 0.01$; lumbar: axillae, 1052.5ms, mid-rib, 323.35ms, $p < 0.05$).

Table 9: Clinical Assessment

Subject & Age	Segmental Level of Trunk Instability	SATCo Group	GMFCS Level	Subtype of CP	GMFM-66 (Average ±SE)	Quest Score	MACS Score
1 (8y 2mos)	Pelvis	Mild	IV	Hypotonic Quadriplegia	47.9 (±1.1)	32.33	II
2 (6y 8mos)	Pelvis	Mild	III	Spastic Diplegia	51.1 (±1.2)	85.20	I
3 (5y 3mos)	Pelvis	Mild	IV	Spastic Diplegia	46.9 (±1.0)	76.01	II
4 (5y 3mos)	Hips	Mild	III	Spastic Diplegia	51.9 (±1.2)	94.15	II
5 (4y 3mos)	Head	Severe	V	Spastic Quadriplegia	20.5 (±2.2)	5.11	IV
6 (7y 9mos)	Axillae	Severe	V	Dyskinetic Quadriplegia	20.5 (±2.1)	12.53	IV
7 (2y 5mos)	Head	Severe	V	Hypotonic Quadriplegia	22.7 (±2.0)	2.22	V
8 (2y 1mos)	Over Below Ribs	Moderate	III	Dyskinetic Quadriplegia	45.6 (±1.0)	36.40	II
9 (3y 7mos)	Over Below Ribs	Moderate	IV	Dyskinetic Quadriplegia	30.0 (±1.9)	39.79	II
10 (2y 1mos)	Below Ribs	Moderate	IV	Spastic Quadriplegia	36.0 (±1.5)	28.71	IV
11 (15y 8mos)	Over Below Ribs	Moderate	IV	Dyskinetic Quadriplegia	50.1 (±1.2)	45.73	II
12 (6y 8mos)	Inferior Scapula	Moderate	IV	Spastic Quadriplegia	26.0 (±2.0)	10.46	V
13 (10y 1mos)	Inferior Scapula	Moderate	IV	Dykinetic Quadriplegia	41.6 (±1.1)	34.45	II
14 (7y 4mos)	Head	Severe	V	Hypotonic Quadriplegia	14.8 (±2.8)	10.00	V
15 (7y 4mos)	Below Ribs	Moderate	IV	Dykinetic Quadriplegia	26.0 (±2.0)	38.47	II
16 (15y 1mos)	Hips	Mild	III	Spastic Diplegia	52.6 (±1.2)	99.07	I
17 (2y 1mos)	Pelvis	Mild	IV	Spastic Quadriplegia	25.3 (±1.9)	55.02	I

Note: Segmental level of trunk instability indicates the anatomical region at which the participant lost postural stability according to the SATCo score. GMFM-66 was measured with the GMFM-66-Item-Set and calculated with the GMAE-2 Gross Motor Ability Estimator. The values represent the GMFM-66 score ± SE. The Modified Ashworth scores are included to describe the level of spasticity of the upper extremity for each participant. Note that the sample of CP was mostly composed by quadriplegic forms of CP (13 cases) and cases with both moderate and severe trunk dysfunction (11 cases).

Thoracic muscles showed a main group effect. The severe participants had significantly delayed onset compared to mildly affected participants (severe, 573.442 ms; mild, 87.30ms, $p < 0.05$).

Amplitude

Changes in muscle amplitude across support levels were observed for cervical and thoracic muscles in both moderate and severe groups; and for lumbar muscles in the moderate group (Figure 25a).

The severely affected group showed reduced iEMG of cervical muscles when supported at axillae level (axillae: 281.65mV; mid-rib: 634.28mV, $p < 0.01$). A similar effect for cervical and lumbar muscles was observed in the moderate group when comparing axillae and mid-rib supports to pelvic support (cervical, axillae: 186.88mV, mid-rib: 205.70mV; pelvic: 423.14mV, $p < 0.01$; lumbar, axillae: 526.67mV, mid-rib: 404.81mV and pelvic: 903.54mV, $p < 0.01$).

For thoracic muscles, the moderate group scaled down its amplitude with axillae/mid-rib compared to pelvic support (axillae: 541.12mV, mid-rib: 743.14mV and pelvic: 1133.49mV, $p < 0.01$) and the severe group displayed augmented iEMG with axillae compared to mid-rib support (axillae: 1171.52mV; mid-rib: 387.50mV, $p < 0.01$).

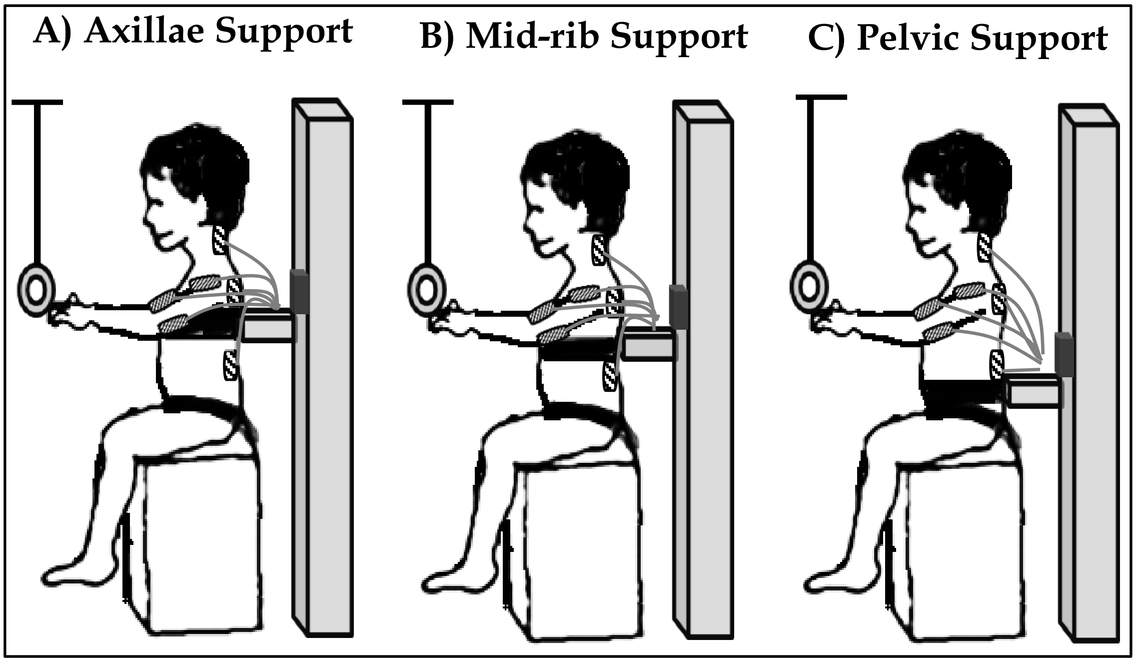


Figure 21. **Experimental Protocol and Electromyographic Setup.** A) axillae, B) mid-rib and C) pelvic levels of trunk support. The EMG sensor configuration is depicted in the figure (note that sensors were located bilaterally).

ARM MUSCLES

Activation Rate

Anterior deltoid activation rate depended on the type of group (mild, 74%; moderate, 55% and severe, 59%). Biceps followed a similar trend (mild, 60%; moderate, 34% and severe, 35%) and triceps activation rate demonstrated a main group effect, being significantly greater in the mild compared to severe group (mild: 86% and severe: 54%, $p < 0.05$).

CPA Latency

Biceps and triceps were activated earlier with axillae and mid-rib compared to pelvic support for the moderate group (biceps: axillae, 89.10ms; mid-rib, 45.77ms; pelvic, 205.59ms, $p < 0.01$; triceps: axillae, 105.68ms; mid-rib, 10.59ms; pelvic, 578.20ms, $p < 0.01$) (Figure 24b).

We also found a group effect for anterior deltoids CPA latency. Mild participants presented earlier activation than moderate participants (12.76ms vs. 133.97ms, $p < 0.05$).

Amplitude

Biceps demonstrated substantial changes in muscle amplitude across levels of support for all groups (Figure 25b).

The severe group increased biceps amplitude with mid-rib compared to axillae support (axillae: 551mV, mid-rib: 2090.84mV, $p < 0.05$). Participants in the moderate and mild groups displayed greater biceps amplitude at mid-rib and pelvic levels, compared to axillae support (moderate group: axillae, 1272.53mV; mid-rib, 1420.37mV; pelvic, 2265.72mV, $p < 0.01$; mild group: axillae, 1033.88mV; mid-rib, 1710.59mV; pelvic, 1620.85mV, $p < 0.05$).

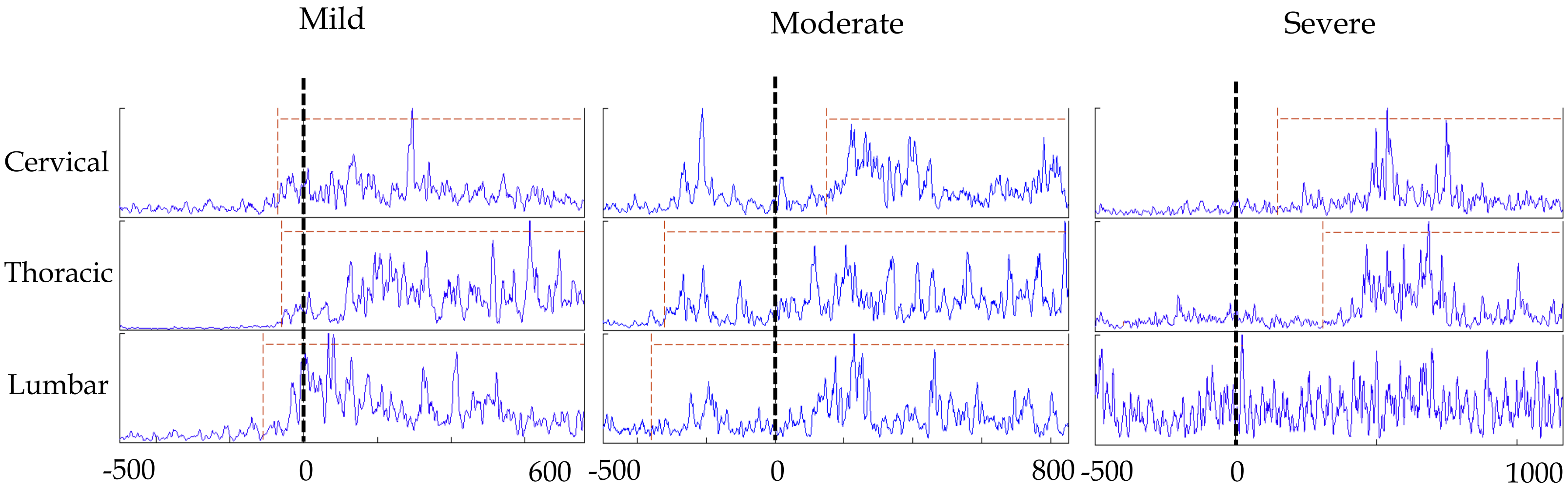


Figure 22. Anticipatory Electromyographic Profiles of Paraspinal Muscles. EMG profiles depicted for one participant of each group (mild, moderate and severe). Vertical black dashed line represents reach onset; red dashed lines represents muscle bursts. Note APA activity more specific to the reach onset for the mild participant compared to moderate participant and the absence of APA activity in severe participant. Muscle amplitudes and times are not scaled across groups for visual purposes.

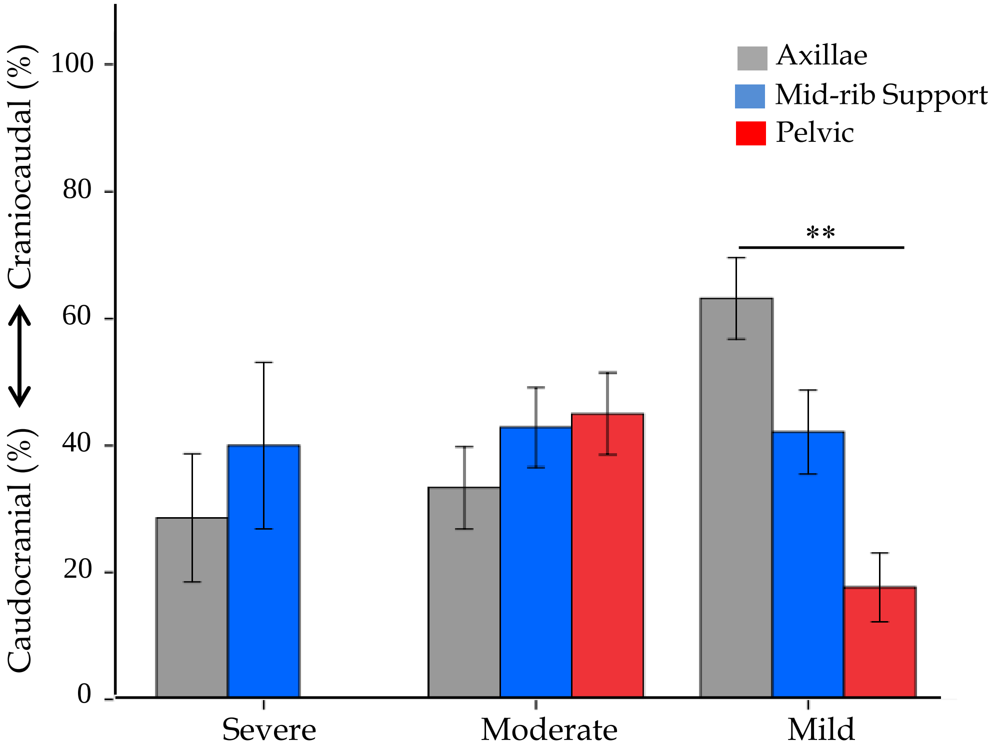


Figure 23. Recruitment Pattern of Paraspinal Muscles. A percentage greater than 50% indicates craniocaudal muscle recruitment, while less than 50% demonstrates caudocranial recruitment. Only those trials in which more than one paraspinal muscle group was activated were considered in the analysis. ** indicates $p < 0.01$.

Similarly, triceps amplitude increased with pelvic compared to axillae support for the moderate group (axillae: 948.16mV and pelvic: 1368.12mV, $p < 0.05$).

DISCUSSION

The neuromuscular control of trunk and arm was investigated in children with CP during seated reaching while providing different levels of external supports. Overall, support at higher levels improved electromyographic profiles, for the severe and moderate groups. Improved efficiency was demonstrated by decreased muscle amplitude and earlier onset latencies of both trunk and arm muscles. These observations were more variable in the severely affected group. Mildly affected participants displayed refined APAs, irrespective of the level of trunk support; however, its location modified the recruitment order of paraspinal muscles.

Children with CP present more postural sway during sitting compared to healthy children, indicating inefficient processing of sensorimotor feedback for keeping the trunk center of mass within the stability limits (Liao, Yang, Hsu, Chan, & Wei, 2003). In this regard, participants in the severe group, mainly classified as GMFCS-V with severe trunk dysfunction were unable to sit independently with pelvic support, but were able to maintain trunk balance during reaching with higher supports. It is well known that these children require adaptive equipment in daily living postural and arm activities (Brogren & Hadders-Algra, 2008; Palisano, et al., 2007).

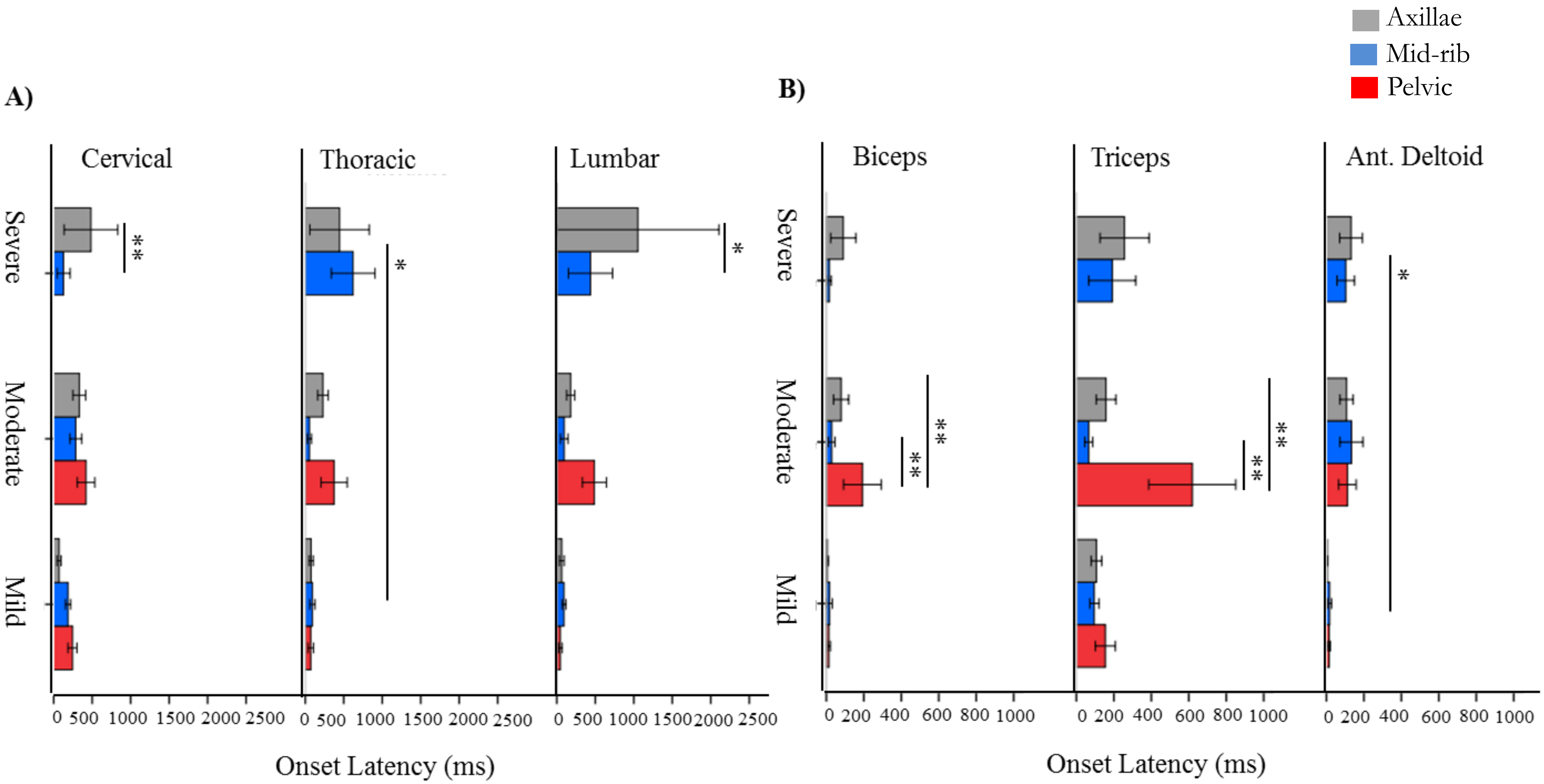


Figure 24. Activation Latencies of Paraspinal and Arm Muscles. In the case of severe participants, onset latencies of cervical and lumbar muscles were reduced with an external support at mid-rib level (A). Also, moderate participants experienced a significant delayed onset in the activation of biceps and anterior deltoid (Ant. Deltoid) (B). * indicates $p < 0.05$ and ** indicates $p < 0.01$.

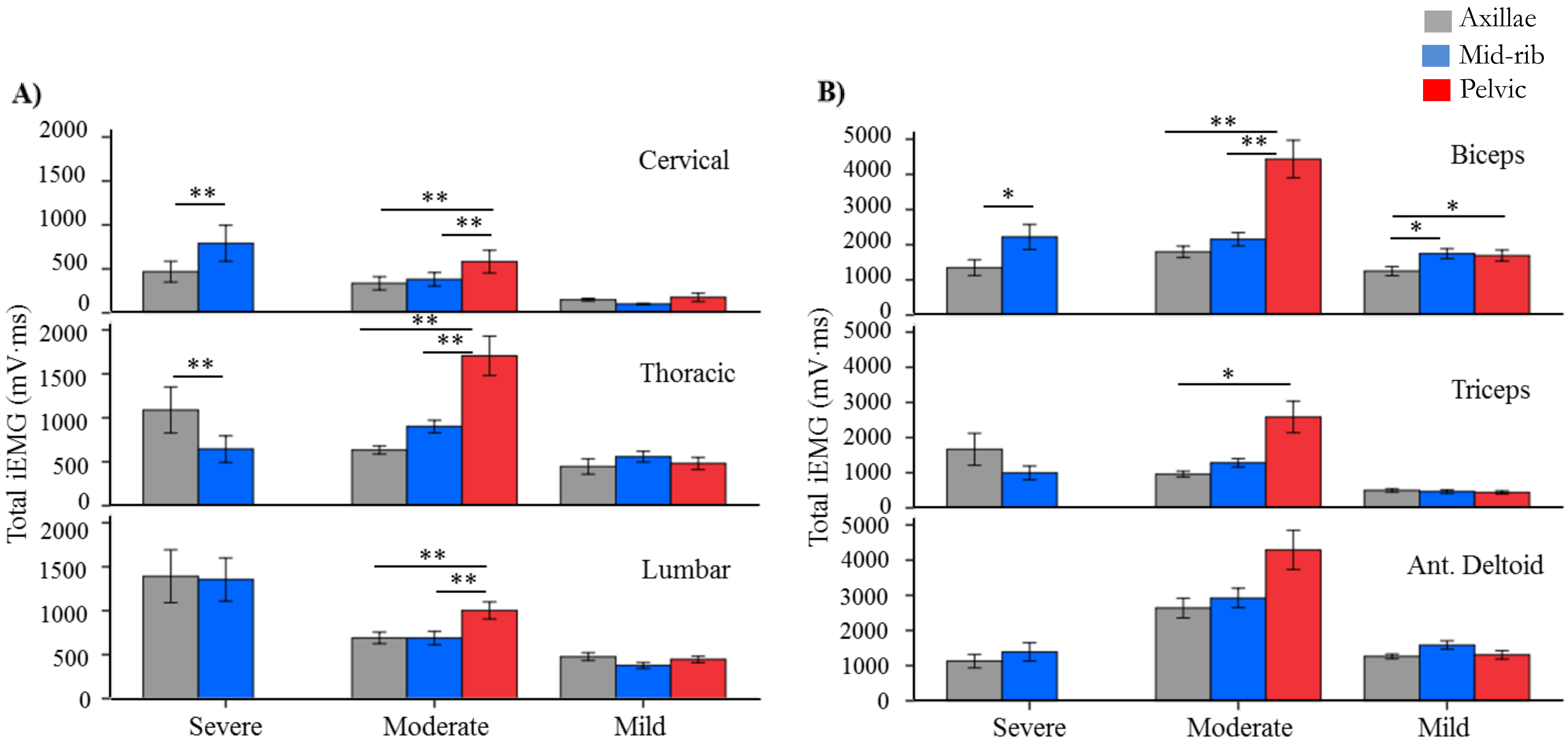


Figure 25. EMG Amplitude of Paraspinal and Arm Muscles during CPA Stage. The moderate group displayed amplitude-specific response of paraspinal muscles to the external level of support provided. EMG amplitude was reduced with higher levels of external support (A). With respect to arm muscles, biceps and triceps displayed changes depending on the level of support. This EMG response was significantly reduced with an external support at axillae level (B). * indicates $p < 0.05$ and ** indicates $p < 0.01$.

Moreover, recent research in our lab has shown that trunk balance during the reach is substantially reduced when progressively raising the external support from lower to higher levels on the trunk in children with moderate-severe CP (Santamaria et al., *under review*). These biomechanical effects are further expanded by the current research in showing distinct neuromuscular adaptations dependent on the level of support.

Research has shown that children with severe forms of CP are capable of fine-tuning muscle responses in reaching tasks only when manual support of legs and hips are provided (Van der Heide, et al., 2004). Our outcomes expand upon this observation by indicating that changes in muscle amplitudes depend on the constraints of the task. Children with moderate-severe trunk impairments displayed decreased CPA amplitudes with higher supports, but when these participants had to maintain an upright sitting position with a low support at pelvic level, muscle amplitudes considerably increased. This suggests that muscle amplitudes were situation-specific and scaled-up when the ability to maintain verticality was considerably disrupted. In contrast, children with complete trunk control (mild group) did not modulate muscle amplitude across support levels, implying that there was no support condition at which sitting balance was being challenged for these participants.

APAs are task-dependent postural responses used to stabilize balance prior to self-initiated actions. They are dynamic, flexible and modulated with respect to expected forthcoming perturbations and external support conditions (Hall, et al., 2010). The severity of neural damage and dysfunction of the trunk can be a primary factor in reducing the capability to generate efficient APAs. Anticipatory profiles across groups revealed that the mild participants (mostly classified as GMFCS level III), elicited more refined cervical and thoracic APAs, specific to the reaching onset, suggesting a more efficient feedforward control of posture. APAs were absent in the severe participants, implying that posture mainly relied on sensory feedback during reaching with resulting changes in amplitudes and latencies during the CPA stage (Santos et al., 2010; Sukal-Moulton, Krosschell, Gaebler-Spira, & Dewald, 2014; Van der Heide, et al., 2004).

In spite of the inefficient feedforward control and inability to increase the activation rate of CPAs, severe participants, were able to elicit earlier activation of cervical and lumbar CPAs with mid-rib compared to axillae support. These faster responses are no doubt a postural compensation in the absence of feedforward mechanisms in order to maintain trunk balance during reaching. However, with axillae support, at which trunk balance was no longer as demanding, severe participants did not display these observed early onset CPA responses.

In line with the results obtained by van der Heide et al (2004), severe forms of CP have shown a stereotyped craniocaudal muscle recruitment order during reaching. Contrary to this observation, caudocranial recruitment of paraspinal muscles was preferred in the moderate and severe groups of our sample and remained invariant across levels of support. This general effect could be explained by the firm fixations adopted at the level of hips and pelvis; consequently, the paraspinal muscle activation pattern followed an ascending order, starting from the most stable point of equilibrium.

The mild group on the contrary, showed more flexibility in modulating the recruitment order of paraspinal muscles according to the support level, as it is commonly found in healthy individuals undergoing external task-specific constraints (Hall et al., 2010; Van der Heide et al., 2004). In mild participants, when the postural locus of control, was placed at the axillae level, the postural synergy followed a craniocaudal direction; however, with pelvic support, this directionality was inverted. This outcome indicates that explicit trunk support is in fact associated with a modulatory effect on paraspinal muscle organization in children with complete trunk control.

Hypertonia and spasticity are typical signs observed in quadriplegic presentations of CP and affect the control of upper extremity movements. Recent findings show that children with CP classified as GFMCS IV-V and displaying trunk control deficits, are able to reach more efficiently when provided with higher levels of trunk support (Santamaria et al, under review). In addition to this, current results demonstrate that these same participants display characteristic patterns of neuromuscular control of the arm during reaching depending on the level of support.

Participants with full trunk control (mild group) had an earlier response of paraspinal and anterior deltoid muscles, and activated arm muscles more frequently during the reach compared to moderate and severe groups. The improved neuromuscular ability in mildly affected participants, regardless of the support level, could be attributed to the extent of neurological damage (Sukal-Moulton, et al., 2014).

In addition, the arm muscles of all participants showed neuro-modulatory effects dependent on the support level. For instance, biceps amplitude was significantly scaled up with lower levels of support. Furthermore, moderately involved participants increased triceps amplitude during pelvic support, which probably served as a stabilizer for counteracting the gravitational effects encountered in this condition.

Lastly, we should take into account the small sample size of the severe group while interpreting the obtained EMG results.

CLINICAL CONSIDERATIONS

This research emphasizes the inter-relation between trunk and upper extremity control in CP (Schneiberg et al., 2010; van der Heide et al., 2004). Our outcomes extend previous research by showing that improvements in the neuromuscular control of the trunk and arm occur when providing higher levels of external support in children with trunk control deficits. We thus propose that the trunk should be approached as a multisegmented structure. Consideration of intrinsic level of control combined with level of external support may improve motor-learning-based approaches in rehabilitation of individuals with neuropathologies that include seated postural deficits, similar to those observed in moderate and severe cases of CP.

CHAPTER VI

FINAL CONCLUSIONS

GENERAL SUMMARY OF FINDINGS

In our daily life activities we are constantly reaching, grasping and manipulating objects. The mobility of the upper extremity is intimately associated with the ability to adapt posture to the inherent constraints of the human body, the task being performed and the surrounding environment. This ability to coordinate posture and upper extremity movements will be essential in early stages of life for building up the repertoire of motor sequences that will lead to the acquisition of higher-order motor activities such as eating or writing.

In reach to grasp tasks, it is not only the movement of the arm, forearm and hand, but also the foundational aspects of postural stability and orientation that must be planned, coordinated and executed as one motor program. When performing seated multi-joint tasks, like reaching, healthy adults show adaptive behavioral responses that provide adequate motor flexibility to face the degrees of freedom problem. Thus, healthy individuals display the ability to smoothly control upper limb movements and trunk posture simultaneously through specific synergistic temporal-spatial muscle patterns. This fact *per se* justifies why the trunk has been traditionally modeled as a non-dissociable unit in the scientific literature related to therapy and clinical assessment in neurorehabilitation.

In healthy individuals, subdividing the trunk into two principal effectors via an external support at mid-rib level showed no changes in reaching behavior at the kinematic level. This observation can be attributed to the physiological flexibility of the CNS for maintaining constant the movement output in order to achieve the goal of the task. However, the neural control of paraspinal muscles (timing, activation rate and amplitude) was significantly modulated depending on both the level of trunk constraint provided and segmental location of the muscle with respect to the reaching arm. With mid-rib support, the anticipatory control of ipsilateral cervical muscles increased and the tonic activity of paraspinal lumbar muscles was bilaterally augmented as well. As expected, adults were able to adapt to the imposed increase of the number of DOF when supported at the pelvic level by incrementing the activation rate of paraspinal muscles; consequently, the arm motion and postural stability remained constant across reaches (measured by movement kinematics). This evidence indicates that a healthy CNS is capable of optimizing the motion of the trunk as a unique functional structure through explicit neuromuscular responses while reaching. Also, the reduction of DOF of the trunk through an external support at mid-rib level improved some parameters of neuromuscular modulation of posture, for example, 1) the feedforward control of cervical muscles that functions to keep the head stable during the reach and 2) activation of cervical and thoracic compensatory postural adjustments at a reduced latency.

CP is a syndrome with multifactorial etiology, which is associated with problems like cognitive impairments and epilepsy that aggravate the characteristic motor dysfunction presented in this neuropathology. Both the central as well as peripheral nervous system are involved in the deficits observed in learning, planning and executing motor actions. Among the motor deficits found in those children with moderate to severe levels of impairment, deficits in static, active and/or pro-active postural control mechanisms would be one of the most disabling problems during activities of daily living.

In relation to the degrees of freedom/motor equivalence problem, children diagnosed with CP will have problems developing motor strategies for dealing with both the redundancy of DOF offered by the joints and the kinematic/kinetic properties that configure voluntary movements. Within the context of the Dynamic Systems and Neuronal Group Selection Theories, the lack of the ability to initiate and modulate appropriate sensorimotor responses across diverse environmental and task conditions will lead to limited motor experience and learning that will definitively impair the motor development of these children. If we model the trunk as a dynamic multisegmented anatomical structure, around which posture and reaching are organized, a key element to consider in CP would be ways to assess and treat trunk stability and balance in order to help them attain sitting balance which is optimally stable for their condition. This applies most specifically to those children who are unable to acquire or maintain independent sitting (GMFCS levels IV-V).

Results of the experiments with this population showed, as expected, that the effects of external support on posture and arm movements during reaching were substantially magnified in children diagnosed with CP compared to healthy young adults. The effect of trunk support on arm kinematics during the reach was specific to those participants classified as GMFCS levels IV and V with moderate and severe trunk dysfunctions, determined by the SATCo. These effects were smaller, or even absent, in those children with full segmental trunk control and independent sitting (mild group).

In contrast to the results seen in adults, a higher level of trunk support significantly improved trunk stability during the reaching task, limiting the abnormal mobility of head-trunk that accompanied the arm transport phase of the reach. Participants belonging to the moderate group of trunk dysfunction (with cervical and partial thoracic control) substantially decreased the time and shortened the arm path of the reach. In addition to these improvements, the arm trajectory was straighter and it was performed more efficiently. This group as well as those participants in the severe group (with only partial cervical control), were able to reach for an object with reduced postural sway of the trunk and head when external support at the axillae was provided.

Nevertheless, reaching smoothness was disrupted with support at the axillae level for participants in the severe group. This could be explained by the increased arm movement demands of the reaching task when the trunk was completely restricted at this level.

In terms of neuromuscular control, there was a relationship between the severity of the neural damage, reflected by the subtype of CP and trunk dysfunction, and the results of the electromyographic analysis of arm and paraspinal muscles. Overall, the mild group demonstrated more refined APAs, activated closer to the reaching onset, as seen in healthy conditions. In the case of severely impaired participants, the EMG analysis corroborated what other research has indicated using other experimental paradigms; that is, the most neurologically involved children diagnosed with CP show almost no activation of anticipatory responses in paraspinal muscles during voluntary reaches. This effect was observed irrespective of the trunk support provided. On the other hand, at higher levels of support, these participants showed improved compensatory neuromuscular reactions of trunk and head after reaching initiation, which is seen in the shorter onset latency of cervical and thoracic muscle responses with mid-rib support. These observations suggest that the severity of brain damage typically found in these severely impaired patients contributes to the profound deficit in feedforward control of paraspinal muscles during reaching.

The influence of level of external support and severity of trunk dysfunction was specifically observed in the way that the different groups of children regulated paraspinal muscle amplitude. Both severely and moderately impaired groups of children scaled up the amplitude of cervical and lumbar muscles when the support was at a lower level, whereas mildly impaired participants did not display changes in paraspinal muscle amplitude across support levels, possibly because they had, by classification, full trunk control.

These children with mild cases of CP who had sitting control (though axial hypotonia, dysregulation of muscle tone and spasticity were present to some degree) showed earlier activation of arm muscles (e.g., the anterior deltoid) across all levels of support, when compared to the other groups. Moderately impaired participants, on the contrary, had earlier arm muscle onsets only with higher levels of support. Mild participants were also capable of dynamically fine-tuning the recruitment order of paraspinal muscles. These participants displayed a craniocaudal recruitment order of trunk muscles when provided with axillae support; however, this directionality was inverted when the trunk support was lowered to the pelvic level.

The biceps brachii, a main and common muscle effector in arm movements, such as reach-to-grasp actions and pointing tasks, was highly influenced by the level of trunk support provided. All children increased the amplitude of biceps responses when the external support was lowered from axillae to pelvic or mid-rib level. As we observed in trunk muscles, higher postural instability could be associated to increased myoelectrical activity of muscles that act as common effectors during the reaching task.

Lastly, in CP the application of an external support at higher levels of the trunk has a positive effect on the kinematic and neuromuscular characteristics of posture and arm movements during a reaching task. The effect of trunk support was indeed determined by the subtype of CP and also by the intrinsic level of segmental trunk control. Altogether, these results provide information for future refinement of current rehabilitation techniques in children with CP having moderate/severe trunk dysfunctions. In this way, we would first assess trunk control by using the Segmental Assessment of Trunk Control and then focus rehabilitation on the identified trunk segment at which the child loses balance, to optimize the coordination between posture and reaching performance.

FUTURE STUDIES AND CLINICAL APPLICATIONS

The results of the studies examining conditions for optimal reaching in children with CP suggest promising designs for clinical research seeking to discover the optimal level of trunk be fixated (via external trunk support) for persons with neuromotor disorders that manifest intrinsic trunk control deficits. One of the main goals of neurorehabilitation is to facilitate as much voluntary activity within the behavioral repertoire of the neurological patient as possible.

Providing optimal levels of external trunk support at the level of the trunk at which balance is lost allows not only for improved biomechanical performance but also for optimal neuromuscular activity of trunk and arm muscles.

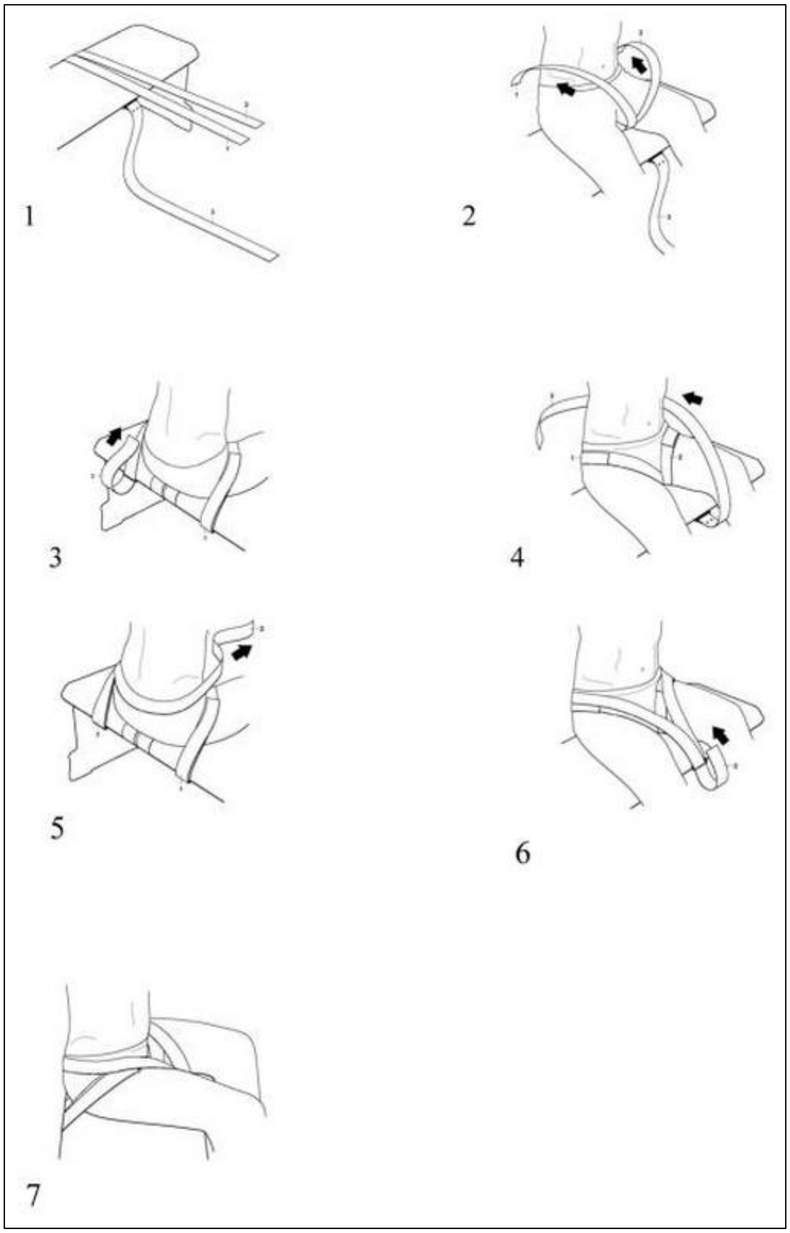
The findings of this dissertation regarding optimal trunk support for children with CP would additionally justify the use of explicit external trunk supports during the training of upper limb functional tasks. Optimal levels of trunk support could be used in combination with evidence-based training protocols of upper extremities such as Constraint Induced Movement Therapy (CIMT) or Hand Arm Bilateral Intensive Therapy (HABIT). These rehabilitative approaches are currently designed for children diagnosed with mild CP, in which posture is not severely disrupted. The results obtained in chapters IV and V suggest that training of the segmental control of the trunk in static, active and pro-active dimensions, in association with an external support at the identified anatomical level of trunk imbalance, could open new frontiers in the rehabilitation of the most neurologically involved children with CP. Thus, facilitating a vertical upright position at a level at which the child with CP has volitional control of the vertebral column against gravity while reaching could enormously facilitate the implementation of active upper limb and postural training strategies in these patients.

Finally, I would like to emphasize that further clinical research, including randomized controlled clinical trials, applying this experimental paradigm to postural and arm training protocols are still required in children with CP and other neuropathologies before conclusions can be made regarding its application to evidence-based clinical therapy.

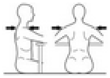
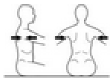
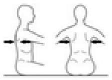
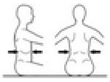
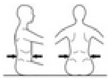
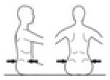
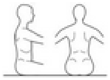
APPENDIX

STRAPPING PROCESS AND SATCO SCORE SHEET

Strapping Process



SATCO Score Sheet

Client Name: **Ref #:** **Tester Name:** **Date:**	**Level of manual support Pelvic / thigh strap used except as indicated**	**Functional Level Arms and hands in air except as indicated**	**Static**	**Active**	**Reactive**	**Comments**
			Maintain vertical neutral position of head and trunk above manual support level			
			minimum of 5 seconds	**while turning head with arms lifted**	**Maintain / quickly regain following brisk nudge**	
	Shoulder girdle Testers hand position may vary from horizontal	**Head control** Arms may be supported throughout			**NOT Tested for Head Control**	
	Axillae	**Upper Thoracic Control**				
	Inferior scapula	**Mid Thoracic Control**				
	Over lower ribs	**Lower thoracic Control**				
	Below ribs	**Upper lumbar Control**				
	Pelvis	**Lower lumbar Control**				
	No support given and pelvic/thigh straps removed	**Full trunk control**				
Fixed spinal deformity? Yes_____No_____Comments__________						
Limitation of Cervical Rotation __Left__Right Comments__________						

REFERENCES CITED

Aisen, M. L., Kerkovich, D., Mast, J., Mulroy, S., Wren, T. a L., Kay, R. M., & Rethlefsen, S. a. (2011). Cerebral palsy: clinical care and neurological rehabilitation. The Lancet. Neurology, 10, 844–852.

Al-Falahe, N., Vallbo, A.B. (1988). Role of the human fusimotor system in a motor adaptation task. Journal of Neurophysiology, 401, 77-95.

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

Andersen, R.A., Bruneo, C.A. (2002). Intentional maps in posterior parietal cortex. Annual Reviews of Neuroscience, 25,189-220.

Anderson, D. I., Campos, J. J., Rivera, M., Dahl, A., Uchiyama, I., & Barbu-Roth, M. (2014). The consequences of independent locomotion for brain and psychological development. In R. B. Shepherd (Ed.), Cerebral palsy in infancy: Targeted activity to optimize early growth and development (pp. 199–223). Sidney, Australia: Churchill Livingston: Elsevier.

Anttila, H., Autti-Rämö, I., Suoranta, J., Mäkelä, M., & Malmivaara, A. (2008). Effectiveness of physical therapy interventions for children with cerebral palsy: a systematic review. BMC Pediatrics, 8, 14.

Archambault, P., Pigeon, P., Feldman, a G., & Levin, M. F. (1999). Recruitment and sequencing of different degrees of freedom during pointing movements involving the trunk in healthy and hemiparetic subjects. Experimental Brain Research, 126, 55–67.

Aruin, A.S., Forrest, W.R., & Latash, M.L. (1998). Anticipatory postural adjustments in conditions of postural instability. Electroencephalography and Clinical Neurophysiology, 109(4), 350-359.

Aruin, A.S., & Latash, M.L. (1995). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. Experimental Brain Research, 102, 323-332.

Arutyunyan, G.A., Gurfinkel, V.S., & Mirskii, M.L. (1969). Organization of movements on execution by man of an exact postural task. Biofizika, 14, 1103-1107.

Ascension Technology Corporation. (2000). *MiniBIRD® Position and Orientation Measurement System*. Burlington, Vermont: Ascension Technology Corporation.

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.

Atkeson, C. G., & Hollerbach, J. M. (1985). Kinematic features of unrestrained vertical arm movements. The Journal of Neuroscience : The Official Journal of the Society for Neuroscience, 5(9), 2318–2330.

Augurelle, A.S., Smith, A.M., Lejeune, T., & Thonnard J.L. (2003). Importance of cutaneous feedback in maintaining a secure grip during manipulation of hand held objects. Journal of Neurophysiology, 89, 665-671.

Babin-Ratte, S., Sirigu, A., Gilles, & M., Wing, A. (1999). Impaired anticipatory finger grip-force adjustments in a case of cerebellar degeneration. Experimental Brain Research, 128, 81-85.

Bayle, N., & Gracies, J.-M. (2014). The syndrome of deforming spastic paresis: pathophysiology, asssessment and treatment. In R. B. Shepherd (Ed.), Cerebral palsy in infancy: Targeted activity to optimize early growth and development (pp. 115–133). Australia, Sidney: Churchill Livingston: Elsevier.

Begliomini, C., De Sanctis, T., Marangon, M., Tarantino, V., Sartori, L., Miotto, D., … Castiello, U. (2014). An investigation of the neural circuits underlying reaching and reach-to-grasp movements: from planning to execution. Frontiers in Human Neuroscience, 8, 1–14.

Belenkii, V., Gurfinkel, V., & Paltsev, Y. (1967). Elements of control of voluntary movements. Biophys, 12, 154–161.

Benarroch, E. E. (2013). Pedunculopontine nucleus: functional organization and clinical implications. Neurology, 80, 1148–1155.

Bernstein, N. (1967). The coordination and regulation of movements. New York, NY: Pergamon Press.

Berret, B., Bonnetblanc, F., Papaxanthis, C., & Pozzo, T. (2009). Modular control of pointing beyond arm's length. Journal of Neuroscience, 29(1),191-205.

Bhakta, B. B., O'Connor, R. J., & Cozens, J. A. (2008). Associated reactions after stroke: a randomized controlled trial of the effect of botulinum toxin type A. Journal of Rehabilitation Medicine, 40, 36–41.

Bigongiari, A., de Andrade e Souza, F., Fanciulli, P.M., Neto Sel, 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.

Bird, A. (2007). Perceptions of epigenetics. Nature, 447, 396–398.

Boudreau, M.J., & Smith, A.M. (2001). Activity in rostral motor cortex in response to predictable force-pulse perturbations in a precision grip-task. Journal of Neurophysiology, 86, 1079-1085.

Bosch-Bouju, C., Hyland, B. I., & Parr-Brownlie, L. C. (2013). Motor thalamus integration of cortical, cerebellar and basal ganglia information: implications for normal and parkinsonian conditions. Frontiers in Computational Neuroscience, 7(November), 163.

Bouisset, S., & Do, M.C. (2008). Posture, dynamic stability, and voluntary movement. Neurophysioly Clinique, 38(6), 345-362.

Boxum, A., van Balen, L., Dijkstra, L. Hamer, E.G., Hielkema, T., Reinders-Messelink, H.A., Hadders-Algra, M. (2014). Postural adjustments in infants at very high risk for cerebral palsy before and after developing the ability to sit independently. Early Human Development, 90(9), 435 - 441.

Brinkman, C. (1984). Supplementary motor area of the monkey's cerebral cortex: short- and long term deficits after unilateral ablation, and the effects of subsequent callosal section. Journal of Neuroscience, 4, 918-929.

Brogren, E., Hadders-Algra, M., & Forssberg, H. (1996). Postural control in children with spastic diplegia:muscle activity during perturbations in sitting. Developmental Medicine and Child Neurology, 43, 534–546.

Brogren, E., Hadders-Algra, M., & Forssberg, H. (1998). Postural control in sitting children with cerebral palsy. Neuroscience and Biobehavioral Reviews, 22(4), 591–6.

Buneo, C.A., & Andersen, R.A. (2006). The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements. Neuropsychologia, 44, 2594-2606.

Bruner, J.S., & Koslowski, B. (1972). Pre-adapted constituents of manipulatory actions. Perception, 1, 3-14.

Bruttini, C., Esposti, R., Bolzoni, F., Vanotti, A., Mariotti, C., & Cavallari, P. (2014). Temporal disruption of upper-limb anticipatory postural adjustments in cerebellar ataxic patients. Experimental Brain Research. DOI 10.1007/s00221-014-4103-x.

Bunderson, N.E., Burkholder, T.J., & Ting, L.H. (2008). Reduction of neuromuscular redundancy for postural force generation using an intrinsic stability criterion. Journal of Biomechanics, 41(7), 1537–1544.

Burke, D., Wissel, J., & Donnan, G. a. (2013). Pathophysiology of spasticity in stroke. Neurology, 80(Suppl 2), 20–26.

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., Sofranac, M., Jarvis, S., & Woollacott, M. (2010). Refinement, Reliability and Validity of the Segmental Assessment of Trunk Control (SATCo). Pediatric Physical Therapy, 22(3), 246–257.

Canedo, A. (1997). Primary motor cortex influences on the descending and ascending systems. Progress in Neurobiology, 51, 287–335.

Caronni, A., Bolzoni, F., Esposti, R., Bruttini, C., & Cavallari, P. (2013). Accuracy of pointing movements relies upon a specific tuning between anticipatory postural adjustments and prime mover activation. Acta Physiologica, 208(1), 111-124.

Castiello, U. (2005). The neuroscience of grasping. Nature Reviews Neuroscience, 6, 726-736.

Center for Disease Control and Prevention, CDC (2010). Data and Statistics for Cerebral Palsy, Web Site. Retrieved from: http://ucp.org/wp-content/uploads/2013/02/cp-fact-sheet.pdf

Chan, G., & Miller, F. (2013). Assessment and treatment of children with cerebral palsy. Orthop Clin North Am, 45(3), 313–325.

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, 12, 281–293.

Changeux, J. (1997). Variation and selection in neural function. Trends in Neuroscience, 20(7), 291–293.

Charles, J., & Gordon, A. (2006). Review Development of hand – arm bimanual intensive training (HABIT) for improving bimanual coordination in children with hemiplegic cerebral palsy. Developmental Medicine and Child Neurology, 48, 931–936.

Cheng, H.Y.K., Lien, Y.J., Yu, Y.C., Yu, Y.Y., Pei, Y.C., Cheng, C. H., Wu, D.B. (2013). The effect of lower body stabilization and different writing tools on writing biomechanics in children with cerebral palsy. Research in Developmental Disabilities, 34(4), 1152 – 1159.

Christensen, D., Van Naarden Braun, K., Doernberg, N. S., Maenner, M. J., Arneson, C. L., Durkin, M. S., … Yeargin-Allsopp, M. (2014). Prevalence of cerebral palsy, co-occurring autism spectrum disorders, and motor functioning - Autism and Developmental Disabilities Monitoring Network, USA, 2008. Developmental Medicine and Child Neurology, 56, 59–65.

Cordo, P., & Nashner, L. (1982). Properties of postural adjustaments associated with rapid arm movements. Journal of Neurophysiology, 47(2), 287–302.

D'Amico, M., & Ferrigno, G. (1992). Comparison between the more recent techniques for smoothing and derivative assessment ni biomechanics. Medical & Biological Engineering & Computing, 30, 193–204.

Dan, B., Bouillot, E., Bengoetxea, A., Boyd, S. G., & Cheron, G. (2001). Distinct multi-joint control strategies in spastic diplegia associated with prematurity or Angelman syndrome. Clinical Neurophysiology, 112(9), 1618–1625.

De Luca, C. (1997). The Use of Surface Electromyography in Biomechanics. Journal of Applied Biomechanics, 13, 135–163.

Del Grande, F., Maus, T., & Carrino, J. (2012). Imaging the Intervertebral Disk: Age-Related Changes, Herniations, and Radicular Pain. Radiol Clin North Am, 50(4), 629–649.

DeMatteo, C., Law, M., Russell, D., Pollock, N., Rosenbaum, P., & Walter, S. (1992). QUEST: Quality of Upper Extremity Skills Test. Hamilton, ON: McMaster University, Neurodevelopmental Clinical Research Unit.

Denny-Brown, D. (1966). The Cerebral Control of Movement. (pp. 124–143). Liverpool: Liverpool University Press.

Di Prisco, V. (1984). Hebb synaptic plasticity. Progress in Neurobiology, 22(2), 89–102.

Dickstein, R., Shefi, S., Marcovitz, E., & Villa, Y. (2004). Anticipatory postural adjustments in selected trunk muscles in post stroke hemiparetic patients. Archives of Physical Medicine and Rehabilitation, 85(2), 261-267.

Diedrichsen, J., Verstynen, T., Lehman, S., Ivry, R., (2005). Cerebellar involvement in anticipating the consequences of self-produced actions during bimanual movements. Journal of Neurophysiology, 93, 801-812.

Downing, P.E., Jiang, Y., Shuman, M., & Kanwisher, N. (2001). A cortical area selective for visual processing of the human body. Science, 293, 2470-2473.

Dunn, P. M. (1995). Dr William Little (1810-1894) of London and cerebral palsy. Archives of Disease in Childhood - Fetal and Neonatal Edition, 72, F209–F210.

Edelman, G. M. (1987). Neural Darwinism. The theory of neuronal group selection. New York, NY: Basic Books.

Eliasson, A.-C., Krumlinde-Sundholm, L., Rösblad, B., Beckung, E., Arner, M., Ohrvall, A.-M., & Rosenbaum, P. (2006). The Manual Ability Classification System (MACS) for children with cerebral palsy: scale development and evidence of validity and reliability. Developmental Medicine and Child Neurology, 48, 549–554.

Evans, G. A. (1998). The Human Genome Project. Applications in the diagnosis and treatment of neurologic disease. Basic Science Seminars in Neurology, 55, 1287–1290.

Evarts, E.V. (1966). Relation of pyramidal tract activity to force exerted during voluntary movement. Journal of Neurophysiology, 31, 14-27.

Evarts, E.V. & Tanji, J. (1976). Anticipatory activity of motor cortex neurons in relation to direction of an intended movement. Journal of Neurophysiology, 39(5), 1062-1068.

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, 9–18.

Farmer, J.-P., & Sabbagh, A. J. (2007). Selective dorsal rhizotomies in the treatment of spasticity related to cerebral palsy. Child's Nervous System : ChNS : Official Journal of the International Society for Pediatric Neurosurgery, 23(9), 991–1002.

Fay, T. (1946a). Observation on the rehabilitation of movement in cerebral palsy problems. W V Med J, 42, 77–80.

Fay, T. (1946b). Problems of rehabilitation in patients with cerebral pasly. Del Med J, 18(57-60).

Fay, T. (1948). The neurophysiological aspects of therapy in cerebral palsy. Archives of Physical Medicine and Rehabilitation, 29(6), 327–334.

Feldman, A., & Levin, M. (1995). The origin and use of positional frames of reference in motor control. Behavioral Brain Science, 18, 723–806.

Fellows, S., Ernst, J., Schawrz, M., Topper, R., & Noth, J. (2001). Precision grip deficits in cerebellar disorders in man. Clinical Neurophysiology, 112(112), 1793–1802.

Fisk, J.D., & Goodale, M.A. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. Experimental Brain Research, 160, 159-178.

Fitts, P. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology., 47, 381–391.

Flanders, M., Tillery, S.I.H., & Soechtinga, J.F. (1992). Early stages in a sensorimotor transformation. Journal of Behavioral and Brain Science, 15(02), 309-320.

Gabor-Mikolos, G., & Rubin, G. (1996). The role of the genome project in determining gene function: insights from model organisms. Cell, 86, 521–529.

Gahéry, Y., & Massion, J. (1981). Co-ordination between posture and movement. Trends in Neuroscience, 4, 199-202.

Galati, G., Pelle, G., Berthoz, A., & Committeri, G. (2010). Multiple reference frames used by the human brain for spatial perception and memory. Experimental Brain Research, 206, 109–120.

Galletti, C., Kutz, D. F., Gamberini, M., Breveglieri, R., & Fattori, P. (2003). Role of the medial parieto-occipital cortex in the control of reaching and grasping movements. Experimental Brain Research, 153, 158–170.

Gandevia, S. C., Hudson, A. L., Gorman, R. B., Butler, J. E., & De Troyer, A. (2006). Spatial distribution of inspiratory drive to the parasternal intercostal muscles in humans. The Journal of Physiology, 573(1), 263–275.

Georgopolus, A.P., Kalaska J.F., Caminiti, R., Massey, J.T. (1982). On the relations between the direction of two-dimensional arm movements and cell discharge in primate motor cortex. Journal of Neuroscience, 2, 1527-1537.

Georgopoulos, A.P., & Massey, J.T. (1988) Cognitive spatial-motor processes. 2. Information transmitted by the direction of two-dimensional arm movements and by neuronal populations in primate motor cortex and area 5. Experimental Brain Research, 69, 315-326.

Gibson, A.R., Horn, K.M., Van Klan, P.L.E., (1994). Grasping cerebellar function. In: K.M.B. Bennet & U. Castiello (Eds.). Insights into the reach to grasp movements. Amsterdan: Elsevier, 129-150.

Girolami, G.L., Shiratori, T., & Aruin, A.S. (2010). Anticipatory postural adjustments in children with typical motor development. Experimental Brain Research, 205, 153-165.

Goesaert, E., Van Baelen, M., Spileers, W., Wagemans, J., & Op de Beeck, H. P. (2014). Visual space and object space in the cerebral cortex of retinal disease patients. PloS One, 9(2), e88248.

Goodale, M.A., & Milner, A.D. (1992). Separate visual pathways for perception and action. Trends in Neuroscience, 15, 20-25.

Goodale, M.A., Milner, A.D., Jakobson, L.S., Carey, D.P. (1992). A neurological dissociation between perceiving objects and grasping them. Nature, 349, 154-156.

Goodwin, G.M., McCloskey, D.I., Matthews, P.B.C. (1972). The contribution of muscle afferents to kinaesthesia show by vibration induced illusions of movement and by the effects of paralyzing joint aferents. Brain, 95, 705-748.

Gordon, A. M., Hung, Y.-C., Brandao, M., Ferre, C. L., Kuo, H.-C., Friel, K., … Charles, J. R. (2011). Bimanual training and constraint-induced movement therapy in children with hemiplegic cerebral palsy: a randomized trial. Neurorehabilitation and Neural Repair, 25(8), 692–702.

Govaert, P., Ramenghi, L., Taal, R., de Vries, L., & Deveber, G. (2009). Diagnosis of perinatal stroke I: definitions, differential diagnosis and registration. Acta Paediatrica, 98, 1556–1567.

Gracies, J. (2001). Pathophysiology of impairment in spasticity, and use of strech as a treatment of spastic hypertonia. Physical Medicine and Rehabilitation Clinics of North America, 12(4), 747–768.

Gracies, J. (2005). Pathophysiology of spastic paresis. II: Emergence of muscle overactivity. Muscle Nerve, 31, 552–571.

Graybiel, A. (2005). The basal ganglia: learning new tricks and loving it. Current Opinion in Neurobiology, 15(6), 638–644.

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

Guillery, R. W. (2003). Branching thalamic afferents link action and perception. Journal of Neurophysiology, 90, 539–548.

Gurfinkel, V., Cacciatore, T. W., Cordo, P., Horak, F., Nutt, J., & Skoss, R. (2006). Postural muscle tone in the body axis of healthy humans. Journal of Neurophysiology, 96(5), 2678–2787.

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: Mc Keith Press: Clinics in developmental medicine.

Hadders-Algra, M., Brogren, E., & Forssberg, H. (1996). Training affects the development of postural adjustments in sitting infants. The Journal of Physiology, 493, 289–98.

Hadders-algra, M., Brogren, E., Katz-salamon, M., & Forssberg, H. (1999). Periventricular leucomalacia and preterm birth have different detrimental effects on postural adjustments. Brain, 122, 727–740.

Hadders-Algra, M., van der Fits, I., Stremmelaar, E., & Touwen, B. (1999). Development of postural adjustments during reaching in infants with CP. Developmental Medicine and Child Neurology, 41, 766–776.

Hall, L. M., Brauer, S., Horak, F., & Hodges, P. W. (2010). Adaptive changes in anticipatory postural adjustments with novel and familiar postural supports. Journal of Neurophysiology, 103, 968–976.

Hanna, S.E., Law, M.C., Rosenbaum, P.L., King, G., Walter, S.D., Pollock, N., Russell, D.J. (2003). Development of hand function among children with cerebral palsy: growth curve analysis for ages 16 to 70 months. Developmental Medicine and Child Neurology, 45(7), 448 - 455.

Heinena, F., Desloovereb, K., Schroedera, A. S., Berweckc, S., Borggraefea, I., van Campenhoutd, A., … Pascual-Pascual, I. (2010). The updated European Consensus 2009 on the use of Botulinum toxin for children with cerebral palsy. European Journal of Paediatric Neurology, 14(1), 45–66.

Henry, T., Pannek, K., Boyd, R. N., & Rose, S. E. (2013). Changes in the integrity of thalamocortical connections are associated with sensorimotor deficits in children with congenital hemiplegia. Brain Structure & Function. DOI: 10.1007/s00429-013-0656-x

Hodges, P.W., Cresswell, A.G., Daggfeldt, & K., Thorstensson, A. (2000). Three dimensional preparatory trunk motion precedes asymmetrical upper limb movement. Gait & Posture, 11(2), 92-101.

Hodges, P.W., Cresswell, A.G., & Thorstensson, A. (1999). Preparatory trunk motion accompanies rapid upper limb movement. Experimental Brain Research, 124(1), 69-79.

Hollerbach, J. (1990). Planning of arm movements (vol. 2). In D. Osherson, S. Kosslyn, & J. Hollerbach (Eds.), Visual cognition and action: an invitation to cognitive science (pp. 183–211). Cambridge, MA: MIT Press.

Hollerbach, M., & Flash, T. (1982). Dynamic interactions between limb segments during planar arm movement. Biol Cybern, 44(1), 67–77.

Hoogan, N., & Stenard, D. (2009). Sensitivity of smoothness measures to movement duration, amplitude and arrests. Journal of Motor Behavior, 41(6); 529-534.

Hopkins, B., & Ronnqvist, L. (2001). Facilitating Postural Control : Effects on the Reaching Behavior of 6-Month-Old Infants. Developmental Psychobiology, 40, 168–182.

Horak, F.B., Diener, H.C., Nashner, L.M. (1989). Influence on central set of human postural responses. Journal of Neurophysiology, 62, 841-853.

Horak, F.B., Henry, S.M., Shumway-Cook, A. (1997). Postural Perturbations : New Insights for Treatment of Balance Disorders. Physical Therapy, 77(5), 517 - 533.

Horak, F.B., & Nashner, L.M. (1986). Central programming of postural movements: adaptation to altered support surface configuration. Journal of Neurophysiology, 55, 1369-1381.

Hua, S., Leonard, J.A., Hilderley, A.J., & Stapley, P.J. (2003). Postural configuration does not alter unperturbed or perturbed reach movement kinematics. Experimental Brain Research, 227(1), 63-78.

Hugon, M., Massion, J., Wiesendanger, M., (1982). Anticipatory postural changes induce by active unloading and comparison with passive unloading in man. Pflügers Archives: European journal of physiology, 393, 292-296.

Hulliger, M., Nordh, E., Thelin A.E., Vallbo, A.B. (1979). The response of afferent fibers from the glabrous skin of the hand during voluntary finger movements in man. Journal of Physiology, 291, 233-249.

Humphrey, D.R., Tanji, J. (1991). What features of voluntary motor control are encoded in the neuronal discharge of different cortical motor areas? In: D.R. Humphrey & H.J. Freund (Eds.). Motor Control: Concepts and Issues. John Wiley & Sons Ltd.

Humprhey, N.K. & Weiskrantz, L. (1969). Vision in monkeys after removal of the striate cortex. Nature, 215, 595-597.

Jacobs, J.V., & Horak, F.B. (2007). Cortical control of postural responses. Journal of Neural Transmission, 114, 1339 – 1348.

Jeannerod, M. (1996). Reaching and grasping: parallel specification of visuomotor channels. In: *Handbook of perception and action* (vol. 2, pp. 405 - 460). London, UK: Academic Press.

Jeannerod, M. (1988). The neural and behavioral organization of goal-directed movements. Oxford: Clarendon Press.

Jeannerod, M. (1984). The timing of natural prehension movements. Journal of Motor Behavior, 16, 235–254.

Jones, P., & Takai, D. (2001). The role of DNA methylation in mammalian epigenetics. Science, 293(5532), 1068–1070.

Kalaska, J., & Rizzolatti, G. (2013). Voluntary Movement: The Primary Motor Cortex. In E. Kandel, J. Schwartz, T. Jessell, S. Siegelbaum, & A. Hudspeth (Eds.), Principles of neural science (5th ed.). United States of America, US: McGraw-Hill.

Kamen, G., & Gabriel, D.A. (2010). *Essentials of Electromyography*. Champaign, IL: Human Kinetics.

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

Ketelaar M, Vermeer A, H. P. (1998). Functional motor abilities of children with cerebral palsy: a systematic literature review of assessment measures. Clinical Rehabilitation, 12(5), 369–380.

Kono, Y., Shimizu, Y., Wakatsuki, Y., Yasui, N., Aso, T., Kawamoto, H., & Kurihara, H. (2002). Letter to the Editor. Journal of Biomechanics, 35, 543–548.

Krageloh-Mann, I., & Bax, M. (2009). Cerebral Palsy. In J. Aicardi (Ed.), Diseases of the Nervous System in Childhood (3rd ed., pp. 210–242). England, London: Mc Keith Press.

Krauker, J. & Ghez, C. (2000). Voluntary movement. In: E.R. Kandell, J.H. Schwartz, T.M. Jessell (Eds.). Principle of neural science (4th ed., pp.757-781). New York: McGraw-Hill, 756-779.

Kuypers, H.G.J.M. (1962). Corticospinal connections: postnatal development in rhesus monkey. Science, 138, 678-680.

Langan, J., Kern, K., Hurvitz, E., & Brown, S. (2014). Upper-Limb Position Sense Deficits in Adults with Cerebral Palsy. American Journal of Physical Medicine & Rehabilitation.

Latash, M.L. (2010). Motor synergies and the equilibrium-point hypothesis. Motor Control, 14(3), 294-322.

Lemon, R.N., Mantel, G.W.H., & Muir, R.B. (1986). Corticospinal facilitation of hand muscles during voluntary movements in the conscious monkey. Journal of Physiology, 381, 497-527.

Lemon, R.N. (2008). Descending pathways in motor control. Annual Review of Neuroscience, 31, 195–218.

Lemon, (2008). Descending pathways in motor control. Annual Review of Neuroscience, 31, 195–218.

Leonard, J.A., Brown, R.H., & Stapley, P.J. (2009). Reaching to multiple targets when standing: the spatial organization of feedforward postural adjustments. Journal of Neurophysiology, 101(4), 2120–2133.

Leonard, J.A., Gritsenko, V., Ouckama, R., & Stapley J (2011). Postural Adjustments for online corrections of arm movements in standing humans. Journal of Neurophysiology, 105, 2375-2388.

Levin, M. F. (1996). Inter joint coordination during pointing movements is disrupted in spastic hemiparesis. Brain, 119, 281–293.

Levin, M.F., Michaelsen, S.M., Cirstea, C.M., & Roby-Brami, A. (2002) Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. Experimental Brain Research, 143, 171–180.

Liao, S., Yang, T., Hsu, T., Chan, R., Wei, T. (2003). Differences in seated postural postural control in children with cerebral palsy and children who are typically developing. American Journal of Physical Medicine & Rehabilitation, 82, 622 - 666.

Liu, W.Y., Zaino, C.A., McCoy, S.W. (2007). Anticipatory postural adjustments in children with cerebral palsy and children with typical development. Pediatric Physical Therapy, 19(3), 188 - 195.

Ma, S., & Feldman, A. (1995). Two functionally different synergies during arm reaching movements involving the trunk. Journal of Neurophysiology, 73(5), 2120–2122.

Mackey, A., Stinear, C., Stott, S., & Byblow, W. D. (2014). Upper limb function and cortical organization in youth with unilateral cerebral palsy. Frontiers in Neurology, 5.

Main, J. K., Paxinos, G., & Voss, T. (2008). Atlas of the Human Brain (3rd ed.). China: Elsevier.

Malhotra, S., Pandyan, A., Day, C., Jones, P., & Hermens, H. (2009). Spasticity, an impairment that is poorly defined and poorly measured. Clinical Rehabilitation, 23, 651–658.

Mansel Sympson, E., & Thomas, O. (1890). Two Cases of congenital and Infantile Cerebral Palsy. The British Medical Journal, 283 - 284.

Marret, S., Vanhulle, C., & Laquerriere, A. (2013). Pathophysiology of cerebral palsy (vol.3). In M. Aminoff, F. Boller, & D. Swaab (Eds.), Handbook of clinical neurology: Pediatric neurology, Part I (pp. 183–195). Amsterdan, The Netherlands: Elsevier.

Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., & Dugas, C. (1987). Constraints on human arm movement trajectories. Canadian Psychological Association, 41(3), 365 - 378.

Martin, J. H. (2005). The corticospinal system: from development to motor control. The Neuroscientist : A Review Journal Bringing Neurobiology, Neurology and Psychiatry, 11, 161–173.

Masani, K., Sin, V.W., Vette, A.H., Thrasher, A., Kawashima, N., Morris, A., Preuss, R., & Popovic, M.R. (2009). Postural reactions of the trunk muscles to multi-directional perturbations in sitting. Clinical Biomechanics, 24, 176-182.

Massion, J. (1979). Role of motor cortex in postural adjustments associated with movement. In H. Asanuma & V.J. Wilson (Eds.), *Integration in the nervous system* (pp. 239-260). Tokyo: Igaku-Shoin.

Massion, J. (1992). Movement, posture and equilibrium: interaction and coordination. Progress in Neurobiology, 38, 35 - 56.

Messier, J., & Kalaska, J.F. (1999). Comparison of variability of initial kinematics and endpoints of reaching movements. Experimental Brain Research, 125, 139-152.

McNamara, L., & Casey, J. (2007). Seat inclinations affect the function of children with cerebral palsy: a review of the effect of different seat inclines. Disabil Rehabil Assist Technol, 2(6), 309 - 318.

Mink, J. W. (2008). The basal ganglia. In L. Squire, D. Berg, F. Bloom, S. Du Lac, A. Ghosh, & N. Spitzer (Eds.), Fundamental Neuroscience (3rd ed., pp. (725–750)). Burlington, MA: Elsevier.

Monzee, J., Lamarre, Y., Smith, A.M. (2003). The effects of digital anesthesia on force control using a precision grip. Journal of Neurophysiology, 89, 672-683.

Morris, C. (2007). Definition and classification of cerebral palsy: a historical perspective. Dev Med Child Neurol Suppl., 109, 3–7.

Muir, R.B. & Lemon, R.N. (1983). Corticospianl neurons with special role in precision grip. Brain Research, 261, 312-316.

Mushiake, H., Inase, M., Tanji, J. (1991). Neuronal activity in the primate premotor, supplementary and precentral motor cortex during visually guided and internally determined sequential movements. Journal of Neurophysiology, 66, 705-718.

Mutlu, A., Livanelioglu, A., & Gunel, M. K. (2008). Reliability of Ashworth and Modified Ashworth scales in children with spastic cerebral palsy. BMC Musculoskeletal Disorders, 9, 44.

Myhr, U., von Wendt, L. (1991) Improvement of functional sitting position for children with cerebral palsy. Developmental Medicine and Child Neurology, 33(3), 246 - 256.

Nashner, L., Shumway-Cook, A., & Marin, O. (1983). Stance posture control in select groups of cildren with cerebral palsy: deficits in sensory organization and muscular coordination. Experimental Brain Research, 49, 393–409.

Newton, J. M., Ward, N. S., Parker, G. J. M., Deichmann, R., Alexander, D. C., Friston, K. J., & Frackowiak, R. S. J. (2006). Non-invasive mapping of corticofugal fibres from multiple motor areas--relevance to stroke recovery. Brain : A Journal of Neurology, 129, 1844–1858.

Novak, I., McIntyre, S., Morgan, C., Campbell, L., & Dark, L. (2013). A systematic review of interventions for children with cerebral palsy: state of the evidence. Developmental Medicine and Child Neurology, 55, 885–910.

O'Dwyer, N. J., Ada, L., & Neilson, P. D. (1996). Spasticity and muscle contracture following stroke. Brain: A Journal of Neurology, 119, 1737–1749.

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.

Palisano, R., Rosenbaum, P., Bartlett, D., & Livingston, M. H. (2008). Content validity of the expanded and revised Gross Motor Function Classification System. Developmental Medicine and Child Neurology, 50, 744–750.

Palisano, R., Rosenbaum, P., Walter, S., Russle, D., Wood, E., & Galappi, B. (1997). Development and reliability of a system to classify function in children with cerebral palsy. Developmental Medicine and Child Neurology, 39(214-223).

Panjabi, M., Abumi, K., Duranceau, J., & Oxland, T. (1976). Spinal stability and intersegmental muscle forces. A biomechanical model. Spine, 14(2), 194–200.

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

Paulignan, Y., McKenzie, C., Marteniuk, R., & Jeannerod, M., (1990). The coupling of arm and finger movement during prehension. Experimental Brain Research, 79, 431-436.

Pearson, K., & Gordon, J. (2013). Spinal reflexes. In E. Kandel, J. Schwartz, T. Jessell, S. Siegelbaum, & A. Hudspeth (Eds.), Principles of neural science (5th ed.). United States of America, US: McGraw-Hill.

Perenin, M.T., & Jeannerod, M., (1975). Residual vision in cortically blind hemifields. Neuropsychologia, 13, 1-7.

Petrarca, M., Zanelli, G., Patanè, F., Frascarelli, F., Cappa, P., & Castelli, E. (2009). Reach-to-grasp interjoint coordination for moving object in children with hemiplegia. Journal of Rehabilitation Medicine, 41(12), 995–100.

Pihko, E., Nevalainen, P., Vaalto, S., Laaksonen, K., Mäenpää, H., Valanne, L., & Lauronen, L. (2014). Reactivity of sensorimotor oscillations is altered in children with hemiplegic cerebral palsy: A magnetoencephalographic study. Human Brain Mapping, 35(8), 4105–4117.

Pitzalis, S., Sdoia, S., Bultrini, A., Committeri, G., Di Russo, F., Fattori, P., … Galati, G. (2013). Selectivity to translational egomotion in human brain motion areas. PloS One, 8(4). doi:10.1371/journal.pone.0060241

Polit, A., & Bizzi, E. (1979). Characteristics of motor programs underlying arm movements in monkeys. Journal of Neurophysiology, 42, 183-194.

Polleux, F. (2005). Genetic mechanisms specifying cortical connectivity: let's make some projections together. Neuron, 46, 395–400.

Porro, G., van der Linden, D., van Nieuwenhuizen, O., & Wittebol-Post, D. (2005). Role of visual dysfunction in postural control in children with cerebral palsy. Neural Plasticity, 12(2-3), 205–210.

Pozzo, T., Berthoz, A., & Lefort, L. (1990). Head stabilization during various locomotion tasks in humans. Experimental Brain Research, 82, 97–106.

Prayson, R., & Hannahoe, B. (2004). Clinicopathologic findings in patients with infantile hemiparesis and epilepsy. Human Pathology, 35(6), 734–738.

Pyles, R. H. (1925). The correction of flexion, adduction, and internal rotation deformities of the lower extremitites, resulting from cerebral palsy of childhood. Cal West Med, 23(12), 1576–1579.

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, 131 – 139.

Randall, J.F., Tresilian, J., & Wing, A.M. (1992). Coupling of grip force and load force during arm movements with grasped objects. Neuroscience Letters, 152, 53-56

Richards, L., & Malouin, F. (2013). Cerebral Palsy: definition, assessment and rehabilitation. In M. Aminoff, F. Boller, & D. Swaab (Eds.), Handbook of Clinical Neurology: Pediatric Neurology, Part I (pp. 169–176). Amsterdan, The Netherlands: Elsevier.

Rizzolatti, G., & Kalaska, J. (2013). Voluntary Movement: The parietal and premotor cortex. In E. Kandel, J. Schwartz, T. Jessell, S. Siegelbaum, & A. Hudspeth (Eds.), Principles of neural science (5th ed.). United States of America, US: McGraw-Hill.

Robertson, G.D.E., Cladwell, G. E., Hamill, J., Kamen, G., & Saunders, W. N. (2004). Research Methods in Biomechanics. Champaign, IL: Human Kinetics.

Roland, P.E., Larsen, B., Lassen N.A., & Skinhof, E. (1980). Supplementary motor area and other cortical areas in organization of voluntary movements in man. Journal of Neurophysiology, 43, 118-136.

Rosenbaum, P. L., Walter, S. D., Hanna, S. E., Palisano, R. J., Russell, D. J., Raina, P., … Galuppi, B. E. (2002). Prognosis for Gross Motor Function Creation of Motor Development Curves. JAMA, 288(11), 1357–1363.

Roby-Brami, A., Feydy, A., Combeaud, M., Biryukova, E.V., Bussel, B., Levin, M.F. (2003). Motor compensation and recovery for reaching in stroke patients. Acta Neurologica Scandinavica, 107(5), 369 - 381.

Russell, D. J., Rosenbaum, P. L., Wright, M., & Avery, L. M. (2013). Gross Motor Function Measure (GMFM-66 & GMFM-88). User's Manual (2nd edition.). Mac Keith Press.

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, 2215 - 2229.

Saavedra, S.L., Woollacott, M.H., & van Donkelaar, P. (2010). Head stability during quiet sitting in children with cerebral palsy: effect of vision and trunk support. Experimental Brain Research, 201(1), 13-23.

Santos MJ, Kanekar N, Aruin AS (2012). The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical Analysis. J Electromyogr Kinesiol 20(3): 398-405.

Saito, N., Ebara, S., Ohotsuka, K., Kumeta, H., & Takaoka, K. (1998). Natural history of scoliosis in spastic cerebral palsy. Lancet, 351(9117), 1687–92.

Santos, M.J., Kanekar, N., Aruin, A.S. (2010). The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology, 20, 388 - 397.

Sasaki, S., Isa, T., Pettersson, L.-G., Alstermark, B., Naito, K., Yoshimura, K., … Ohki, Y. (2004). Dexterous finger movements in primate without monosynaptic corticomotoneuronal excitation. Journal of Neurophysiology, 92(5), 3142–3147.

Scheck, S. M., Boyd, R. N., & Rose, S. E. (2012). New insights into the pathology of white matter tracts in cerebral palsy from diffusion magnetic resonance imaging: a systematic review. Developmental Medicine and Child Neurology, 54(8), 684–696.

Schepens, B., & Drew, T. (2006). Descending signals from the pontomedullary reticular formation are bilateral, asymmetric, and gated during reaching movements in the cat. Journal of Neurophysiology, 96(5), 2229–2252.

Schneiberg, S., McKinley, P., Sveistrup, H., Gisel, E., Mayo, N. E., & Levin, M. F. (2010). The effectiveness of task-oriented intervention and trunk restraint on upper limb movement quality in children with cerebral palsy. Developmental Medicine and Child Neurology, 52, 245–253.

Schneiberg, S., Sveistrup, H., McFadyen, B., McKinley, P., & Levin, M. F. (2002). The development of coordination for reach-to-grasp movements in children. Experimental Brain Research, 146, 142–154.

Shaikh, T., Goussev, V., Feldman, A.G., & Levin, M.F. (2014). Arm-Trunk Coordination for Beyond-the-Reach Movements in Adults with Stroke. Neurorehabilitation and Neural Repair, 28(4), 355-366.

Shinoda, Y., Sugiuchi, Y., Izawa, Y., & Hata, Y. (2006). Long descending motor tract axons and their control of neck and axial muscles. Progress in Brain Research, 151, 527–563.

Shumway-Cook, A., & Woollacott, M. H. (2011). Motor Control: Translating research into clinical practice (4th ed.). Baltimore, MD: Lippincott Williams & Wilkins.

Shumway-Cook A, Woollacott M (1985). The Growth of Stability: A Postural Control from a Developmental Perspective. Journal of Motor Behavior, 17(2), 131-147.

Sohn, M.H., McKay, J.L., & Ting LH (2013). Defining feasible bounds on muscle activation in a redundant biomechanical task: practical implications of redundancy. Journal of Biomechanics, 46(7), 1363-1368.

Spencer, J.P., Thelen, E. (2000). Spatially Specific Changes in Infants' Muscle Coactivity as They Learn to Reach.PDF. Infancy, 1(3), 275 - 302.

Spiegel, D., & Flynn, J. (2006). Evaluation and treatment of hip dysplasia in cerebral palsy. Orthopedic Clinics of North America, 37(2), 185–196.

Sterr, A., Dean, P. J, Szameitat, A. J., Conforto, A. B., & Shen, S. (2014). Corticospinal tract integrity and lesion volume play different roles in chronic hemiparesis and its improvement through motor practice. Neurorehabilitation and Neural Repair, 28(4), 335–343.

Sukal-Moulton, T., Krosschell, K.J., Gaebler-Spira, D.J., Dewald, J.P. (2014). Motor impairment factors related to brain injury timing in early hemiparesis. Part I: expression of upper-extremity weakness. Neurorehabilitation and Neural Repair, 28(1), 13 - 23.

Taub, E., & Berman, A.J. (1968). Movement and learning in the absence of sensory feedback. In S.J. Freedman (Ed.), The neurophysiology of spatially oriented behavior (pp. 173-192). Homewood, NJ: Dorsey.

Thelen, E. (1988). Dynamical approaches to the development of behavior. In J. Kelso, A. Mandell, & M. Schelesinger (Eds.), Dynamic patterns in complex systems (pp. 348–369). Singapore: World scientific.

Thelen, E. (1995). Motor development: A new synthesis. American Psychologist, 50(2), 79–95.

Thorley, M., Lannin, N., Cusick, A., Novak, I., & Boyd, R. (2012). Construct validity of the Quality of Upper Extremity Skills Test for children with cerebral palsy. Developmental Medicine and Child Neurology, 54(11), 1037–1043.

Thorley, M., Lannin, N., Cusick, A., Novak, I., & Boyd, R. (2012). Reliability of the quality of upper extremity skills test for children with cerebral palsy aged 2 to 12 years. Physical and Occupational Therapy in Pediatrics, 32(1), 4–21.

Ting, L. H., & Macpherson, J. M. (2005). A limited set of muscle synergies for force control during a postural task. Journal of Neurophysiology, 93, 609–613.

Ting, L.H., & McKay, J.L. (2007). Neuromechanics of muscle synergies for posture and movement. Current Opinion in Neurobiology, 17, 622-628.

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

Tresch, M.C., Saltiel, P., & Bizzi, E. (2002). The construction by the spinal cord. Nature Neuroscience, 2, 162-167.

Tsutsui, Y., Nagahama, M., & Mizutani, A. (1999). Neuronal migration disorders in cerebral palsy. Neuropathology : Official Journal of the Japanese Society of Neuropathology, 19, 14–27.

Utley, A., & Sugden, D. (1998). Interlimb coupling in children with hemiplegic cerebral palsy during reaching and grasping at speed. Developmental Medicine and Child Neurology, 40, 396–404.

van der Fits, I.B.M., & Hadders-Algra, M. (1998). The development of postural response patterns during reaching in healthy infants. Neuroscience and Biobehavioral Reviews, 22, 521-526.

van der Fits, I.B.M., Klip, A.W.J., van Eykern, L.A., & Hadders-Algra, M. (1998). Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults. Experimental Brain Research, 120, 202-216.

Van der Heide, J. C., Begeer, C., Fock, J. M., Otten, B., Stremmelaar, E., van Eykern, L., & Hadders-Algra, M. (2004). Postural control during reaching in preterm children with cerebral palsy. Developmental Medicine and Child Neurology, 46(4), 253–66.

Van der Heide, J. C., Fock, J. M., Otten, B., Stremmelaar, E., & Hadders-Algra, M. (2005). Kinematic characteristics of reaching movements in preterm children with cerebral palsy. Pediatric Research, 57(6), 883–889.

Van der Heide, J. C., & Hadders-Algra, M. (2005). Postural muscle dyscoordination in children with cerebral palsy. Neural Plasticity, 12(2-3), 197–203.

Van Doornik, J., Kukke, S., & Sanger, T.D. (2009). Hypertonia in childhood secondary dystonia due to cerebral palsy is associated with reflex muscle activation. Movement Disorders, 24(7), 965 - 971.

Van Hof, R., van der Kamp, J., & Savelsbergh, G. (2002). The relation of unimanual and bimanual reaching to crossing the midline. Child Development, 73(5), 1353–1362.

Viallet, F., Vuillon-Cacciuttolo, G., Legallet, E., Bonnefoi-Kyriacou, B., & Trouche, E. (1995). Bilateral and side-related reaction time impairments in patients with unilateral cerebral lesions of a medial frontal region involving the supplementary motor area. Neuropsychologia, 33(2), 215-223.

von Hofsten, C. (1984). Developmental changes in the organization of prereaching movements. Developmental Psychology, 20(3), 378–388.

Von Hofsten, C. (1991). Structuring of early reaching movements: a longitudinal study. J Mot Behav, 4(23), 280–289.

Von Hofsten & C. Woollacott, M. (1989). Anticipatory postural adjustments during infant reaching. Neuroscience abstracts, 15, 1199.

Wallace, S.A., Weeks, D.L., & Kelso, J.A.S. (1990). Temporal constraints in reaching and grasping behavior. Human Movement Science, 9, 69-93.

Wang, J., & Stelmach, G.E. (1998). Coordination among the body segments during reach-to-grasp action involving the trunk. Experimental Brain Research, 123, 346-350.

Weinrich, M., & Wise, S.P. (1982). The premotor cortex. Journal of Neuroscience, 2(9),1329-1345.

Weiskrantz, L., Warrignton, E.R., Sanders, M.D., & Marshall, J. (1974). Visual capacity of the hemianopic field following a restricted occipital ablation. Brain, 97, 709-728.

Wiesendanger, M., & Serrien, D.J. (2001). Toward a physiological understanding of human dexterity. Journal of Physiology. Journal of Physiology, 16, 228-233.

Williams, A., & Kirkham, F. (2011). Childhood stroke-the unkindest cut of all: A history of cerebrovascular disease in childhood. In V. Ganesan & F. Kirkham (Eds.), Stroke and cerebrovascular disease in childhood (pp. 1–16). Mac Keith Press.

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

Williams, P., & Goldspink, G. (1978). Changes in sarcomere length and physiological properties in immobilized muscle. Journal of Anatomy, 127, 459–468.

Winter, D. (2005). Biomechanics and Motor Control of Human Movement (3rd ed.). New Jersey: Jhon Wiley & Sons.

Wing, A.M., & Frazer, C (1983). The contribution of the thumb to reaching movements. The Quarterly Journal of Experimental Psychology, 35, 297-309.

Winzeler-Merçay, U., Mudie, H. (2002). The nature of the effects of stroke on trunk flexor and extensor muscles during work and at rest. Disability and Rehabilitation, 24(17), 875-886.

Witney, A.G., Wing, A., Thonnard, J.L., & Smith, A.M. (2004). The cutaneous contribution to adaptive precision grip. Trends in Neuroscience, 27,638-643.

Wolpert, D., Ghahramani, Z., & Jordan, M. (1995). Are arm trajectories planned in kinematic or dynamic coordinates? An adaptation study. Experimental Brain Research, 103, 460–470.

Woodbury, M.L., Howland, D.R., McGuirk, T.E., Davis, S.B., Senesac, C.R., Kautz, S., & Richards, L.G. (2009). Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: A pilot study. Neurorehabilitation and Neural Repair, 23, 78-91.

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 disroders of balance posture and gait (pp. 41–63). Great Britain, (UK): Arnold.

World Health Organization, WHO (2001). International Classification of Functioning, Disability and Health (ICF) Web Site. Retrieved from: http://www.who.int/classifications/icf/en/.com.

Wright, P., Durham, S., Ewins, D., & Swain, I. (2012). Neuromuscular electrical stimulation for children with cerebral palsy: a review. Arch Dis Child, 97(4), 364–371.

Wu, G., van der Helm, F. C. T., DirkJan Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., … Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. Journal of Biomechanics, 38, 981–992.

Yam, W. K. L., & Leung, M. S. M. (2006). Interrater Reliability of Modified Ashworth Scale and Modified Tardieu Scale in Children With Spastic Cerebral Palsy. Journal of Child Neurology, 21, 1031–1035.

Zimmerman, M., Ruud, G., Meulenbroak, R., & de Lange, F. (2012). Motor planning is facilitated by adopting an action's goal posture. Cerebral Cortex, 22, 122–131.