Adaptive seating and adaptive riding in children with cerebral palsy

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Chapter 1

General introduction

Introduction

Interventions in children with cerebral palsy (CP) are generally aiming to enhance the child's functioning and his/her ability to perform activities in daily life. Daily activities largely depend on the ability to control posture, balance, gross- and fine-motor function; and therefore, most interventions necessarily include elements that aim to improve aspects of postural control and motor function.[1–3] The use of adaptive seating is one of the commonly used interventions in children with CP. It aims at a clinical management of postural dysfunction.[4] Another type of intervention targeting the postural dysfunction of children with CP is horseback riding therapy, also known as equine-assisted activities.[1] However, little is known about the effectiveness of adaptive seating and horseback riding therapy.[5] This thesis deals with the evaluation of these two types of intervention in children with CP.

To understand the complex interactions between the broad spectrum of impairments influencing postural dysfunction, various forms of interventions and everyday activities of children with CP, this PhD thesis uses the International Classification of Functioning, Disability and Health, Children & Youth version (ICF; WHO 2007)[6] as a framework. The ICF-CY framework has two parts: (1) functioning and disability and (2) contextual factors. The framework views 'health condition, e.g. cerebral palsy' and 'functioning and disability' as a dynamic interaction of three components: (1) body functions and structures/impairments, (2) activities/activity limitations, and (3) participation/restrictions. Environmental factors, e.g. assistive technology, and adaptive seating belong to the contextual part of ICF-CY.[6] See for an overview of the position of adaptive seating and horseback riding therapy in the framework of the ICF-CY Figure 1.

The nature of the postural interventions can be guided by both the child's circumstances and his/her level of functioning.[4,6] Thus in this thesis, the functional status of children with CP is systematically categorized by using the Gross Motor Function Classification System (GMFCS).[7] The GMFCS uses a five-level system (I to V) that corresponds to the extent of ability limitation, with level V indicating the highest degree of limitation. The GMFCS emphasizes sitting, movement transfers and mobility, charting independence and reliance on adaptive technology.[7]

In the following paragraphs, I will first briefly review the clinical aspects of cerebral palsy (paragraph 2). In paragraph 3, I will present what is known about postural control and reaching in typically developing children, which is followed by a discussion of postural control and reaching in children with CP (paragraph 4).

In paragraph 5, postural interventions in children with CP (adaptive seating and adaptive riding) will be addressed.

Finally, in paragraph 6, the objectives of the thesis are presented.

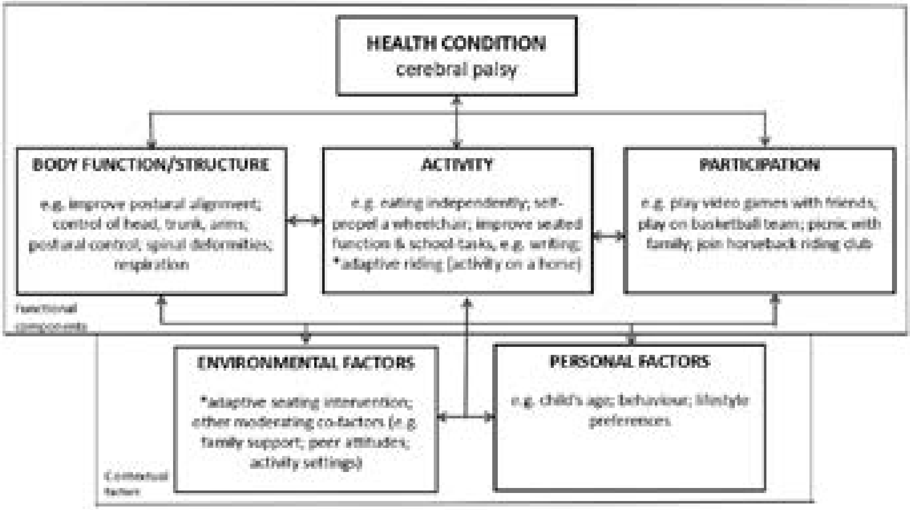

Figure 1 Adaptive seating and adaptive riding in children with CP in the framework of the ICF-CY (*adapted from: Ryan, 2016; WHO 2007*)

What is cerebral palsy?

Cerebral palsy (CP) is the most prevalent cause of physical disability in childhood.[8–10] The complex of signs, the disorder's severity, the patterns of motor involvement, and the associated impairments such as those of communication, cognitive ability, and epilepsy vary broadly.[11] During the last decade, cerebral palsy has been defined as "a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances occurring in the developing fetal or infant brain. The motor disorders are frequently accompanied by impairment of sensation, perception, cognition, communication, and behaviour, by epilepsy, and by secondary musculoskeletal problems".[11,12] According to the Surveillance of Cerebral Palsy in Europe (SCPE)[13], a collaboration of registers of children with CP which was formed in 1998, three subtypes of CP are distinguished: the spastic, dyskinetic, and ataxic form of CP. The spastic form has two main subtypes: spastic bilateral CP (BS-CP) – previously named diplegia and quadriplegia – and spastic unilateral CP (US-CP) – previously named hemiplegia.[13] Children with CP put a strong demand on services, treatment and technical adaptations.[9,10]

Prevalence

The overall prevalence, using livebirths as a denominator, indicated by multi-centre registries in several developed countries has been relatively consistent and remained stable for the period 1967 – 2006, despite dramatic changes in prenatal and perinatal care.[8,14–18] The overall prevalence in Europe and Australia has been reported as 2.08 per 1000 livebirths (95% confidence interval [CI] 2.02–2.14).[16,18] The estimated birth prevalence in the USA appears to be higher than that in Europe and Australia: 3.6 cases per 1000 livebirths (95% CI: 3.3– 4.0).[17] Prevalence in developing countries, however, varies widely. For example, those in India and China have been reported to be 2.0 to 2.8 per 1000 livebirths[19], whereas in Pakistan a prevalence rate of 5.4 per 1000 livebirths was described.[20] The variance in numbers among these developing countries may be related to differences in inclusion and exclusion criteria and in system surveys.[19–21]

Aetiology

The aetiology of CP is heterogeneous, and its profile varies with time and location. This interferes with finding clear cut aetiological pathways resulting in CP.[18] The use of advanced neuroimaging techniques has led to a better understanding of the aetiological origins. When considering gestational age, more than 50% of children with CP have been born at term; these children often have a severe form of CP.[22,23] The aetiological events playing a role in the origin of CP may occur during the antenatal, peri- or neonatal period, and postnatal period up to the age of 5 years.[22] In developed countries the aetiological event of CP in general occurs in the prenatal period[22,23], whereas in developing countries the majority of causative factors is more heterogeneous – it may occur during the pre-, peri-, and post-natal phase.[19] In developed countries the most significant prenatal factor is major and minor maldevelopment of the nervous system. Other antenatal factors that are significantly associated with CP are placental abnormalities, maternal infection, inflammation, multiple births, small for gestation age and low birthweight. Very low gestational age and very low birthweight are in particular strongly associated with CP, for instance the prevalence of CP is 40 –100 per 1000 livebirths among babies born very early (at a gestational age below 32 weeks) or with very low birth weight (less than 1500 grams).[16] In preterm children, CP shows a substantial link with focal and diffuse white matter injury, in general called periventricular leukomalacia (PVL).[24] Lastly, genetic research nowadays increasingly often clarifies familial forms of CP.

The most significant and constant risk factor associated with CP in the peri- and neonatal period is birth asphyxia resulting in hypoxic ischemic brain injury. Other peri- and neonatal factors associated with CP are seizures, respiratory distress syndrome, hypoglycaemia, and perinatal and neonatal infections. Among the perinatal infections chorioamnionitis is most frequently associated with CP.[22,23]

Pathogenesis

The causes of CP are heterogeneous as a result of the insults occurring at different times during early age. Krägeloh-Mann and Cans (2009)[24] reported the following findings. In BS-CP, the most frequent cause is a lesion of the periventricular white matter. The periventricular lesions are more often found in children with BS-CP born preterm than in those born at term. Other lesions that may result in BS-CP are cortical lesions (parasagittal lesions or diffuse cortico–subcortical lesions also termed multicystic encephalomalacia), deep grey matter lesions (basal ganglia and thalamus lesions), and brain maldevelopments (disorders of cortical development with a bilateral distribution such as schizencephaly, lissencephaly or polymicrogyria). In US-CP, the most frequently reported underlying brain lesions are periventricular white matter lesions, focal periventricular gliosis or posthaemorragic porencephalic lesions. These periventricular lesions occur more frequently in children with CP who have been born preterm than in those born at term.[24] Other lesions that may result in US-CP are cortical and deep grey matter lesions, i.e., usually due to infarction in the area supplied by the middle cerebral artery. In addition, brain maldevelopment in the form of focal cortical dysplasia or unilateral schizencephaly may underlie US-CP. Little information is available on the exact nature of the lesions underlying dyskinetic and ataxic CP. It is generally assumed that dyskinetic CP is associated with cortical or deep grey lesions (basal ganglia and putamen lesions), while ataxic CP is associated with cerebellar malformations and lesions.[24]

Postural control

Postural control is the basis of motor function; it is characterized by a complex organization.[25] It is defined as the ability to control the body's position in space for the dual purpose of stability and orientation. To create stability, postural control is organized to maintain the projection of the centre of mass (COM) within the stability limits of the body.[26] It involves the integration of the anti-gravity forces and mechanical support during movement.[27] Postural orientation involves the ability to maintain an appropriate relationship between the body segments, and between the body and the environment for a task.[28,29] One of the major goals of postural control is to stabilize the head in space.[30–32] The head is the segment that serves as the base for the visual and vestibular systems. A stable head optimizes clear vision and better visual and vestibular processing, both of which play an essential role in the control of postural and locomotor equilibrium.[28]

To maintain posture and balance in space or in correspondence to gravity, such as sitting posture during reaching, playing, or while sitting on a moving horse, human postural control requires a complex interaction of the musculoskeletal and neural systems. In terms of motor control, this means that the nervous system has to deal with the problem of the many degrees of freedom.[29] Bernstein (1935)[33] suggested that the adult nervous system solves this problem by creating postural synergies. Postural synergies are interpreted in several ways.[34,35]

In the present thesis postural synergies are explained with the central pattern generator model. According to the model the nervous system uses a 'central pattern generator' (CPG) which uses pre-structured neural commands, i.e., a repertoire of synergies embedded in the spinal cord and brain stem, to command the neural mechanisms involved in postural control.[36] The model suggests that in the neural control of postural synergies two functional levels can be distinguished. The first level of control deals with the direction specificity of postural adjustments. Direction specificity means that when the body sways forward, for example during reaching, the dorsal muscles of the body are primarily activated, whereas a perturbation causing a backward body sway is accompanied primarily by the muscle activity on the ventral side. The second level of control takes part in fine-tuning of the basic, direction-specific adjustment, using multi-sensorial afferent input from somatosensory, visual, and vestibular systems. This modulation can be accomplished in many ways, such as by altering the order in which the agonist muscles are recruited, i.e. in a caudal-to-cranial order or in a reverse sequence; by modifying the muscle contraction's size, which is reflected by the electromyography (EMG) amplitude; or by changing the degree of antagonistic muscle activity.[36,37]

Typical development of postural control

Postural control improves with increasing age, from infancy up until adolescence.[38,39] In the clinical context the term 'posture' is generally used to describe behaviour of the human body aiming at maintaining an upright position up-against-gravity. The head, trunk, pelvis, lower limbs and feet are known as body 'segments', while spinal joints, hips, knees, ankle and shoulder joints are considered the body 'linkages'.[26,40] Human posture is influenced by a number of associated factors such as muscle tone (i.e. high or low), body shape and size (i.e. height and weight), gravity, the surface (e.g. uneven ground, slopes, firmness, footwear), the task in hand, length of time needed to be in a particular posture, including the behavioural state and alertness.[39,40]

The achievement of postural milestones that can be observed by the clinical eye shows overlap in age.[41] In general infants develop at about 3 months of age a stable head balance, i.e. the ability to stabilize the head on the trunk.[42] From this age onwards until six months old infants spend ample time to learn how to control their head more precisely in a variety of conditions, i.e. in supine and prone, and during rolling, getting up from the floor and sitting with their hands to support their posture. Infants usually develop independent sitting between six and nine months of age, and meanwhile accomplish the ability to crawl on all fours.[41] In the age period of 12 – 18 months, children generally develop the ability to stand and walk.[41,43] In novice walkers the task of balancing is difficult; this is reflected by a wide base of support of the feet and a high-guard position of the arms. The ability to control posture and motility gradually increases, with substantial inter-individual variation.[41,43,44] After the first post-natal year, the postural milestones of children are continuously developing until adulthood.[38,39,45] For instance, toddlers (1–3 years of age) are able to perform more complex motor skills such as jumping and running. Pre-schoolers (3 – 5 years) learn to master several motor milestones needed in daily life such as riding a tricycle at age 3 and a bicycle with training wheels by age 5, or even playing sports. Children at school age (6–12 years) are becoming skilled in physical activities that need coordination between their body and the task-specific environment, such as riding a two-wheeler bike, hopscotching, rope skipping; they also increasingly often participate in team games.[41] In short, the development of postural control as displayed in functional motor behaviour in typically developing children has a long and variable course.[39,41,44,45]

Previous studies assessing typical development of postural control in more detail mostly used one of the following assessment paradigms[38] : (1) external perturbations applied by means of a brief translation or rotation of the support surface; (2) self-generated voluntary movements, such as reaching movements of the arm; and (3) spontaneous postural sway. In the next paragraphs, I will briefly summarize what these studies revealed.

Perturbation studies using surface electromyography and kinematics

Hedberg et al. (2004)[46], who studied young infants' postural adjustments during perturbations in a sitting position, proposed that the first level of control of the postural adjustments is a human innate ability: they found that at the age of 1 month, direction specific adjustments are already generated in 70–85% of the perturbations. The rate of direction specific postural adjustments during perturbations in sitting position increases with increasing age, reaching a frequency of above 90% at 6 months. From 7–8 months, direction specific adjustment is virtually consistently present during perturbations in sitting position.[47–49]

When children learn to stand, presumably similar developmental processes occur. In infants at the sit-to-stand ages (8 – 10 months) whose balance was perturbed during standing with support, Hedberg et al. (2007)[50] found that they exhibited direction specific adjustments, but also that these adjustments were expressed with large variation. Similar results were not reported by Sveistrup and Woollacott (1996)[51], but they provided the standing infants with substantial more support than Hedberg et al.[50] did. The presence of direction-specific adjustment before standing age may imply that activity of the basic level of control is a prerequisite for the development of the standing milestone. With increasing age and increasing ability to stand and walk, direction specific adjustments occur increasingly consistent.[50]

From about 3 months of age, the second level of postural control starts to develop. The first sign of the emergence of functional activity at the second level of control is that the infant gradually learns to select from the repertoire of direction-specific adjustments (consisting of the activation of direction-specific muscles in any combination) those adjustments in which all direction-specific muscles are activated, the so-called 'complete pattern'.[48] Interestingly, the use of the 'complete pattern' in sitting infants aged 7- 8 months is associated with better head stability in space.[49] The 'complete pattern' is the child's preferred direction-specific pattern during perturbations in sitting position. However, this preference for the 'complete pattern' during perturbations in sitting disappears at 2½ and 3 years of age.[52] In the early developmental phases of standing a similar process of an increased selection of the 'complete pattern' occurs.[50] Selection of the 'complete pattern' remains the preferred response modus to maintain balance when it is externally perturbed in standing position.[51,53,54]

Secondly, another form of fine-tuning of the direction-specific adjustment starts around 4–6 months: during perturbations in sitting, infants prefer a specific recruitment order of the direction-specific muscles: they prefer a so-called top-down recruitment. In this top-down recruitment, the neck muscle is recruited prior to the trunk- and upper leg muscles.(49)[49] This recruitment order is reversed when children develop the independent sitting skill (±8 months): the bottom-up order is the main preference. From preschool age onwards, the preference of recruitment order in a sitting position is largely variable. When being perturbed in standing, the novice standing infant shows large variation in recruitment order, but from 10–12 months old onwards the preferred recruitment order is bottom-up.[50] In contrast to sitting, the preference for bottom-up in stance persists as a life-long strategy.[55,56]

A third way to fine-tune postural adjustments is by adjusting antagonistic muscle activity. Interestingly, little antagonistic co-activation occurs during perturbations in sitting position. In fact, antagonistic co-activation is only temporarily observed in the upper leg muscles, i.e., between 6 months and 2 years of age, and only during external perturbations inducing a backward sway of the body.[49,52] Meanwhile the co-activation of antagonistic postural response during perturbed stance occurs from independent standing age (±1-year-old) until 5 years old. After the age of 5 years antagonistic activity is found as an occasional strategy to cope with a sudden loss of balance.[53]

Lastly, the direction-specific adjustment may be fine-tuned by means of EMG amplitude modulation; this is considered as the most subtle way to modulate direction-specific activity.[57] This type of modulation emerges during postural perturbations in sitting position at 9 to 10 months of age onwards; it occurs especially in the trunk and leg muscles.[49,52] After the first year of age, the location of modulation is more variable.[42] The exact nature is however not clear as amplitude modulation has not been well studied in children with the perturbation paradigm.[42]

Some studies combined surface EMG and kinematic recordings in the perturbation paradigm. Kinematic data are gathered to analyse specific body movements with the help of reflective markers mounted on the anatomical landmarks and recorded by one or more cameras.[29] In the past, Hadders-Algra et al. (1996a; 1996b)[25,49] reported that the kinematic properties of postural adjustments during perturbation in sitting position between 5 and 10 months of age showed large variation, i.e. variations occurred in 1) the spatial angle of the head in space, 2) pelvic sway and 3) body sway. The variation was most pronounced at the youngest ages and decreased with increasing age and with trial-and-error based experience. This was most obvious in the developmental changes of the pelvis sway.[25] Interestingly, better stability of the head in space was associated with a more frequent use of the 'complete EMG pattern'.[49] In line with this, similar developmental changes with decreasing variation and decreasing sway of the body also occur during perturbations in stance. It takes however longer time to master the adult-like standing capacity.[39,58]

In summary, the data from the perturbation studies suggested that the first level of postural control has an innate origin[46], and with increasing ability to sit, stand and walk, direction specific adjustments are consistently present when balance is abruptly perturbed.[50] Meanwhile, the development of the second level of control is complex, taking many years to develop an adult configuration. Development of postural adjustments used when perturbed during sitting clearly differs from that used when being perturbed during standing. The difference may be largely attributed to the differences in the size of the base of support. The sitting position has a larger base of support which makes it easier to keep the centre of gravity within the stability limits. This explains why at school age postural adjustments during sitting are characterized by variation[52] whereas those during stance are characterized by a clear selection of preferences for the 'complete pattern', a distal-to-proximal order and antagonistic activation, as necessarily coping strategies.[53,59,60]

Postural control during reaching

The first reaches, which emerge around 4 months are inconsistently accompanied by direction-specific activity: about 40% of reaches is accompanied by direction-specific activity in the dorsal postural muscles.[61,62] The rate of direction-specific adjustments during reaching while sitting gradually increases to 60% and 100% of reaches between 18 months and 2 years, respectively.[57,62]

Functional activity at the second level of control emerges between 4 and 6 months – similar to the development of postural adjustments during external perturbations. The child learns to select the 'complete pattern' from this early sitting age onwards.[38,62] The recruitment order of the direction-specific muscles during reaching while sitting in early infancy is characterized by variation. Similar to the postural adjustments during perturbations in sitting, a slight preference for top-down recruitment is observed in young infants who sit with support at the age of 4–6 months.[62] This preference may point to the priority of stabilization of the head in space during these first active explorations of the environment by means of reaching behaviour.[42] From 8–10-months recruitment order is still largely variable with a mild preference for a bottom-up recruitment. This means that when the infants are just able to sit independently, the focus of control is near the support surface.[42,62,63] At school age, recruitment order during reaching while sitting is mainly characterized by variation.[57] At the end of school age around 12 years, children develop the adult-like preference of a cranial-to-caudal recruitment order. This implies that from school age onwards the significance of the head in space plays a role again as the dominant frame of reference.[57]

Antagonistic postural muscle activity during reaching while sitting emerges around 9 months and can be observed in the neck muscles during reaching until the age of 18 months.[57,64] Thereafter it disappears, implying that postural adjustments during reaching in a sitting position at school age and during adulthood are characterized by the absence of antagonistic co-activity.[57] The temporarily presence of antagonistic muscle activity during reaching while sitting corresponds to what has been observed in the postural adjustments during perturbations in sitting.[25,52]

Postural adjustments during reaching whilst sitting involve anticipatory mechanisms with feed-forward processing.[26,27,38] In EMG studies, anticipatory postural activity has been referred to as postural muscle activity that anticipates the activation of the 'first arm muscle' which initiates the reaching movement, so called the 'prime mover'.[62] Van Balen et al. (2012)[62] demonstrated that throughout infancy approximately one-third of reaching movements is accompanied by anticipatory postural muscle activity. Interestingly, Van der Heide et al. (2003)[57] reported that children aged 2–11 years show very little anticipatory activity during reaching in sitting position, whereas adults frequently show this activity – especially in the neck muscles.

Girolami and colleagues (2010)[65] who studied arm reaches in stance in children aged 7 to 16 years found that children show anticipatory postural muscle activity in the direction-specific dorsal muscles. It was suggested that the anticipatory activity in the children below age 10 was somewhat less consistent than that in the older children. The latter may suggest that during school age, anticipatory activity during reaching while standing continues to be refined via trial-and-error based experience before the adult capacity of anticipatory activity is achieved.[65] The data on anticipatory postural control during reaching in sitting and standing indicate that condition, age and experience continue to affect anticipatory activity during school age.

The development of the ability to fine-tune the EMG-amplitude during reaching, i.e. by means of modulation of the degree of muscle contraction of the direction specific muscles, has been studied little. Van der Fits et al. (1999)[64] showed that 18-months-old infants could adapt the amplitude of the dorsal and ventral neck muscles to the velocity of arm movements, i.e., higher velocities of arm movements were associated with higher EMG-amplitudes of the neck muscles. When the reaching arm was loaded with extra weight the 18-month-old infants not only adapted neck muscle activity to the velocity of the reaching arm but also trunk muscle activity.[64] Contrary to infancy age, children at pre-school and school age do not show a clear focus of EMG-amplitude modulation. For example, in 5- to 7-year old the initial arm configuration of the reaching arm affected the amplitude of neck and lumbar extensor muscles while maximum wrist velocity was associated with the amplitude of the trunk extensor. In 8- to 11-year-olds more shoulder anteflexion at the onset of reaching was associated with higher trunk extensor amplitudes. Position of head and trunk also affects postural EMG-amplitudes: in the 2- to 4-year old both the head and trunk initial position affected the amplitude of the neck extensor EMG, while in the 5- to 7-year old children head position affected the EMG-amplitude of the lumbar extensor.[57] The postural EMG-modulation during reaching: adults show a clear preference for varied way in which children modulate EMG-amplitude differs from the adult way of the modulation of the amplitude of the neck extensor muscle.[57] Therefore, the data on EMG amplitude modulation suggests that during reaching: 1) in adults, EMG-amplitude modulation during reaching focuses in the neck muscles, supporting the idea that the stabilization of the head in space is one of the primary goals of postural control[30,57], 2) the development of the second level of control is varied and follows a non-linear and protracted course.

Relatively few studies addressed the development of postural adjustments during reaching in stance and most of those studies focused on anticipatory activity in children[53,65,66] and adults.[67,68] However, evidence in studies on adults suggested that the principles of the modulatory activity during reaching while standing may be similar to those while sitting. First, it depends on task-specific conditions, i.e., the mass of the extremity or of the task-load to be moved influences the EMG-amplitude of postural muscles.[68,69] Second, fast reaching results in earlier and stronger postural muscle responses than slow reaching movements.[68–70] Remarkably, this adult adjustment in terms of anticipatory amplitude modulation occurs only during tasks involving larger challenges of postural control, e.g., during fast movements of arm, or during bilateral instead of unilateral arm raising. Even though the principles of the anticipatory EMG modulation are similar, EMG-amplitude modulation in stance is larger than that in sitting–due to the differences in the size of the support surface.[68,69]

In summary, the development of the direction-specific postural adjustments during reaching is characterized by variation, such as variation in the participation of direction-specific muscles; in the recruitment order; and in amplitude modulation. From 2 years of age, reaches in an unsupported sitting position are not accompanied by antagonistic co-activation of postural muscles, and only rarely by anticipatory activity. From 5 years of age, a top-down recruitment re-emerges, which does not become the dominant pattern until adulthood. Especially the focus of modulation throughout pre-adolescent age is variably related to the specifics of the sitting and reaching conditions. After adolescent age, amplitude modulation gradually moves to the neck muscles which underscores the notion of the importance of the head stability in space for postural control in reaching.[28,42,57,62]

Spontaneous postural sway

Postural sway is usually measured via the behaviour of the centre of pressure (CoP) at the base of support, which is measured with force plates. CoP is the term given to the point of application of the ground reaction force vector. Postural sway is traditionally referred to as an active process of the nervous system in maintaining balance within the stability limits.[71] In the spontaneous postural sway paradigm using non-linear time series of CoP behaviour, posture is defined as the dynamic stability of a continuously moving body. Harbourne and Stergiou (2003)[72], who applied non-linear analysis of CoP behaviour in sitting infants, indicated that newly sitters freeze their degrees of freedom, while more experienced independent sitters increase the degrees of freedom. The latter would provide the infant with increased adaptability or flexibility in maintaining postural control over the base of support in sitting. During standing, similar developmental processes occur. Studies on spontaneous sway during stance indicated that children of 3 years of age restrict their degrees of freedom, while 5-year-old children allow themselves more degrees of freedom, thereby increasing the dimensionality and complexity of their postural behaviour, similar to that observed in adults.[73]

Typical development of reaching

Reaching towards an object is the basis for the fine motor skills of daily human activities[38], for example, it is used during feeding, dressing, and grooming. Soon after birth, the neonate has some capacity for goal-directed arm control.[74] For instance, with firm support in reclined or upright sitting position the neonate is able to purposefully move the arms towards an attractive toy.[75,76] Nevertheless, in typical situations it takes till about 3 months of age before infants play with the hands in the midline. At 3 months, infants cannot grasp an object, but they can bat at toys repeatedly. Around the age of 4 months, with the development of binocular vision – the eyes learning to work together on depth perception – infants are able to reach and grasp an object.[41]

Successful reaching is defined as arm movements that result in grasping of an object.[64] Reaching for an object involves transportation of the arm and hand in space.[29] For adults, the velocity profile of reaching (velocity of arm versus time) is characterized by a bell-shaped pattern with a single peak of velocity, i.e. containing one acceleration and one deceleration which together are identified as "movement unit (MU)".[77] In other words, a MU is a correction of the movement trajectory and a submovement of reaching.[42] However, an adult-like reaching pattern takes many years to develop. The first successful reaching movements at 4–5 months of age are characterised by jerky and zig-zag trajectories[78], consisting of 3 to 7 MUs.[79,80] The first reaches are also characterized by variation in movement velocity, amplitude and duration.[78,79] Thereafter, in the following months the reaches become increasingly less variable and more smooth and fluent, movement velocity increases and the number of MUs decreases.[78–80] Shortly after the age of 6 months, the majority of reaches consist of 1 to 2 MUs with an increase of the relative length and duration of the first MU, i.e., with an increase of the so-called transport MU.[77,81] From about 6 months onwards, fine-tuning of reaching continues slowly over many years. How the reaches are performed during childhood depends on the condition: (i) in supported sitting, the milestone of consistent reaches with 1 MU is accomplished at 2 years of age[82], (ii) while in unsupported sitting position, the 1-MU-milestone starts at 7 years.[83,84] With increasing age, reaching movements gradually become more smooth and linear, to obtain a consistent adult-configuration of one MU around the age of 12 years.[83,84]

Development of postural adjustments in children with CP

Dysfunctional postural control is one of the major limitations in children with CP.[42,85] This postural dysfunction directly influences daily-activity performance, the extent depending on the degree of the disability. However, not only the severity of disability but also biomechanical constraints, such as the size of the support-base, affect the child's possibility to control posture. For instance, standing with its small base of support challenges postural control more than sitting, which provides larger stability limits. This is a major reason that many children with CP spend ample time in sitting to perform the vital tasks of daily life.[42]

Postural dysfunction during external perturbations

Basic level control of children with CP

Postural control in children with CP has been studied in particular with the help of movable platforms either in sitting[86–90] or standing.[55,91–94] The children assessed aged 1 to 17 years. The studies revealed the following. Children with CP can generally produce the basic direction-specific adjustments both in sitting[88,89] and standing perturbations.[91] Similar to typically developing children, the postural adjustments of children with CP are characterized by variation. However, the children show a reduced ability to adapt the postural adjustments in comparison to the age-matched controls.[87] Only the few children with severe CP that were assessed, i.e., children functioning at GMFCS level V who were not able to sit independently, showed a complete lack of the basic level of control. These children had a bilateral CP.[89,90] This severe deficit of the direction-specific pattern in children with severe bilateral CP at GMFCS level V can be explained in two ways: 1) the postural synergies cannot be programmed, 2) the sensory pathways cannot induce activity in the synergies.[95] An incomplete loss of direction-specific adjustments at the hip level during backward body sway was found in some children at GMFCS levels IV and V.[87,88] This means that the children recruited the antagonistic hamstrings before the onset of hip flexor activity. This incomplete pattern of direction-specificity was associated with difficulties in sitting independently. These postural control data are in line with the clinical notion that children with severe CP generally are relying on adaptive seating equipment in daily activities.[42,95]

Second level control of children with CP

Children with CP most commonly show difficulties in modulation of the second level of control.[42] These adaptations are predominantly stereotyped, for instance they consist of the selection of the 'complete pattern', i.e., 'all' direction specific muscles are recruited, especially during backward body sway.[87,89] Another example is the selection of a top-down recruitment order, i.e., the neck flexors are recruited first which is in contrast to the more variable recruitment order in age-matched typically developing children.[87–89] The behavioural strategy of preschool and school age children with CP during external perturbations experiment resembles the strategy of typically developing infants age up to 6 months old.[48,49] The strong preference of children with CP for top-down recruitment illustrates that this recruitment order is one of the main strategies used for the stabilization of the head in space in situations where the ability to control posture is not yet fully developed.[42]

Children with CP show a higher rate of antagonistic co-activation than typically developing children, particularly in the neck and hip muscles.[86–89] The external perturbation experiments showed that in sitting position the antagonistic muscles were more often recruited during backward body sway than during forward body sway, implying that children profit from the larger stability limits in anterior direction during forward body sway.[87] Hadders-Algra and Brogren (2008)[42] also suggested that the relatively high degree of antagonistic co-activation provides stability for functional purposes. Brogren et al. (2001)[88] showed that in children with CP who can sit independently, the rate of antagonistic activity is influenced by the sitting position, i.e. an upright, erect sitting position induced a more frequent use of antagonistic co-activation than did a crouched position. Therefore, a high degree of co-activation could be viewed as a strategy to cope with postural control problems rather than being a problem for the children with CP.[95]

In the majority of children with CP, the ability to modulate EMG-amplitude to task specific constraints, e.g. to different sitting positions, is impaired.[88] Brogren et al. (2001)[88] showed that children with CP were not or only to a minor extent able to adapt the EMG-amplitude to initial pelvis position in the erect sitting position. However, this ability improved in the crouched sitting position as the children showed modulation of abdominal muscles with respect to the degree of backward rotation of the pelvis. This suggests that a better modulatory activity in the crouched sitting position may be a solution to a sensorimotor problem of experienced instability of children with CP.[42]

Similarly, children with CP have an impaired ability to fine-tune the basic direction-specific adjustments during perturbations in stance. Children with CP show a high degree of antagonistic co-activation, and a reversal in the recruitment order from a preference of bottom-up in typically developing children[50] to a top-down recruitment which involves an early recruitment of the neck extensor muscles.[55,91,92] Limited evidence suggested that the capacity to modulate EMG-amplitude is absent[91], and anticipatory activity is incomplete.[93] The latter was also reported in a recent study[94] in 11 ambulatory youth with CP aged 7–17 years. The study showed that the youth studied were able to use anticipatory activity during repeated stance perturbation at a relatively low oscillating frequency of a moving platform, similar to age-matched typically developing youth. However, the youth with CP showed still limited anticipatory postural adjustments when the platform oscillated at a higher frequency.[94]

Postural dysfunction during reaching in children with CP

Basic level control during reaching

Most of the studies on the development of postural muscle activity during reaching in children with CP studied relatively small numbers of children.[85,90,96–99]

The first study addressing postural adjustments in infants developing CP was the study by Hadders-Algra et al. (1999b).[90] The study included two infants with BS-CP and five infants with US-CP aged 4 to 18 months; the infants were assessed longitudinally.[90] The infants with US-CP and one of the two children with BS-CP produced the basic direction-specific adjustments much later than typically developing infants; direction-specific adjustments first emerged at the age of 15 months. The infants with US-CP learned to sit independently at the age of 10 to 15 months and the child with BS-CP at the age of 2.5 years. The other child with BS-CP had a severe form of CP including the presence of signs of dystonia; she did not develop the capacity to sit independently and did not have direction-specific adjustments.[90] More recently, Boxum et al. (2018)[97] longitudinally assessed postural adjustments in 18 infants later diagnosed with CP. They reported that these infants showed direction-specific adjustments during reaching, but that the increase in direction-specific adjustments with increasing age developed slower than in typically developing infants.[97] This meant that in early infancy the rate of direction-specific adjustments in infants later diagnosed with CP did not differ from that in typically developing infants, but that the rate did differ at the end of infancy. Two infants were diagnosed with CP functioning at GMFCS level V; they had not developed the ability to sit independently at the end of the study at 21 months corrected age (CA); nevertheless they showed direction-specificity.[97] The discrepancy between the findings on direction-specificity in the infants with severe BS-CP in the Hadders-Algra et al. study (Hadders-Algra et al.,1999b[90]; direction-specificity absent) and the Boxum et al. study (Boxum et al., 2018[97]; direction-specificity present) is presumably caused by the fact that the infant with BS-CP in the former study[90] had not only spasticity but also dystonia while the infants in the latter study[97] did not exhibit dystonia.

Thus, the large majority of infants later diagnosed with CP does have direction-specific postural adjustments during reaching. Yet, the age-dependent increase in direction-specificity is slowed down compared to typically developing infants, resulting in a significantly lower rate of direction-specific adjustment at the end of infancy in infants with CP than in typically developing infants: the infants with CP grow into a postural deficit.[97,98]

Second level control during reaching

The postural fine-tuning of direction specific postural adjustments during reaching is impaired in virtually all children with CP. According to the study of Boxum et al. (2018)[97] during early infancy, the infants later diagnosed with CP showed a deficit of postural fine-tuning from early age onwards. For example, unlike typically developing infants they lacked ability to develop a preference for bottom-up recruitment at 18 months CA.[62] In addition, they used the 'complete pattern' and anticipatory activity at trunk level less often, and they lacked the ability to modulate EMG-amplitude at the age of 21 months CA.[97] The deficits in fine-tuning of the postural adjustments were associated with a worse kinematic quality of reaching movements.[97]

The study of Van der Heide et al. (2004)[85] assessed postural activity during seated reaching in 58 children with CP aged 2–11 years together with 29 age-matched typically developing controls. The data showed that at preschool age, the children with CP mostly used the 'complete pattern' of postural muscular activity. After four years of age the 'complete pattern' was rarely observed.[85] Importantly, the level of severity affects the dysfunctions in fine-tuning of postural muscular activity. Children with milder forms of CP at all ages significantly elicited higher activation rate of the neck extensors than children with moderate and severe CP did, while the school age children with severe CP less often generated the trunk extensors activity.[85]

Preschool and school age children with CP always have a strong preference for top-down recruitment order during reaching. Interestingly, this strategy more frequently occurs in children with mild to moderate forms of CP (GMFCS I-III) than in children with more severe forms of CP (GMFCS IV-V). This might suggest that the preferred cranio-caudal recruitment reflects the child's strategy to deal with deficient postural control.[85,100] Similar to perturbation studies, the top-down recruitment strategy of children with CP confirms the importance of the head stability in space during reaching in sitting position.[30,85,100]

During reaching, antagonistic co-activation and anticipatory activation is absent in children with CP.[85] This implies that the capacity of antagonistic co-activation and of anticipatory activity in children with CP depends on task-specifics as it is absent during reaching in sitting position, but heavily present in more challenging situations like external perturbation in sitting or standing.[42,85,94] It thus might be that children with CP possibly select to use this strategy only when they deal with very difficult balance situations.[42,94]

Lastly, another postural dysfunction of children with CP at preschool and school age during reaching is the substantially reduced capacity to modulate EMG-amplitude to task-specific constraints such as difficulties in using information originating from the arm, the speed of the reaching arm, and information of the initial head, trunk, and pelvis position.[85] This impairment is more severe in children with BS-CP than in children with US-CP. As suggested by Van der Heide et al. (2004)[85], the former group may be able to use information from the velocity of the reaching arm but very limited. The latter group can use information in particular from the arm, including the velocity of the reaching arm; and may use to some extent information from the pelvis position. The authors also reported that the reduced modulation of EMG amplitude is related to poor quality of reaching movements and to worse function in daily life.[85]

Kinematics of postural control during reaching

The kinematics of postural adjustments during reaching in sitting position is commonly studied in conjunction with the EMG studies. Boxum et al. (2017)[101] studied head stability in space during reaching in infants at very high risk of CP. They demonstrated that head sway of the 18 infants later diagnosed with CP was similar to that of the very high-risk infants without CP. However, the infants with CP needed more MUs of the head than the very high-risk infants without CP to achieve this goal. They also reported that for infants at the age of about 13 months CA a more stable head, in terms of less MU of the head, was associated with a better reaching quality and better motor function.[101]

Van der Heide et al. (2005a)[102] also evaluated the kinematics of posture during reaching in sitting condition. They reported that children with CP aged between 2–11 years sat with a more reclined pelvis and a more bent trunk compared to age-matched typically developing children. The more reclined pelvis position was associated with a better kinematic quality of reaching. The displacement of head, trunk, and pelvis during reaching was similar to that of the control group. Even though bodily displacements of children with CP were similar to those of typically developing children, in the children with CP a more stable head, a more mobile trunk, and a more stable pelvis was associated with a better quality of reaching and a better functional daily performance.[102]

Concluding remarks

As children with CP are very heterogeneous, the difficulties in their postural control during reaching vary. In infancy, the basic control of direction-specific adjustment during reaching is virtually always present, but the increase in direction-specific adjustments with increasing age develops slower than in typically developing infants.[97] In preschool and school age children functioning at GMFCS level I-III, the basic control of direction specific is consistently present. In children functioning at GMFCS level V, in particular when they exhibit dystonia in addition to spasticity, the basic level of control may be lacking,[90] while children with severe spastic CP without dystonia generally do have access to the basic level of control.[97] Yet, the presence of direction-specificity is not a prerequisite for the development of independent sitting in children with the most severe forms of CP.[97] At the second level of control, children with CP virtually always have impairments from early age onwards.[85,97,102] This holds true especially for the school age children with BS-CP: 1) a stereotyped top-down recruitment, 2) an absent antagonistic co-activation and anticipatory activity, and 3) a severely impaired capacity to adapt the degree of postural muscle contraction to the specifics of conditions. The latter, which is the main deficit, is related to poor quality of reaching movements[85,101] and to worse function in daily life.[85]

Reaching in children with CP

Children with CP often have limitations in reaching activity, resulting in difficulty in daily arm-hand function. A worse kinematic reaching quality is associated with dysfunctional postural control as described in the previous paragraph.

The longitudinal study of Boxum et al. (2017)[101], on the kinematics of reaching in infants at very high risk of CP showed that the 18 infants later diagnosed with CP showed a worse kinematic reaching quality (more MUs, smaller transport MU) throughout infancy than the very high-risk infants without CP.[101]

Also at preschool age and school age, reaching movements of children with CP show impairments: they are slower, have a longer movement duration, the trajectory of reaching is less straight and less smooth, and especially consists less often of 1 MU than the reaching movements of typically developing children; this holds true for both the dominant (the least affected arm)[103] and non-dominant hand.[104–108] Only the study of Van der Heide et al. (2005b)[103] focused on the dominant hand which is the more often used in individual's daily-life. The authors reported that the quality of reaching in children with BS-CP was worse than that in children with US-CP. The difference in performance of the groups could be partially attributed to the fact that the disorder was more severe in the children with BS-CP. It is conceivable that the slower reaching movements, occurring in particular in the children with the most severe forms of CP, is a compensatory strategy of the child, as slower reaching movements are associated with lower reactive forces and thus may be associated with more truncal stability.[100] The less often use of reaches with 1 MU can be explained by the assumption that children with CP have a primary deficit in feed-forward motor control and rely more on visual or sensorimotor feedback to help their movement program, which might be effective but time-consuming.[103,109] Van der Heide et al. (2005b)[103] also found that a worse kinematic quality of reaching was associated with a higher degree of spasticity in the non-dominant arm, but the association disappeared when the severity of the brain lesion was taken into account.

In conclusion, the kinematic quality of reaching movements of the dominant arm of children with CP from early age is worse than that of typically developing children. The impaired quality is especially related to the severity of the brain lesion, the severity of the motor disorder and limitations in the ability to perform activities of daily life; it is less related to the degree of spasticity.

Postural interventions in children with CP

In order to optimize participation in everyday life, postural interventions in children with CP may focus on either (a) providing the children with optimal postural support, thereby easing the task load of postural control and (b) training of postural control.

The current thesis addresses both types of intervention, the first one by paying attention to adaptive seating interventions, the second one by focusing on adaptive riding and horseback riding therapies.

Adaptive seating interventions

Effect of seating inclination for children with CP functioning at GMFCS level I-III

Seating adaptations aim to improve the child's function by means of affecting postural control.[42,110] An important question in paediatric physiotherapeutic guidance is: what is the "most appropriate" sitting position in children with various types of CP? "Most appropriate" may be defined in terms of good postural stability or for instance in the adequacy of upper extremity function. From a theoretical perspective, the position of the pelvis is considered to be a crucial factor to achieve a seating position that is optimal for upper extremity function (Pope, 2002).[40] The idea is to achieve a seating position in which the line of gravity of the child's trunk and pelvis is close to the ischial tuberosities. The mechanical effects of this position are considered to improve stabilization of the proximal body segments (pelvis, trunk, or head), which in turn is associated with increased freedom to move and functional effectiveness of the distal parts (upper extremities).[40] Notwithstanding these theoretical considerations, the nature of optimal seating is debated, especially during an activity that is associated with a subtle shift in the center of gravity of the body segments, such as during reaching. In children with CP functioning at GMFCS level I-III, it is debated whether inclination or tilting of the seat surface improves the child's function.[42]

Some studies supported the use of a horizontal seat surface[111–113], some of a special seat resulting in a forward-tip of the trunk.[114–116] On the other hand, evidence is emerging that backward tilting of the seat surface is associated with worse functional performance in children with GMFCS levels I to IV (Hadders-Algra et al. 2007)[117], and in children with GMFCS levels I to III (Nwaobi, 1986).[118] Nevertheless, the studies disagree on the effect of forward (FW) tilting, due to the use of different methodology, outcome parameters, and differences in the nature of the CP of study participants, and whether or not foot support was provided. The suggestion that heterogeneity in the groups studied may play a role, is supported by the study of Hadders-Algra et al. (2007)[117], where the authors found that the results of children with BS-CP differed from those with US-CP. The study[117] showed that in children with BS-CP, 15° FW-tilting resulted in a larger head sway, i.e., worse head control, and had no effect on the kinematics of reaching. The study[117] also indicated that in children with US-CP, anterior-tilting of the seat improved postural efficiency and quality of reaching, whereas posterior-tilting of the seat surface induced more postural muscle activity and less stability of the head. The signs of improving postural efficiency were expressed as reduced phasic activity of the postural muscles, which was associated with a better kinematic quality of reaching.[117] The better quality of reaching was reflected by the finding that a greater part of the reaching movements was covered by the transport MU. In children with BS-CP both forward and backward seat inclination was associated with more postural instability. Therefore, these results suggested that in children with US-CP the forward tilted seat may be the best sitting position and may be associated with a better reaching quality, whereas the horizontal seat surface may well be the optimal sitting condition in children with BS-CP.[117]

It should be realized however, that Hadders-Algra et al. (2007)[117] studied postural control during reaching while sitting in a situation without a foot support. Meanwhile in most daily-life situations children with CP do have foot support. Some studies used foot support while evaluating the effect of seat surface inclination[111,116,118–120], but focus was always on the seat inclination, never on the evaluation of the effect of foot support. Interestingly, clinicians have a firm belief that the use of postural support, e.g. at feet, improves postural control.[121,122]

With respect to the seat base angles used, they varied between 5 degrees[123,124], 10 degrees[119,123,125], and 15 degrees.[116,117,119,123,124,126] Literature suggested that in children classified at GMFCS levels I to III, the 15° FW tilting was associated with a slightly better postural stability during forward reaching than the 10° FW tilting[123], in particular with improved kinematics of reaching movements.[117,123]

In conclusion, the effects of tilting of the seat surface on postural muscle activity, head stability, trunk mobility and reaching are inconsistent and heterogeneous, perhaps because effect varies between children with various types of CP. In addition, little is known on the effect of additional foot support in children with CP sitting on a horizontal seat surface or a forward-tilted seat surface on postural control and reaching.

Adaptive seating systems in children with CP functioning at GMFCS levels IV and V

Within the ICF-CY framework, intervention with an adaptive seating system (AdSS) is viewed as an intervention addressing the immediate environment of the child. That is, the AdSS may act as a facilitator of change in function across all the levels of ICF-CY.[6,127,128] Most AdSSs (80%) and other environmental modifications are used by children with CP functioning at GMFCS level IV–V.[6,127] The AdSSs are especially used at school and outdoors.[129]

The survey of the Surveillance of Cerebral Palsy in Europe showed that about 40% of children with CP function at GMFCS levels IV and V, and they are faced with serious limitations in functioning, activity, and participation.[130] In children and youth classified at GMFCS level IV, the motor problems and particularly the postural dysfunction are already apparent early in life. They need AdSS to control the trunk and to optimize hand function and tend to be transported in a manual wheelchair or use powered mobility. A recent study suggested that children with CP aged 3–6 years functioning at GMFCS level IV benefitted more from AdSS than children functioning at levels III and V.[131] Children classified at GMFCS level V have the most and clear difficulties in maintaining head and trunk stability, including very limited voluntary control of movements. These functional limitations can only be compensated partially by the use of AdSS and assistive technology. The children at level V have no means of independent mobility and most children develop severe deformities[1], such as scoliosis, which occurs in 15–67% of children with CP.[132]

Traditionally AdSS in children at GMFCS levels IV and V were used to facilitate optimal control of the head and trunk in daily-life situations, to improve positioning and functioning during eating and feeding, and to prevent long-term complications, such as spinal deformity, hip displacement, and respiratory problems.[131,133–137] In other words, the AdSS interventions focused on the impairment level of the ICF-CY. Currently, the focus of the use of AdSS intervention is changing, implying that the goal of the AdSS increasingly more often is to enhance participation. The enhanced participation may be mediated by optimized control of posture and better arm-hand activities.[6,127,128,138] However, currently we know little about the effects of ASSs on daily life activities or the child's and the family's well-being.

In the past, five systematic reviews examined the literature available, but none of these integrated the significance of the methodological quality of evidence and the ICF-CY framework in the discussion for the effects of the various forms of AdSS.[139–143] Therefore, the thesis will evaluate and update the evidence of the effects of AdSS in the scope of the ICF-CY framework, while taking into account the methodological quality of studies reviewed.

Adaptive riding intervention

A popular form of postural training nowadays is therapy that uses horseback riding. It is carried out in the context of activity-focused interventions and requires the child's active participation.[1,6]

The American Hippotherapy Association (AHA, Inc)[144] recently described standard terminology of the two basic forms of equine-assisted activities and therapies: (1) hippotherapy, implying that a therapist uses the movement or the environment of the horse (or both) to reach specific therapy goals, and (2) adaptive riding (AR; previously named horseback riding/therapeutic riding), implying recreational horseback riding lessons adapted for individuals with disabilities. Hippotherapy sessions are one-to-one sessions of a therapist and a patient, whereas AR is provided to groups.[144] A group-training like in AR may however facilitate more than individual therapy the capacities of the child with CP to participate in everyday life.[6,145,146] Clinicians generally assume that hippotherapy and AR therapy improve postural control, gross motor function and daily-life activities of children with CP.[145–151] However, the meta-analysis of Tseng et al. (2013)[152] indicated that neither hippotherapy nor AR was associated with an improvement in gross motor function. Moreover, this systematic review revealed that hippotherapy has been better investigated than AR.[152] This means that our knowledge about the effect of AR intervention on the child's function is limited. This thesis includes a feasibility study on the potential effect of a specific form of AR on the child's gross motor function and postural control.

Aim and outline of the thesis

Aim of this thesis

The focus of our thesis is on two types of postural interventions in children with CP. The thesis aims to evaluate the effect of adaptive seating and adaptive riding intervention on a set of outcome measures, including postural control and quality of upper extremity function.

Outline of the thesis

The thesis consists of four parts.

PART I

Chapter 2 (SEAT-CP Project I) and *Chapter 3* (SEAT-CP Project II) of this thesis address the effect of forward tilting of the seat-surface with or without foot support in children with spastic CP (US-CP and BS-CP, GMFCS[7] levels I-III), during sitting while reaching. During the reaching movements, simultaneously kinematics of the head and the reaching arm and surface electromyograms (EMG) of neck, trunk and arm muscles were recorded. *Chapter 2* addresses the effect of the seating conditions on kinematic head stability and kinematic reaching quality; *Chapter 3,* the effect on postural muscle activity.

PART II

Chapter 4 systematically reviews on the effects of adaptive seating systems (AdSS) in children with severe CP, functioning at GMFCS[7] level IV or V in all the domains of the ICF-CY, and taking into account the methodological quality of the studies reviewed; in this chapter special attention is paid to the levels of Activity, and Participation of the ICF-CY.

PART III

Chapter 5 addresses AR intervention, a specific form of postural training. To this end a new form of AR was developed, Therapist Designed Adaptive Riding (TDAR). TDAR was applied in children functioning at GMFCS levels II to III, with primary objectives to: (a) explore the feasibility of an extensive assessment protocol for a randomized controlled trial of the TDAR; (b) assess gross motor function and postural control, measured with the 88-item Gross Motor Function Measure (GMFM-88)[151], and surface electromyography recorded during reaching while sitting

PART IV

Chapter 6 comprises the general discussion, the conclusions and implications for clinical practice and also proposes suggestions for future research.

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Part I

Chapter 2 (SEAT-CP Project I)

Chapter 3 (SEAT-CP Project II)