Chapter 1: Introduction
Postural control is not the first thing that comes to mind when people think about motor development. In fact, many healthcare professionals are unfamiliar with the term. Yet the control of posture is a skill that underlies all motor activities of daily life, and without postural control we would never develop the ability to reach, sit, stand or walk. The development of motor skills and the development of postural control are tightly intertwined and depend upon each other in a reciprocative fashion. This makes postural control a subject worthy of investigation. Although the knowledge on the subject is accumulating, many things are still unknown. This is particularly true for early development of postural control, both in typical and atypical motor development.

The aim of this thesis is to gain more insight into postural control during early development, both typical and atypical. We examined parameters of postural control during reaching movements of typically developing infants and infants at risk of developmental motor disorders. However, since the term is so unfamiliar to many, perhaps the first question to answer is: ‘What exactly is postural control?’ Therefore, in this chapter, an introduction to the field of postural control is given. It starts with some history of neuroscience and biology, since this history has been very influential in the consecutive theories of motor development that have dominated the ideas on postural development. It then addresses the definition of postural control and describes the relevant current knowledge of postural development in both typically developing infants and infants at risk of developmental motor disorders. Since we also studied the effect of physiotherapeutic intervention on postural control, a short history of the field of early physiotherapeutic intervention is also given. These sections will then have paved the way for the introduction of the research projects that led to this thesis, followed by an outline of the thesis itself.

THEORIES OF MOTOR DEVELOPMENT

The mechanisms of motor development are a long-standing subject of debate. Over the last century, several theories to explain these mechanisms have been put forth. In this paragraph, the Neuromaturation Theory, Dynamic Systems Theory and Neuronal Group Selection Theory (NGST) will be discussed. These theories, like many others in biology and medicine, have been strongly influenced by the nature vs.
nurture debate, which deserves mentioning in this context. In the first half of the 20\textsuperscript{th} century, the ideas of Darwin were beginning to be accepted while at the same time, in psychology, behaviourism was in full bloom.

The behaviourists, for example John B. Watson and B. F. Skinner, felt that behaviour was the only objectively observable and interpretable variable that was produced by the black box that was the nervous system. The finding that reflexes could be conditioned, which was famously demonstrated by Pavlov’s dog, convinced the behaviourists that behaviour was able to cause changes in neural organisation. At the same time, embryologists and biologists studying the anatomy of the nervous system in relation to its function, were of the opinion that changes in neural organisation caused changes in behaviour. The neuromaturation theory was set forth in these surroundings. It will be explained primarily with the work of Arnold Gesell, who has become the icon of maturationism. Gesell (1880-1961) observed that all infants go through a series of developmental milestones. Although the individual timing was subject to variation, the order of the milestones was consistent between infants and Gesell concluded that motor development must be following a genetically predetermined developmental program that naturally unfolds over time.\textsuperscript{1,2} This view is now called ‘Maturation Theory’ or ‘Neural Maturation Theory’, in which motor development is described as the natural maturation of the nervous system according to a genetically predetermined plan. Based on his countless observations of developmental trajectories, Gesell compiled schedules of developmental norms that could be used to assess the ‘developmental age’ of a child.\textsuperscript{3,4} Although the neuromaturation theory is now adapted with or replaced by views that incorporate a more important role of environmental experience, such schedules of developmental milestones are still in use today. In the Netherlands, the ‘van Wiechenschema’,\textsuperscript{5} in which acquisition of milestones is compared to norms derived from percentiles of the population, is used in public health services as a screening instrument for developmental disorders in almost all Dutch children from birth to the age of 4 years.

Gesell’s ideas were not only inspired by his observed milestone sequences, but also by the work of Darwin and Coghill.\textsuperscript{1} George Coghill was a neuro-embryologist who described how changes in neural connections in the \textit{Amblystoma} salamander species were followed by the emergence of specific motor behaviors.\textsuperscript{6} For Gesell, these observations served as a model for his ideas on human motor development.
and motor behaviour. The fact that new behaviours in the salamander were preceded by physical changes in the nervous system caused him to conclude that the behavioural changes must be a result of physical growth and not the other way around. Development of motor behaviour, therefore, was essentially the result of development of the physical human and the physical brain. Combining the ideas of Darwin and Coghill, he viewed motor development as growth patterns that, as a result of thousands of years of evolution, had been anchored in the human genes. He compared motor development to embryological growth, stating that development takes place in successive epochs of directional growth, in a cephalo-caudal and proximal-distal direction, following the direction of embryological neuronal growth. The influence of the environment is reduced to a minimal role. Gesell wrote that the environment consists of factors that can support growth and development, but can never generate the progressions of ontogenesis.

A contemporary of Gesell, Myrtle McGraw (1899-1988), was more flexible in her interpretation of the nature-nurture debate. Her initial work clearly reflects maturationist ideas such as the cephalo-caudal direction of development, and the idea that many motor tasks can only be acquired after the nervous system has reached a certain level of maturity. However, unlike Gesell, McGraw was not focused on tables of developmental norms but instead observed development while trying to influence learning processes. In a famous experiment, she selected identical twins Jimmy and Johnny and manipulated Johnny’s development by teaching him new skills, while leaving Jimmy to grow up without interference. She showed that practice could advance the acquisition of certain motor skills, and induce changes in motor performance that were measurable later in life. During her career she came to the conclusion that development is an ongoing, ever-changing process of interaction and feedback, and that one should try not to think in dichotomies such as cortical vs. subcortical, maturation vs. learning and nature vs. nurture. In her countless observations of developing infants, she noticed how normal development was characterized by variation, both within and between infants. She was probably one of the first researchers who acknowledged the bidirectional nature of motor development, in other words that neuronal maturation not only influenced behaviour, but also the other way around. However, her contributions went relatively unrecognized as the interest in motor development diminished during the 1950s and 1960s, and McGraw is often characterized as a maturationist.
With the advent of the computer, theories that viewed the mind as a logical, computing system became popular. The brain was seen as a thinking machine that performed logical operations on sensory input and produced motor actions or other behaviour as a result. Learning takes place as a result of feedback loops of the computational system, and sensory, processing and motor units are regarded as separate systems. While this can be a useful model for some tasks, it was increasingly recognized in the 1980s and 1990s that in reality, it is impossible to regard the brain as a separate system from the body and its inputs and outputs. It is in this setting that the Dynamic Systems Theory of development was born.

Originally, Dynamic Systems Theory is a field in mathematics, physics and chemistry in which differential equations are used to describe the behaviour of complex dynamic systems with multiple measurable quantities. Examples of these systems are numerous: the flow of water through a pipe, the weather, the stock market and so on. At any given time, the system is said to be in a certain state that can be described by a set of numbers representing the components of the system. By continuous interaction between intrinsic and extrinsic factors that influence the system, the system moves from one state to another. These states are coherent, higher-order structures that spontaneously emerge from the dynamic interaction of the system’s components. For example, in the so-called Belousov-Zhabotinskii chemical reaction, the interaction between simple chemicals in a reaction chamber produces moving coloured patterns of circles and spirals that are not intrinsic properties of the chemicals themselves, but emerge from the dynamic interaction of the reaction’s components. As such, dynamic systems are said to be nonlinear. As Farmer and Packard put it (quoted by Thelen and Smith): “Adaptive behaviour is an emergent property which spontaneously arises through the interaction of simple components. Whether these components are neurons, amino acids, ants or bit strings, adaptation can only occur if the collective behaviour of the whole is qualitatively different from that of the sum of the individual parts. This is precisely the definition of nonlinear”.

In chemistry, most reactions and systems are in thermodynamic equilibrium, meaning that the energy and momentum of the system are uniformly distributed and there is no flow from one region to another. Such a system is stable unless energy is added to the system. Dynamic systems such as the Belousov-Zhabotinskii reaction, however, are far from thermodynamic equilibrium, yet are stable because
they are open systems that continuously extract energy from the environment, using part of this energy to maintain or reach certain states, and dissipate part of the energy back to the environment (this is why these systems are called \textit{dissipative structures}).\textsuperscript{9} Within the constraints of the system caused by its elements and their interaction with the environment, the system can occupy different states of its potential \textit{‘state space’}. States that are relatively stable are called \textit{attractor states}. For example, if physical fitness could be described by a two-dimensional state space of heart rate and body temperature, the attractor state would be the small part of this state space that constitutes the normal values of these variables. Through exercise or illness, the values of these parameters may be temporarily shifted in one direction or the other, but they would return to their normal \textit{‘attractor state’} once the external stimulus that causes the shift disappears.

In Dynamic Systems Theory, the concept of \textit{variability} gains a new meaning. While in Maturation Theory, variability is a deviation from the normal pattern and as such is regarded as \textit{noise}, in dynamic systems variability is regarded as an indicator for stability of the system. A strong attractor state results in less variable behaviour than a weak attractor state. In other words, variability is part of the \textit{data}, not simply noise. When a child has recently learned to stand upright, the attractor state is weaker and the displacements of the centre of gravity are greater than those of an adult. Thus, changing variability is an indicator for learning and development. Variability is deemed largest when the system is in transition from one attractor state to another. From a developmental view, therefore, variability is very important as it enables the system to explore other states and find new attractor states.

In Dynamic Systems Theory, the physical substance of the elements that comprise the system is deemed relatively unimportant and can be molecules, cells, tissues, organs, neurons, neural networks, or entire organisms. What counts is the dynamic interaction that produces patterns at a higher level of abstraction, such as behavioural patterns from interaction between neurons, and social patterns from interaction between individuals. Not surprisingly, Dynamic Systems Theory opposes maturationist views of development. The nervous system and development are seen as an integrated whole from which behaviour emerges, and the brain and genes are not credited as driving forces of development. For example, walking and learning to walk self-organises because of the behavioural attractor states occupied by the dynamic system that is formed by earlier developmental events, anatomical and
neural constraints, a motivation to move, and environmental factors such as gravity. With the concepts of emergence and self-organisation through interaction between components, Dynamic Systems Theory deals with the problem of how complex behaviour can arise from simple elements such as neurons, without referring to a ‘homunculus’ in the brain or genes that controls the process. However, in this way the role of the biological substrate (including genes and heredity) is reduced to a degree that does not do justice to the importance of its contribution. The fact that the behaviour of a system can be described by a set of equations that primarily deal with interactions between elements, doesn’t mean that the elements themselves and their evolution deserve no attention. Therefore, while Dynamic Systems Theory is a very useful frame of reference for explaining certain aspects of development, for others a different framework that pays more attention to the biological substrate and its evolution may be more suitable.

This is where the Neuronal Group Selection Theory (NGST) comes into play: a theory that was also formulated as a reaction to the information processing views of brain function and development, but regards development from an evolutionary perspective while acknowledging the role of the environment. It was formulated in 1978 by Gerald Edelman, who had won a shared Nobel Prize in 1972 for his work on the immune system. He compared the development of the brain to the development of the immune system in an individual, in which an abundance of diverse lymphocytes is created, followed by selection of only the ones that meet the selection criteria and degeneration of the non-qualifying surplus. His theory of neural Darwinism and neuronal group selection is now referred to as the Neuronal Group Selection Theory (NGST).

According to this theory, large amounts of structured neuronal groups containing $50 \cdot 10^5$ neurons are formed during embryogenesis and development. Primary connections between and within these groups are determined by genetic programming and epigenetic events, including cell growth, cell migration, cell death, synapse formation and synaptic selection. Together, these interconnected groups form a primary repertoire of responses in such a way that there is a very large diversity of responses, yet many groups can respond, to a smaller or larger extent, to a given signal. This provides the basis for the enormous variability in neuronal activity that is needed for adaptive behaviour. The strengthening and weakening of synaptic connections (by temporal correlations between firing patterns of connected cells and
cell groups) provides a mechanism by which the system can select connections based on input signals. In this way, a secondary neural repertoire is formed that is shaped by experience. Memory and consciousness result from phasic re-entrant signalling, which is defined as ongoing parallel signalling between different neuronal groups (or back into the same single neuronal group) in a bidirectional and recursive fashion. This results in associations between stored patterns and current sensory or internal input. Novelty of signals is dealt with by comparison of re-entrant and new signals in a cycle as well as by the fact that there are primary and secondary repertoires. Completely new information must activate the primary repertoire, with subsequent information activating selected subsets from the secondary repertoire based on the earlier experience.\textsuperscript{10,11}

The Neuronal Group Selection Theory was formulated in general terms to provide a framework for understanding higher brain function and development, but can nicely be translated to motor development. The primary and secondary neural repertoires translate into variation and adaptability of motor behaviour. Similar to Dynamic Systems, variability is a key concept in NGST, as it provides the basis for selecting adaptive behaviour. For the purpose of clarity, I will devote some words to the various terminology used in this context. Based on NGST, there are two aspects to the concept of variability, which are visible in two phases of motor development. The first is \textit{variation},\textsuperscript{12} previously referred to as \textit{primary variability}.\textsuperscript{13} \textit{Variation} refers to the size of the primary and secondary repertoire. This is visible in the variation in motor behaviour that is seen when the nervous system explores all options provided by the primary repertoire, and in the number of adaptive strategies available in the secondary repertoire. The second aspect of variability is \textit{adaptability}, previously referred to as \textit{(secondary) variability}.\textsuperscript{12,13} It emerges in the phase of secondary variability and refers to the ability to adapt motor behaviour to the specifics of the situation.

Learning a new motor skill starts with the phase of variation, in which all possibilities of the primary repertoire are explored. Part (but not all) of the primary repertoire are the so-called central pattern generators (CPG), which are groups of cells with a more or less pre-defined activation pattern resulting in certain motor behaviour. For example, rhythmical movements such as chewing and early locomotion in animals have been shown to be generated by CPGs.\textsuperscript{14} This is where NGST is different from Dynamic Systems theory: in Dynamic systems theory, the
complex movement patterns are assumed to emerge by self-organisation of the different parts of the system in conjunction with environmental factors, while NGST proposes a genetic foundation in the form of CPGs and anatomical growth patterns that are adapted throughout development as a result of epigenetic processes and experience. Exploring the options of the primary repertoire results in abundant variation in motor behaviour as well as a wealth of self-produced afferent information that can be used to adapt the neural networks to specific needs. This results in the phase of adaptability, in which optimal strategies are selected and adapted to the situation. In this phase, situations are compared to earlier experience, and synaptic strengthening has led to fast and selective activation of signalling pathways that were successful in the past.

The principles of NGST have proven very useful for explaining various developmental phenomena (they will also be discussed in the subsequent section on the development of postural control). For example, very early in life, it can already be demonstrated that variation is an important characteristic of normal motor development. Already in the foetal stage, the nervous system produces spontaneous movement patterns which are termed ‘general movements’ (GMs).\(^\text{15}\) These patterns consist of continuous, elegant movements potentially involving all parts of the body, which have a certain randomness to them and are rich in diversity. General movements continue to be expressed until approximately 4 months after term birth, when goal-directed movements appear.\(^\text{15}\) There are age-related changes in GM characteristics.\(^\text{16}\) The integrity of the quality of the GMs, in which variability and complexity are important characteristics, depends on a normal and intact developing nervous system, and changes in the quality of GMs predict developmental motor disorders such as cerebral palsy (CP).\(^\text{17-19}\) In terms of NGST, general movements can be seen as explorations of the primary repertoire that give the infant trial-and-error information, thus laying the groundwork for formation of the secondary repertoire of goal-directed movement. In the next section, the neuronal group selection theory will also be used as a framework for explaining the development of postural control.
DEVELOPMENT OF POSTURAL CONTROL

Posture refers to the relative position of the body and its parts with respect to each other and the environment. Postural control or the regulation of posture is necessary for practically all motor actions. It involves maintaining balance (i.e., keeping the centre of gravity within the support surface) and providing the prerequisite link between perception and action. The development of postural control is therefore highly intertwined with development of other motor skills and has been the subject of many studies on motor development. Nevertheless, there is still a lot to be learned.

The ability to maintain balance has often been studied with perturbation studies, in which a person’s balance is disturbed by a sudden movement of the support surface on which the person sits or stands. The postural responses to a sudden balance disturbance can be measured by electromyography (EMG). The perturbation causes a complex pattern of muscle contractions independent of muscle stretch, suggesting that these postural adjustments are centrally generated and not just a combination of reflexes generated from the spinal cord. In 1985, Nashner & McCollum found several more or less fixed postural recruitment patterns and suggested that the postural adjustments evoked by such sudden balance disturbances were derived from a limited set of distinct muscle recruitment strategies that they referred to as ‘movement synergies’. Forssberg & Hirschfeld noted that backward sway was always accompanied by early recruitment of the ventral muscles, while forward sway was accompanied by early recruitment of the dorsal muscles. In other words, the postural adjustments were direction-specific. Similar responses were seen in five- to eight-month-old infants who had not yet mastered sitting independently. Given these characteristics, they proposed a two-level central pattern generator for postural adjustments: at the first level, a simple format such as the spatial pattern of the muscle activation would be generated; at the second level, the centrally generated pattern could be shaped and timed by interaction from the entire somatosensory, vestibular, and visual input. Supporting the supposition that the ability to produce direction-specific postural adjustments is a basic level of postural control with an innate origin, direction-specific postural adjustment were also found after the majority of perturbations in one-month-old infants. In other words, direction-specificity or a basic spatial organisation of postural adjustments could be part of the primary repertoire, while fine-tuning of the postural response
would be part of the secondary repertoire. This fine-tuning is visible in, for example, the number of muscles that are recruited and the amplitude of the postural response as measured by EMG. Initially, these parameters are characterized by variation. However, between 3 and 10 months of age, a preference for the so-called ‘complete pattern’ emerges, in which all direction-specific muscles are recruited in concert in response to a perturbation. During the same period, the ability to adjust the EMG amplitude of the postural response to the degree of perturbation develops.

Inducing balance disturbances by perturbations is, of course, a rather artificial way of studying postural adjustments. In addition, only reactive postural adjustments can be studied with this design. This is why postural control has also been studied during reaching movements, since such movements are more subtle, internally triggered balance disturbances. Not only is this experimental design a better approximation of real life, but it also has the advantage that anticipatory postural adjustments can be studied. These are postural adjustments that result from feedforward processes in anticipation of a balance disturbance. Anticipatory adjustments are seen in adults before the onset of the actual movements that might induce a balance disturbance, but knowledge on the development of anticipatory postural adjustments in infants is still scarce. In general, studies using a reaching movements design show a less clear-cut picture of postural development than perturbation studies. At the age of 4 months, only 40-50% of reaching movements are accompanied by direction-specific postural adjustments. Little is known on the development of postural fine-tuning – this is one of the subjects of this thesis: chapter 2 deals with development of postural adjustments during reaching in typically developing infants between 4 and 18 months of age.

Finally, the development of postural control has also been studied by measuring postural sway. The most often used approach for this is measuring displacements of the centre of pressure (COP), which is the point of application of the sum of all forces acting between the body and its support surface. Both linear and nonlinear COP measurements have been studied. Linear COP aspects include amplitude and velocity of COP displacement, usually measured in the anterior-posterior and lateral directions. Characteristic of the COP is that it is never entirely still; there is always some displacement around a central point even in quiet stance or sitting. This variation in linear COP measurements was traditionally regarded as noise of the nervous system combined with measurement error. However, it is now recognized
that this variation is a key element of balance control, reflecting a purposeful search of the limits of stability. Such an active search provides sensory information about posture, orientation and the dynamics of the interaction between the body and the environment, enabling the individual to adjust balance control processes to the current situation. In other words, perception supports action and action supports perception.\textsuperscript{27,28} In terms of NGST, the variation reflects active exploration by the nervous system of the possibilities and limits of balance. In terms of Dynamic Systems theory, the system shows continuous variation due to interaction of the limbs, muscles, nervous system, gravity and the environment, causing the system to move within and between attractor states of balance. Dynamic Systems theory has inspired the use of nonlinear COP measurements, which have become increasingly popular in recent years. Nonlinear measurements include the Lyapunov Exponent, which is an indicator of the stability (as opposed to degree of variability) of COP trajectories; the Correlation Dimension, which is a method to evaluate the number of degrees of freedom during posture; and Approximate Entropy, which is a method to determine the complexity of the COP time series.\textsuperscript{29} These nonlinear measurements show differences between infants who have not yet mastered a certain motor skill, such as sitting, and infants who have mastered the skill.\textsuperscript{29} They are also different for typically developing infants compared to infants at risk of motor disorders,\textsuperscript{30,31} providing opportunities for evaluating postural development and therapy.

INFANTS AT RISK OF DEVELOPMENTAL MOTOR DISORDERS

The most common cause of serious childhood disability in developed countries is Cerebral Palsy (CP). CP was traditionally defined as a ‘disorder of posture and movement due to a defect or lesion in the immature brain’, but this definition has undergone several revisions over the years and is still the subject of debate.\textsuperscript{32} It is now considered to be an umbrella term for a heterogeneous group of developmental disorders, described as ‘permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing foetal or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, behaviour, by epilepsy and by secondary musculoskeletal
problems'. CP is attributed to brain lesions that occurred during the foetal stage or early infancy. Many factors can contribute to the development of CP, including premature birth, infections (both during pregnancy and in early infancy), asphyxia (usually in combination with other factors), intoxications and genetic abnormalities.

As implied by the definition, postural control is impaired in children with CP. The extent of the impairment varies with the degree of disability, which ranges from minor dysfunction to major impairments causing severe disability in daily life. This broad range has given rise to several classification schemes for CP, of which the most widely used is the Gross Motor Function Classification System (GMFCS). The GMFCS classifies children with CP into five levels of disability, based on functional mobility or activity limitation. Emphasis in this classification is on sitting and walking ability and to which extent assistive devices are needed. For example, a child at GMFCS level I walks without restrictions, can sit independently and only has limitations in more advanced gross motor skills, while a child at level III walks with assistive mobility devices and eventually learns to sit independently but often needs additional support. Finally, a child at level V has severely limited self-mobility even with the help of assistive technology, requires extensive support in sitting and never learns to sit independently.

A stable sitting position enables an individual to use the arms and hands for all sorts of tasks, which is why considerable effort has been invested in studying postural control during sitting in children with cerebral palsy. In perturbation studies, children with cerebral palsy usually show direction-specific postural adjustments, like typically developing children. Those that do not, presumably never develop the ability to sit independently. Thus, the basic level of postural control is present in most children with CP, and seems to be a prerequisite for independent sitting. However, there may be some impairment at the basic level, as infants at high risk of CP (with the ability to sit independently) less often show direction-specific postural adjustments after perturbations. In contrast, fine-tuning of postural adjustments is almost always impaired in children with cerebral palsy. Responses to perturbations are more stereotyped and less adapted to task constraints, which is visible in both the number and order of muscle recruitment and (lack of) amplitude modulation.

Reaching studies also show that the development of postural control is impaired in children with CP. Like in perturbation studies, children with CP usually show direction-specific postural adjustments during reaching, but they only start using
them consistently at a later age than typically developing children. The second level of control is characterised by stereotyped top-down recruitment, where typically developing children show much more variation. In addition, like in perturbation studies, postural adjustments during reaching are not or to a lesser degree adapted to task constraints, for example in amplitude modulation.

Due to the inscrutable plasticity of the developing brain, cerebral palsy can only be reliably diagnosed at the age of 1½-2 years. Therefore, studies in early infancy are usually performed with groups of children at risk of developing CP, for example infants born prematurely, infants with brain lesions, or infants with abnormal general movements or development. Part, but not all, of these infants will eventually develop CP. Those who do not develop CP usually develop a minor neurological dysfunction (i.e. their neurological development is suboptimal but not impaired to such a degree that it can be diagnosed as CP). As a group, infants at risk of CP seem to have a postural development that is different from that of typically developing infants. For example, preterm infants at 4-6 months corrected age show relatively immobile postural behaviour (i.e., fewer and/or smaller COP displacements) than typically developing infants. Similar findings were reported by Kyvelidou et al. in infants who later developed CP. Nonlinear COP measurements also show that high-risk infants have more repetitive (less varied) and less complex postural sitting behaviour than typically developing infants.

**EARLY INTERVENTION**

Many children with or at risk of developmental motor disorders are given physiotherapy from an early age onwards. The rationale for starting physiotherapeutic intervention as early as possible is that plasticity of the brain is largest in early infancy, thus early intervention has the greatest potential for beneficial effects. The goals of intervention, however, are not only to optimize motor development and maximize the potential of the child, although these form an important focus of therapy. Early intervention programmes also increasingly focus on general well-being of the child, parenting and coping techniques of the caregivers, and overall family functioning.
In the Netherlands, early paediatric physiotherapy is mainly based on the principles of Neurodevelopmental Treatment (NDT) and functional physiotherapy. NDT was developed by Karel and Berta Bobath in the 1940s. The Bobaths considered the handicap of children with CP to be due to an interference with the development of normal postural control against gravity. According to them, the underlying brain lesion results in the release of abnormal movement patterns, in association with various types of abnormality of postural tone. NDT uses ‘key points of control’ from which patterns of abnormal activity can be inhibited, while at the same time facilitating normal movements. Treatment consists of ‘handling’ the child: the therapist guides the child and the child guides the therapist in continuous feedback loops with the goal of making the child’s reactions as normal as possible. Through the close relationship between muscle tone on the one hand and patterns of posture and movement on the other, the Bobaths advocated that normal movements obtained during treatment would also normalise muscle tone. Thus, treatment consists of inhibiting abnormal movement patterns while at the same time facilitating normal movement patterns by special handling techniques. The idea behind this is that the damaged brain has produced (only) abnormal movement, and the child needs the experience and the sensation of normal movements in order to learn these patterns: these sensations produce memories that the child can use to produce normal movements. Nevertheless, therapy should not focus on following a ‘normal’ developmental sequence, but rather on the needs of the individual child. Treatment should be flexible and guided by the child’s response to it, and individualised therapy develops on the basis of the close interplay between child and therapist. It should focus on those motor skills that are needed for development of the most needed functional skills of that particular child.

Although the Bobaths had initially thought that the exercises from treatment would automatically carry over into activities of daily life, this turned out not to be the case. Therefore, they later sought to actively incorporate preparation for specific functions into the treatment. They also saw the need to teach the parents to continue therapy at home, as the time the child spends with the therapist is limited and most movement is carried out at home. However, despite these adaptations of NDT, studies have shown that there is little carry-over of results into daily-life activities and that early interventions based on NDT do not seem to have a beneficial effect on motor development. Under the influence of Dynamic Systems theory, the goal
of physiotherapy therefore shifted from ‘normality’ to ‘functionality’. Functional physiotherapy emphasizes the importance of practicing functional tasks, especially those that are problematic in daily life. Rather than striving for ‘normal movement patterns’, it is important to set goals of therapy in the functional domain, based on the interaction of the individual with the environment with respect to functional skills. This also implies that therapy should always be given in a context-specific environment. Another major conceptual difference between NDT and functional therapy is that the functional approach is based on an active rather than a passive view of motor learning; people learn by actively attempting to solve the problems inherent to a functional task, rather than repetitively practicing normal patterns of movement.\textsuperscript{44} The different approach of functional therapy has gained popularity and has been compared with NDT-based therapy in clinical trials, but with inconsistent results. Some studies have shown better results for functional therapy than for NDT-based therapy,\textsuperscript{44,48} but not in all studies a difference was found.\textsuperscript{49} Early paediatric physiotherapy in the Netherlands is usually based on NDT, functional therapy, or a mixture of both, with or without influences of other schools of physiotherapy.

Another concept that is now becoming increasingly influential in infant physiotherapy, is the concept of family-centred care. In a family-centred approach, the service provider (meaning any healthcare professional involved in the infant’s care, for example a physiotherapist or paediatric neurologist) forms a collaborative partnership with family and child and actively involves them in the care process, including information exchange for informed decisions, collaborative goal setting, and responsiveness to family priorities and choices.\textsuperscript{50,51} Caring for children with or at risk of developmental motor disorders involves more than just helping the child to achieve optimal motor development; coping with the situation of a child who may have life-long special needs can be a challenge that requires different coping strategies from parents. The goal of family-centred care is to increase quality of life of all family members. Fostering parental well-being, in addition to that of the child, promotes 1) a positive caregiving environment, 2) better family functioning and a better parent-child relationship, and 3) an active role of the parent in managing their child’s care and supporting their child’s development, all of which may contribute to the well-being and developmental outcome of the child. Several studies have shown beneficial effects on both child and parental outcomes.\textsuperscript{50,51}
In the last decade, a family-centred physiotherapy programme was developed at the University Medical Center Groningen (UMCG). The COPCA programme (COPing with and CAring for children with special needs) is based on two components: (1) family involvement and educational parenting and (2) the neuromotor principles of the neuronal group selection theory. The family-involvement and educational component focuses on family autonomy, family responsibility and family-specific parenting. The therapist takes on a coaching role in which there is a bidirectional, open dialogue to uncover the family’s competences, goals, hopes and coping strategies. Through this coaching strategy, the COPCA coach aims to promote autonomous decision-making of the family, and to encourage their capacity for solving problems of daily care, while respecting individuality in parenting. COPCA aims to promote activities and participation of the family, including the infant with special needs.

The neurodevelopmental component of COPCA is based on the principles of NGST, with emphasis on self-exploration and trial-and-error. As discussed earlier, NGST proposes a phase of extensive exploration, which is characterized by variation, followed by a phase of adaptability, which is characterized by learning to select optimal strategies for adapting motor actions to the task at hand. An infant with an early brain lesion not only have a limited repertoire of motor strategies, but also a limited ability to select optimal strategies (due to deficits in sensory information processing). Therefore, far more exploration and trial-and-error experience is needed for selecting an optimal strategy. To this end, COPCA promotes ample active motor experience in a variety of conditions, as well as challenging the infant to test his/her limits. While NDT promotes facilitation of movements using handling techniques, COPCA uses a hands-off approach that challenges the infant to explore his/her own motor repertoire, as hands-on facilitation may interfere with the infant’s active motor learning process. Since the limited repertoire of the child may not include all strategies of typical development, the goal of COPCA is not to obtain the ‘normal’ strategy, but to obtain the best and most adaptive strategy given the infant’s ability. This implies accepting atypical strategies, in contrast to the NDT approach that tries to inhibit ‘abnormal’ strategies. COPCA aims to increase functionality while acknowledging the impairments of the infant.
THE VIP AND L2M 0-2 PROJECTS

The effects of COPCA were first evaluated in the ‘vroegtijdige interventie project’ (VIP; Dutch for ‘early intervention project’). This was a randomized controlled trial comparing COPCA to traditional infant physiotherapy (TIP) consisting of a mix of NDT and functional approaches. From 2003 to 2005, infants admitted to the neonatal intensive care unit of the University Medical Center Groningen were eligible for inclusion if they showed definitely abnormal general movements at 10 weeks corrected age, indicating a high risk of developmental disorders. The infants were block-randomized to receive either COPCA or TIP between 3 and 6 months corrected age. Outcome measures of the study included neurological condition, gross motor development, and cognitive development. Results of the VIP project show that although motor development was similar between the groups, typical COPCA actions such as family involvement, variably challenging the infant to produce active motor behaviour and stimulating at the limit of the infant’s capabilities, had positive correlations with developmental outcome at 18 months corrected age. In addition to the primary endpoints, EMG measurements were taken at 4, 6 and 18 months corrected age to evaluate postural control during reaching movements. Results of these EMG measurements are described in chapter 3 and 4 of this thesis.

In the VIP trial, about 25% of infants eventually developed CP, which made the CP subgroup rather small for proper evaluation of effects in this group. Therefore a second trial, named LEARN 2 MOVE 0-2 or L2M 0-2, was designed in which infants with a very high risk of CP were investigated.L2M 0-2 was set up as part of the Dutch national LEARN 2 MOVE research programme L2M, which evaluates new interventions in rehabilitation for children and adolescents with CP in different age cohorts. Infants between 0 and 9 months corrected age were recruited based on the presence of either 1) cystic periventricular leukomalacia diagnosed by serial ultrasound, 2) a unilateral or bilateral parenchymal lesion of the brain, 3) term/near-term asphyxia resulting in Sarnat with brain lesions on MRI and/or with neurological dysfunction during infancy suggesting the development of CP, or 4) neurological dysfunction suggestive of development of CP. Infants were randomized to receive either COPCA or TIP once a week for a year. Outcome measures focused on performance of mobility-related activities, participation and family function and on body functions and structures. The infants were assessed at inclusion (T0), and at
3, 6 and 12 months after the onset of the intervention (T1, T2, and T3). Infants included prior to the corrected age of 8 months were also assessed at 21 months corrected age (T4). The assessments also included EMG measurements of reaching movements. Part of the results of these postural control assessments form chapters 5 and 6.

**OUTLINE OF THE THESIS**

This thesis studies the development of postural control mechanisms in both typically developing infants and infants at risk of developing CP. The field of motor development is highly influenced by the history of neuroscience and biology in general, particularly the nature-nurture debate, which is why the current chapter (chapter 1) began with a historical perspective. The aim of this chapter was to give the necessary background for the subsequent chapters, by first introducing different theories of motor development, and subsequently introducing the relevant current knowledge and recent advances leading to the research reported in this thesis.

Chapter 2 describes the development of postural control in terms of EMG parameters during reaching movements of typically developing infants between 4 and 18 months of age. The EMG parameters studied include direction-specificity, postural recruitment patterns, recruitment order of direction-specific postural muscles, and anticipatory postural activation.

Chapter 3 compares the results of the postural control data from the typically developing infants described in chapter 2 to those of infants at risk of developmental motor disorders. These at-risk infants formed the control group (receiving traditional infant physiotherapy; TIP) of the VIP trial that evaluated the effects of the new intervention programme COPCA compared to TIP.

Chapter 4 evaluates whether intervention according to COPCA has a different effect on the infant’s postural parameters compared to those of TIP intervention.

Chapters 5 and 6 explore the relationship between changes in postural control and the acquisition of the developmental milestones of independent sitting and independent walking, respectively. To this end, in chapter 5, the data of the children of L2M 0-2 were compared to those of the typically developing infants from the VIP-project, but this time the groups were not based on age but on stage of sitting
development. Similarly, in chapter 6, the data of L2M-infants who developed the ability to stand and walk independently were compared to those of a newly recruited group of typically developing infants, with groups also based on developmental stage instead of age.

Chapter 7 presents a discussion of the findings reported in the previous chapters.
REFERENCES


Chapter 1


