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The development of coordination for reaching movement in children

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The development of coordination for reaching movements in children

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Directeur de recherche :	Mindy Levin
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Sommaire

Ce mémoire portant sur le développement de la coordination du mouvement d'atteinte chez les enfants est une étude qui décrit l'évolution et l'acquisition des patrons matures de mouvement d'atteinte chez les enfants à l'aide d'une approche cinématique du mouvement. Jusqu'à maintenant la majorité des études concernant l'analyse cinématique du développement du mouvement d'atteinte ont été effectuées chez les enfants de moins de 3 ans.

L'intégration sensorimotrice est essentielle pour accomplir une tâche comme l'atteinte et la saisie d'un objet. Nous suggérons que les adultes produisent les mouvements d'atteinte en déplaçant leur cadre de référence dans l'espace.

Trente-huit enfants âgés entre 4 et 11 ans ont participé à cette étude. Ils étaient en position assise et devaient utiliser le bras dominant pour atteindre et saisir un objet situé sur la ligne médiane corporelle. L'objet pouvait être placé à trois distances différentes, de l'intérieur à l'extérieur de la portée. La cinématique a été captée avec 11 marqueurs infrarouges (Optotrak).

Les résultats ont démontré que, contrairement aux adultes, les plus jeunes enfants (4 à 7 ans) n'utilisent pas une trajectoire lisse et droite. Lorsque la cible est localisée à l'intérieur de la limite d'atteinte, les plus jeunes enfants effectuent le mouvement avec une plus grande amplitude de déplacement du tronc que les enfants plus âgés et que les adultes. La coordination interarticulaire n'est pas aussi constante chez les enfants de moins de 8 ans que chez les adultes. La variabilité des paramètres cinématiques diminue avec l'âge. Ces résultats suggèrent que pour acquérir un mouvement d'atteinte coordonné, les enfants doivent solutionner le problème de redondance des degrés de liberté. Il est possible qu'ils apprennent à maîtriser ce problème en explorant la diversité du système afin de sélectionner le patron approprié.

Mots Clés : Développement moteur, atteinte, contrôle moteur, maturation, synergies, coordination interarticulaire, tronc, bras, pédiatrie, réadaptation.

Summary

This thesis on the development of coordination for reaching movements in children is a study that describes the evolution and acquisition of mature patterns of reaching in children through a kinematic perspective. Previously, the majority of studies that have used a kinematic analysis of development of reaching have been done in children under three years old.

Sensory-motor integration is essential to accomplish tasks such as reaching to grasp an object. We suggest that adults produce reaching movements by shifting their frame of reference in the space.

A random sample of 38 children between the ages of 4 and 11 years reached from a seated position with the dominant arm and grasped an object placed at three distances from within to beyond reach in front of the midline of the body. Kinematic data was collected with 11 infrared markers (Optotrak).

Our results demonstrated that younger children (4-7 years) do not have smooth and straight trajectories as demonstrated by adults. Younger children used more trunk movement to reach targets located within the limits of reaching than older children and adults. Interjoint coordination was not as consistent in children under 8 years old as in adults. Variability of kinematic parameters decreased with age. These results suggest that in order to acquire coordinated reaching, children should solve the problem of the redundant number of degrees of freedom. Specifically, children search for this coordinative structure by exploring the diversity of the system and by selecting the appropriate motor pattern.

Key words: Motor development, reaching, motor control, maturation, synergies, interjoint coordination, trunk, arm, paediatrics, rehabilitation.

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À titre de coauteur de l'article identifié ci-dessus, je suis d'accord pour que Sheila Schneiberg inclut cet article dans son mémoire de maîtrise qui a pour titre The development of coordination for reaching movement in children.

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List of Abbreviations

CCT	Central Conduction Time
CMTC	Central Motor Conduction Time
CNS	Central Nervous System
CP	Cerebral Palsy
CS	Corticospinal
CV	Coefficient of variability
EMG	Electromyography
FRs	Frames of Reference
G1…G4	Group one…Group four
IC	Index of Curvature
IREDs	Infra-red emitting diodes
SDd	Standard Deviation of distance
SDt	Standard Deviation of targets
TMS	Transcranial Magnetoelectrical Stimulation
T1…T3	Target one… Target three

Dedication

I would like to dedicate this masters thesis to four special people; without their support and encouragement I would not have succeeded:

To my supervisor Dr. Mindy Levin, for sharing her knowledge and experience with me, and especially for providing me with this opportunity to realise my dream, and for believing in my abilities.

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To my parents for their love, and for teaching me to fight for the things that are important to me.

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Chapter I: Literature Review and Rationale

1.0. Introduction

The study of motor development contributes to our understanding of how a motor skill is learned and changed across the life span. During development, children will experience a vast repertoire of movements until a mature or adult performance evolves. It is through the study of normal motor development that we can determine if the process of skill acquisition is normal or abnormal. This includes the understanding of how transitions occur, and what drives a motor skill to become coordinated. This information can help in the treatment of children with motor problems.

Cerebral palsy (CP) is a major cause of motor impairments or disability in children (Stanley and Alberman, 1984). In North America about one in 500 children is affected with CP (Molnar, 1987). Cerebral palsy is a neurodevelopmental disease resulting from a non-progressive lesion of the immature brain. It involves one or more limbs and frequently the trunk. It causes disorders of voluntary movements and a variety of symptoms (Campbell, 1995).

One of the major functional impairments in children with CP and other neurological disorders is the inability to reach for objects (Fetters, 1996). This inability leads to a greater dependence in many other functional activities. In order to better characterize upper extremity impairment in disabled children, we need to know how healthy children make reaching movements. Specifically, in our study we addressed how healthy children develop coordinated reaching and at what age adult kinematic patterns emerge. Through this knowledge, we will have a basis of comparison with which to identify deficits in reaching in impaired populations.

The following review of the literature is divided into three sections. The first section gives a historical review of different theories of motor development in healthy children and their influence on rehabilitation practices. Included in this section is a review of neuromuscular maturation and motor milestones that contribute to the acquisition of reaching skills. The second section focuses on the production of reaching movement from infancy to adulthood within the context of the principal theories of motor control. Finally, the third section will describe the rationale of the study.

1.1. Motor Development

1.1.1. Historical perspective

Much research has focused on elucidating the organisational principles underlying the gradual development of motor skills from birth to adulthood. Multidisciplinary approaches, based on biomechanics, neurophysiology, psychology, and more recently for development, dynamical system approaches have been used to address these principles (Thelen, 1995).

Motor development refers to the development of motor skill and all changes in movement related to age. This is the principal difference between motor development and motor learning. Motor learning specialists are concerned with changes in movements that are relatively permanent but not necessarily age related. Motor learning focuses on changes within relatively brief time frames compared to motor development that focuses on a longer period during which a sequence of changes occurs (Haywood and Getchell, 2001).

Karl Newell (1986) suggested that movement arises from the interactions of the organism or individual with the environment in which the movement occurs and the specific task demands. If any of these three factors change, the resultant movement will be modified. He called these three factors movement constraints. Newell's model can be considered as a guideline for the study of motor development.

Interest in motor development grew in the 1930's when pioneer developmental scientists such as Mary Shirley, Arnold Gessel and Myrtle McGraw, wishing to understand the relationship between neural structure and behaviour, began intensive studies in the field. They reported how infants gained control of movement through stagelike changes. These scientists believed that motor development was sequential and inevitable. They described *the motor maturation theory* in which motor development was believed to be due to the acquisition of "motor milestones". A "motor milestone" expresses a motor event that characterizes a particular motor skill. According to this theory, motor development was described as progressing in a cephalo-caudal direction. In addition, changes in motor skills are attributed to direct changes in neuronal elements of the central nervous system (CNS; Lockman and Thelen, 1993). However, some motion analysis studies have demonstrated that control apparently develops simultaneously in different parts of the body or a limb

(Green and Nelham, 1991), and changes in motor skill are not necessarily due to changes in neuronal elements of the CNS (Zelazo, 1984; Thelen, 1987). Compared to Newell's model, the motor maturation theory focuses more on structural changes in the CNS and excludes the other constraints such as environment and task demands.

Since the 1960's, developmental scientists moved toward a new, more cognitive approach originally proposed by Piaget (1952): The *information processing* theory. This theory emphasizes the interaction between the environment and the cognitive neural structures to promote action. Piaget also described motor development in 4 stages. The first is the state of sensorimotor intelligence from birth to about 18 to 24 months of age. The second stage of representational thought, from 1.5 to 2 through 6 years of age, involves the development of language and logical thoughts that allow classifications to be developed. In the third stage, concrete and abstract operations become reversible. The final stage, at about age 11, is characterized by the ability to think logically and make deductions. According to Thelen and Smith (1994), Piaget's theory fails in that it does not consider how lower systems (e.g. sensory feedback) interacts in the hierarchical structure. In addition, they disagree with the three central claims of this theory that it has: 1) an impoverished beginning state, 2) global discontinuities in cognition across stages, and 3) monolithic cognitive growth. Thelen and Smith (1994) do not believe that the beginning stage is empty. They affirmed that the infant could have perceptual and conceptual skills, and also Bertenthal (1990) showed that there is a coupling of perception and action even at birth. Thelen and Smith (1994) also criticize the idea of discontinuity across the stages. Finally they suggest that cognition does not move forward in a "lockstep" manner but rather follows a nonlinear pattern.

Most recently, *the dynamical system's theory* has been applied to the understanding of motor development. This theory argues that the older reductionist theories only investigate motor development in terms of stages or phases. Older theories have also been criticised in that they describe the details of movement at each stage of development without consideration of the transitional stages. For example: the maturational approach suggests that increasing complex motor skills are acquired sequentially. According to Thelen and Smith (1994), this is a very simplistic interpretation and it suggests that the "*organism develops because everything is getting better*". The dynamical approach to motor development, different from the other theories, is based on contemporary analysis of movement. It is inspired in part, by the work of Bernstein (1935/1967) who described 'the systems theory in motor control' (Shumway-Cook and Woollacott, 1995). Bernstein described movements in terms of coordination defined as the cooperative interaction of the body with different sensory and cognitive systems. He rejected the idea of a monotonic relationship between the neural code governing a movement and the actual movement pattern. He suggested that the motor control system has to solve the problem of it having a redundant number of degrees of freedom. A degree of freedom is each axis of rotation found in a joint. The problem of 'redundancy' implies that for a specific task, there are many more ways or joint combinations available to perform the movement that are necessary but the system must choose only one combination or synergy of movement. According to Thelen (1995), the system's theory proposes that the subsystems and components that produce the movement are assembled from whatever segments and joints are available to fit the task. This organisation gives the system a great flexibility to meet the demands of the task within a continually changing environment while keeping the goal of the movement in mind.

These ideas of motor organisation in motor development led to the idea that development may be multicausal, involving a group of different subsystems that are developing in their own way. For example internal systems of the organism (e.g. musculoskeletal, nervous, visual, cognitive subsystems), each have their own dynamic developmental history that may be linear or nonlinear. These systems become progressively integrated with the self-organised properties of the overall system. No single subsystem has priority for organising the behavior of the entire system. In this theoretical approach, all these systems of the organism and the external context of the task are equivalent in determining the outcome of behavior because behavior is task specific (Campbell, 1995).

In contrast with the other theories, the dynamical system's theory suggests that motor skill acquisition is driven equally by the developing nervous system and its interaction with perceptual processes, energetic properties of the body, the environment and the task. In addition, variability is essential for development to occur, and skill is acquired through selection and practice. The theory also attempts to explain how the transition from a specific stage of movement to another (i.e. stepping to walking) occurs. The dynamic system's theory is in agreement with Newell's model of motor development. Because I believe that the individual, the environment and the task can influence movement behavior, I have chosen as framework for analysis and discussion in this study, the dynamical system's theory.

1.1.2. Theories of motor development and their influence on rehabilitation

In spite of the differences in conceptual approaches, all three theories in motor development described in the last section have had important influences on rehabilitation science. Fundamental to the practice of pediatric physiotherapy is knowledge of motor development. This knowledge allows therapists to understand how and when a new skill is learned during the life span, to evaluate motor deficits and to increase treatment efficacy. Most paediatric physiotherapy treatment is based on traditional theories of motor development such as the motor maturation theory. Recently this traditional approach has been reconsidered in light of new theories such as information-processing and dynamical system's theories. In this section, it will be reviewed how each of these theories has contributed to treatment approaches for children with developmental disabilities and will be discussed their advantages and drawbacks.

The motor maturation theory: According to this theory, treatment is based on the inhibition of primary reflexes that are believed to persist and produce functional limitation, and on the facilitation of righting and equilibrium reactions that are supposedly responsible for the coordinated motor behavior developed throughout the lifespan (Campbell, 1995). Tests of motor milestones have been developed for use in clinical practice. Physiotherapists believed that in order to acquire a hierarchically superior function such as walking, an infant should master the sequence of postures starting from the prone position to standing, according to a cephalo-caudal and proximo-distal progression. This can be illustrated by the following example: To encourage independent head lifting in an infant, the maturational approach would suggest working on head control from prone prior to a sitting or standing position. However, according to evidence from biomechanical studies, the best position for head control training would be in standing, in which vision provides facilitatory inputs for head control and gravitational forces on the head are lower than those in the prone lying position (Shepherd, 1995). Following the hierarchical approach would deny a disabled child the possibility of experimenting with hierarchically higher postures such as sitting and standing. This is a limitation of the maturational approach.

Cognitive or information processing theory has had some effect on treatment approaches in pediatric physiotherapy. According to this theory, problem-solving activities assist in motivating or facilitating motor development. For example, therapists use problems such as searching for hidden objects in containers, or other game-like activities to motivate children to move and to promote the perceptual-cognitive aspects of development (Campbell, 1995).
The theories discussed above were developed at a time when little was known about motor behaviour in terms of movement analysis. The fact that those theories attribute the stability of the behavior to the status of only one subsystem – the maturation of the nervous system- fails to recognise that behaviour is also constrained by other systems such as biomechanical one.

According to the dynamical systems theory, movement is planned in a preferred pattern related to an attractor element. An attractor element is a stable state or an equilibrium configuration. It is important to note that an attractor is a preferred, but not an obligatory, configuration of the system. " *Like the ball rolling into a pit in the sand, attractors are described as having relatively deep or shallow attractors wells, based on the ease with which the system returns to the attractor and how difficult it is to move the system away from or out the attractor well"* (Kamm et al., 1990). In other words, this attractor element allows the motor system to adopt a preferred pattern easily and return to that pattern even when perturbed or interrupted. In order to reach this pre-determined pattern the system integrates information from all associated systems (i.e. cognition, sensorimotor, memory, etc.) required by the task (Kamm et al., 1990).

According to Kamm et al. (1990), therapy for developmental delay should identify the movement patterns that the patient prefers and the stability of these patterns in the context of tasks that are normally encountered. Physiotherapists should identify the different subsystems involved in the task in order to focus treatment on the missing elements of the whole system. Therapists must discover the parameters that push the system to a new level or state. Parameters can be highly specific like maturational changes in the CNS or particular muscle strength changes, or nonspecific, like the emotional or motivational state. The goal of treatment is to work on the system when it is in transition, because during this transition the system is more vulnerable to outside influences. For example, the production of movement in a damaged nervous system may lead to the development of a deep and inflexible well, or a stable attractor. A child with cerebral palsy who does not receive early treatment could develop pathological movement synergies that would become stable over time. Therapists should identify whether or not this pattern is functional and not damaging to the system. Then they should test the stability of the pattern by asking the child to move in different conditions and under different task constraints. If poor patterns are already well established, interventions are required that disrupt this current stability, if it is still possible. Examples of methods to influence maladaptive patterns are the use of orthotic devices to improve locomotor patterns, or muscle strengthening to improve endurance (Kamm et al., 1990).

1.1.3. Neuromuscular maturation

This section will review the structural changes that occur during the development of the neuro- muscular system from birth until 11 years old.

After birth, 85% of brain growth takes place. The cerebral cortex of the neonate is only half of its adult thickness. The increase in thickness results from an increase in the size of nerve cells and sprouting of nerve processes. The ascending afferent fibres in the spinal cord are relatively well-myelinated at birth, but the descending motor tracts do not become fully myelinated until years 1 and 2. The cerebellum is immature until the child is 2 years old. Only by 5 years of age, is myelination of all cerebral structures complete but functional maturation may still occur up until the age of 6 years (Shepherd, 1995). However, according to a review of the ontogenesis of goal-directed behaviour based on anatomo-functional considerations such as structural, chemical and electrophysiological events during the development of the brain, physiological maturation occurs much later (Kostović et al., 1995). Indeed, these authors found that movement-related brain macropotentials (MRBMs, or the electrical representation of cognitive activity) became adult-like only around the age of 16 years old. The MRBMs correlated with the developmental plateau of synapse production at this age. They concluded that the prolonged maturation of goal-directed behavior or the continuous improvement in movement performance (i.e. the appearance of anticipatory preparation for action) as well as the emergence of different cognitive functions correlated with the maturation of associative, motor and sensory cortical areas. This associative circuitry production has its peak at 2 years of age.

The development of both sensory and motor pathways is essential for the skills of reaching and grasping an object. The processing of cognitive and motor information in the CNS cannot occur without the normal development and function of lower level sensory and motor systems. The majority of sensory pathways mature earlier than motor pathways and most sensory pathways are already myelinated at birth (Shepherd, 1995). The corticospinal tract (CS) plays a special role in the control of hand function and it has been suggested that it is not completely mature until late childhood (Müller and Hömberg,1992; Nezu et al., 1999; Fietzek et al., 2000; Eyre et al., 2000).

A study by Eyre et al. (2000) questioned whether the development of the CS was related to the appearance of fine hand movements in man. They used anatomical, neurophysiological, and functional studies to determine if CS innervation occurs as late in postnatal development as 6-12 months of age, when fine manipulative skills appear. They found that CS axons reach the lower cervical spinal cord by 24 weeks post-conceptional age and that after a few weeks they progressively innervate the grey matter such that there is extensive innervation prior to birth. They also found neurophysiological evidence for the prenatal establishment of functional connections from the cortex to the spinal cord. Furthermore, the cortico-motoneuronal projections preceded the onset of relatively independent finger movement. As a result they concluded that corticospinal innervation occurs early in man, so that the cortex can be intimately involved in spinal motor centre development from an early age.

It has been suggested that the diameter of the thickest fibres in the CS tract increases linearly as a function of body height. In addition, central conduction time observed in the motor pathways of both human and nonhuman primates decreases during childhood and adolescence (Paus et al., 1999). Central motor conduction time (CMCT) is important during a movement because it can facilitate information flow by allowing for precise temporal coding of high frequency bursts of neuronal activity and it is determined by the diameter of the nerve and its myelination (Connolly et al., 1997). Müller and Hömberg (1992) studied the relationship between the maturation of CS efferents, by transcranial magnetoelectrical stimulation of the motor cortex (TMS), and the development of repetitive movements of the hand and fingers. They tested 68 neurologically normal children in the age range from 2-13 years. They measured central conduction time (CCT) and movement time in two different tasks: tapping (open loop), aiming moving pegs on pegboards (closed loop). They looked at the covariation of the maturational pattern of the fastest cortico-motoneuronal efferents with the developmental profile of fast voluntary alternating motor activities by comparing the curve profile of CCT and the curve profile of the three tasks. The curve profiles of CCT and the three tasks varied as a function of age and movement time. They found no difference in the maturational profiles of the three tasks and they found an identical maturational profile between CS efferents (CCT, curve profile) and the three tasks. The results indicated that movement time in the three tasks follows the same functional dependence on age as CCT. They suggested that the development of central conduction times determines the speed of repetitive movements in children. On the other hand, Fietzek et al. (2000) did not find similar correlations between hand motor performances. They tested central motor conduction time (CMCT) also obtained with TMS and tested motor skill and speed on five different tasks in 112 subjects aged from 0.2 to 30 years. They wanted to assess the maturation of the fast CS and the developmental course of several different parameters of hand motor function. CMCT matured earlier (around 4 years of age) as muscles that were tonically active had CMCT's similar to those in adults. Whereas CMCT's in relaxed muscles had mature values around 7 to 10 years of age. All of the five tasks tested, auditory reaction time, ballistic arm movement, repetitive movements (finger tapping), repetitive and associated movement (diadochokinesis), and visual manual tracking, achieved adult values at different rates. The most dynamical period or steepest part of the learning curve in these tasks occurred in the first 10 years and they did not reach a plateau during childhood. Because the curve profile of CMCT differed in all five tasks and profiles did not reach a plateau at the same time as CMCT, they concluded that maturation of CS transmission appears to precede the development of movement speed and skill.

Even though cortico-motoneuronal connections have already been established, the conduction velocity time is not the same as adults until 8-10 years of age (Müller et al., 1991). Ten year old children were not able to perform like adults in some of the motor tasks tested by Fietzek et al. (2000). This could be due to the fact that the tasks studied were complex and required the integration of more than one system (i.e. sensory and motor). This suggests that children need to integrate all information to perform as well as adults.

The integration of sensory information and motor commands requires the maturation of parietal and frontal associative regions of the brain, which is not complete until the age of 16 years (Kostović et al., 1995; Paus et al., 1999). In addition, some studies demonstrated that sensorimotor processes are not fully integrated even by 11 years old. In a study by Hay (1979), children aged from 5 to 11 years old performed a pointing task wearing prismatic glasses. This task was used to determine at what age movement is controlled by predominantly afferent systems, visual systems or both. By analyzing the corrections in movement trajectories, she postulated that if the system depended only on afferent feedback, corrections would occur later than if it depended on visual feedback. She found that 5-year-old children made late corrections in the trajectories during the task. Seven-year-old children modified their movement early in the task and the oldest children performed intermediate corrections indicating that they integrated both visual and afferent systems. In another study about sensorimotor integration, von Hofsten and Rösblad (1988) tested if the ability to use proprioceptive information during pointing tasks improved between the ages of 4 to 12 years old. They tested 270 children (30 children per age). The task was to place drawing pins underneath a table top at the locations of dots placed on its upper side. They divided the task into four conditions: visual, visual-proprioceptive, proprioceptive and memory. They found that for all age groups, children in the visual condition obtained the best scores and placing errors in all conditions decreased as age increased. A similar result was found later by Ferrel et al. (2001) concerning the visuomotor representation of space. In their experiment, children aged 6-11 years old had to point to four different targets. The children could not see their arms but they had visual information about hand trajectories provided on the computer screen. However the visual representation was rotated in order to study the ability of the children to adapt their visuomotor transformation. They analysed error measures in relation to age and visual rotation. They postulated that a unidirectional representation resulted in a linear increase of errors from 0° to 180° rotation, and a bidirectional representation would cause an increase in error from 0° to 90° and a decrease from 90° to 180° rotation. They found that the unidirectional representation, shifted to a bidirectional one in children aged 8 years old. Moreover this group also showed a high variability in constant errors, which suggests that these children have difficulty in performing the task with spatial distortion, since such variability was absent from pointing movements with direct vision (Fayt et al., 1992). Eleven-year-old children and adults had almost the same results. They both used bidirectional coding of space, which means that their errors increased from 0° to 90° rotation and then decreased it from 90° to 180° rotation. However, 11-year-old children still moved slower than adults. This result suggests that complete maturation of space coding occurs at an age older than 11 years.

Overall these studies demonstrated that adult-like performance in children is acquired in parallel with the maturation of the CNS. Children cannot move as fast as adults because the conduction times of the CS tract and peripheral nerves are slower. In addition they do not perform as well as adults in complex tasks because their information (i.e. proprioceptive and vision) may be processed in a different way.

Besides the changes in the CNS during development, there are other changes resulting from musculoskeletal growth that also influence motor performance. Postnatal bone growth in length occurs at a secondary ossification center at the end of the shaft, termed the epiphyseal plate. Growth at the ossification centers ceases at different times in various bones. Almost all epiphyseal plates are closed by age 18 or 19. In addition to the growth in length, bones also grow in circumference, which contributes to the additional weight of limb segments during development (Haywood and Getchell, 2001).

Muscle cells grow during prenatal life by hyperplasia, which is an increase in the number of muscle cells, and by hypertrophia, which is an increase in muscle cell size. Hyperplasia continues only a short time after birth. Thus, most of the postnatal muscle growth is by hypertrophia. An adult muscle is composed of three types of fibers: type I (slow- twitch) that are more resistant to fatigue and are used in endurance activities; type IIa and IIb (fast-twitch) that are less resistant to fatigue and are used in intense and short duration activities. At birth, muscles consist mostly of fast twitch units. After two years of postnatal life some units become slow twitch (Haywood and Getchell, 2001). In a study of 22 subjects aged 5 to 36 who had died accidentally, it was demonstrated that muscle cross-sectional area in the vastus lateralis more than doubled with age. There was also a 20% decline in the proportion of type I fibres between the ages of 5 and 20 years, suggesting that muscle fiber types become faster in the first 20 years of life (Lexel et al., 1992). In a histochemical study, Elder and Kakulas (1993) studied 43 subject ranging from 22 weeks gestational age to 28 years. They pointed out that as an infant becomes a child and then an adult, the muscles undergo a fast–slow-fast phenotype.

With the goal of analysing if muscle maturation significantly contributes to dexterity, Lin et al., (1994) investigated the speed of alternating repetitive movements and correlated the findings with measured muscle twitch parameters (half relaxation time) in the ankle, metacarpo-phalangeal, and wrist joints in 38 children aged 3 to 11 years, and eight adults. They defined dexterity as the number of taps made by the hand or foot per second. They demonstrated that dexterity increased with age in all joints tested and the maximal speed of the joint tested showed a high curvilinear dependence of muscle half relaxation time (i.e. ankle tapping speed decreased with the increase of half relaxation time of the soleus muscle). They suggested that in addition to neuronal maturation, the factor responsible for the maturation of dexterity is the muscle itself as some of the mechanisms by which muscle dynamics change with age may reflect changes in the calcium re-uptake mechanism of the sarcoplasmic reticulum, which is known to control muscle relaxation.

Changes in inertial and physical properties of muscle such as viscoelastic, resistance due to fiber type composition and muscle contractile properties also influence movement outcome. These properties are in continuous change during motor development obliging the system to adapt to them (Connolly et al., 1997).

1.1.4. Events in motor development that influence with the acquisition of reaching.

In this section we review some of the most important milestones of motor development in the progression towards the acquisition of **reaching**. This review has a purely descriptive aim since the classification of development into stages does not necessarily explain how development occurs. In addition, except for reaching and walking (Zelazo, 1984; Thelen and Cooke, 1987), few studies have tried to explain how the transition through different phases of skill acquisition occurs.

Bower (1974) and Von Hofsten et al. (1979) observed in neonates the presence of reaching movements towards visual targets. Reaching movements were made closer to the object when the infant fixated his or her eyes on it than when the infant was looking elsewhere or when both eyes were closed, suggesting a kind of primitive eye-hand coordination. However these early reaching attempts were only possible when positioning of the neonates allowed head control, trunk stabilisation and visual stimulation. Infants at this age do not have head or trunk control and without manipulation or facilitation of the posture, reaching would not be elicited at this age. Amie-Tison and Grenier (1980) studied the influence of posture on these early reaching movements. They demonstrated that fine eye-hand coordination can be obtained when the neonate is placed in a sitting position with the back of the neck firmly held by the experimenter's hand, and his attention is attracted by an object. They explained that this was possible because of an inhibition of tonic neck reflexes, a decrease in the basic level of muscle tone and a reinforcement of trunk tone. These two studies suggested that the motor programs responsible for eye-hand coordination, and therefore early reaching, do exist in the infants' repertoire but they cannot be elicited without facilitation. Thus, some events during development necessarily contribute to the acquisition of reaching in children such as: head control, trunk control, and coordination of arm and hand synergies.

The beginning of head control is observed in the neonate when placed in prone. They can slightly lift the head as a protective reaction to keep the nose and mouth free to breathe. Within a few weeks after birth, infants can activate neck and upper trunk extensors to raise the head higher (Shepherd, 1995). At about two months, infants can sustain the head in the midline in the frontal plane during supported sitting but often appear to be looking down, so that their eyes are oriented thirty degrees below horizontal. By the third month, the head is more stable in the vertical position, allowing turning to follow visual stimulation. By the end of the fourth month due to a more organized trunk and lower extremity extension, the head can be positioned stably in space leading to a further development of eye-head-hand control (Campbell, 1995).

According to some studies, it seems that postural and voluntary movements develop together and the increase in postural stability is concurrent with improved performance in reaching (Thelen and Spencer, 1998; Berthental and Von Hofsten, 1998; Van der Fits and Hadders-Algra, 1998; Fallang et al., 2000). In a standing position, adults sway in response to the movement of a platform placed under their feet using a stereotyped muscle activation pattern in which EMG onsets were seen first in distal muscles closest to the base of support (Nashner and Woollacott, 1979). Infants aged from 1 ½ to 3 years presented the same distal to proximal activation, although the activations were longer in duration and larger in amplitude than those in adults. Belenkii et al. (1967), Lee (1980), Bouisset and Zattara (1981) and Cordo and Nashner (1982) have shown in adults that when they perform arm raising and reaching in standing and sitting, lower limb muscles are activated before arm muscles and that these anticipatory postural adjustments were also followed by joint rotations and changes in the center of pressure in the lower limbs. In sitting infants, however, Van der Fits and Hadders-Algra (1998), did not find consistent postural anticipatory activity during reaching in children aged from 3 to 18 months but their results revealed that by 4 months, the age at which successful reaching emerges, reaching movements were accompanied by complex postural adjustments that resembled adult patterns. These adjustments were spatially organized in a dorso-ventral sequence and temporally organized in a cranial-caudal order (preference for neck muscle activation).

In early reaching movements, the arm and hand are coupled so that when the arm is extended there is a tendency for the hand to open and when the arm is flexed the hand tends to close (Von Hofsten, 1982). A change in the earlier reaching synergy is seen in 2 month old infants, who reach towards an object with the arm extended but the hand closed and there are also fewer reaching attempts (Von Hofsten, 1984). By 3 months of age, when looking at the object, the infant opens the hand when reaching and the number of reaching attempts increases. At 4 months, reaching is more controlled with the open hand raised to the proximity of the object and then brought closer to it, until the object can be grasped, but at this time the infant will bat at objects more than grasp them (Bart et al, 1990). Around 5 months of age, reaching is completely developed and grasping is seen more often. Early voluntary grasping is with the whole hand, tending towards the ulnar side. During the second half of the first year, a change to the radial side occurs, and by 8 months, most objects will be grasped towards this radial side (Shepherd, 1995). Calibration of the reaching movement with regard to object properties seems to appear around 9 months (Bart et al, 1990). According to Jeannerod (1982) reaching movements are initially visually triggered until around 5 to 6 months and by this time a guided component will be progressively integrated. Bushnell (1985) pointed out three major differences between early reaching in neonates and reaching in infants aged 4 months: neonatal reaching is less accurate, is ballistic and is based on *"prewired"* visuoproprioceptive coordination. In contrast, later reaching is more controlled suggesting a better eye-hand-target coordination that it is only possible with the development of trunk and head control.

1.2. Reaching movement

This next section will be concerned more about reaching with the intention of grasping an object. The focus will be on the transport phase, and on how reaching is executed more than how it is produced. Although some theories of motor control will be mentioned, this will not be the focus of the section. Then, this section will describe how reaching movement is performed in adults and what is known about the development of reaching in children through an analysis of kinematic parameters such as trajectory formation, interjoint coordination, and trunk involvement.

Studies of reaching to a target in humans and nonhuman primates have documented two distinct phases, the transport and grasping phase of the arm and the hand (Jeannerod et al., 1984). In addition, Pigeon et al. (1998, 2000) have suggested that reaching movements are also composed of several units of coordination or synergies. The first component is the transport synergy that is aimed at changing the arm configuration according to the desired direction and extent of movement. The second is an arm-trunk compensatory synergy, used when trunk movement is also required to increase the reaching distance. The compensatory synergy determines the relative contribution of arm and trunk movement during the transportation of the hand to the target; The third is the grasping synergy whose functional goal is to prepare the hand aperture, shape and orientation for grasping an object.

The cortical control of visually guided reaching involves many structures, such as: primary motor cortex, pre-motor cortex, the supplementary motor area, cingulate motor area, primary somatosensory cortex, and posterior parietal areas, as shown by studies of the distribution of reaching movement related cell activity in the cerebral cortex of the macaque monkey (Kalaska et al.1997). The control of reaching also involves sub-cortical structures like the basal ganglia and the cerebellum.

The neural systems that control visually guided reaching movement result from an integration of different sensory modalities that are used to build an internal representation of space. This spatial representation could be formed by different modalities such as vision, somatosensation, audition, and vestibular sensation (Andersen, 1997). Many studies support the idea that spatial representations of limb position, target locations, and potential motor actions, are combined in the posterior parietal cortex. Interesting findings were found in the superior parietal cortex (SPL) area 5 of Brodmann, that for many years was considered only a somatosensory region. Results of some studies have shown that neurons in this area respond during active arm movements towards a target more than during random arm movements, that they indicate the direction of joint movements, and also that they can supply the frontal motor lobe and premotor areas not only with proprioceptive information but also with visual input (Kalaska, 1996).

Although reaching is commonly followed by grasping, anatomical evidence and neurophysiological recordings have demonstrated that separate but parallel parieto-premotor channels mediate visuomotor transformations for reaching and grasping (Kandel et al., 2000). Damage to the pyramidal tract results in impairments of fine finger control, thus impairment in grasping objects. Damage to the extrapyramidal tract results in impairment of gross arm movements, thus impairment in hand transport. In addition, developmentally, the pyramidal tract also matures later than the extrapyramidal tract (Rosenbaum, 1991). Some studies argue that in spite of the independence in neuromotor control, reaching and grasping are temporally and spatially coordinated (Gentilucci et al., 1992; Hoff and Arbib, 1993). Others said that the coordination between the two components involves more than a temporal coupling and a higher order control system is responsible for their integration (Jakobson and Goodale, 1991; Marteniuk et al., 1990). Some findings that support the existence of coordination between reaching and grasping are the dependence on speed for the maximum separation between finger and thumb when the hand is brought towards the object. The widening of the fingers increases when the hand travels with high speed. Another kind of dependence between transport and grasp concerns the timing of aperture between index and thumb that coincides with the phase of deceleration of the approach or transport phase.

1.2.1. How do adults reach?

It has been suggested that reaching movement is planned in hand or endpoint coordinates (Georgopoulos et al., 1986; Flash and Hogan, 1985; Flanagan et al., 1993, Gordon et al., 1994). According to Rosenbaum (1991), if the motor system, instead of selecting a direct path of the hand to a target, selects a convenient set of muscle torques, one would expect simple patterns of joint angle and complex hand patterns. In contrast, if hand path is planned, the opposite will occur. Thus, the motor system may plan the movement with respect to joint space using the intrinsic coordinates of the body, or with respect to hand space using the extrinsic coordinates of the external environment.

Morasso (1981) analysed hand trajectories in healthy adults when they pointed to targets. He found that subjects' hands tend to move in a straight line, and their joints demonstrated complex angular changes. Another study (Abend et al., 1982) reported that even when subjects were asked to draw curved lines, hand trajectories were composed of a series of straight line segments. These studies support the view that the motor system plans reaching in the hand extrinsic coordinates. However, Soechting and Lacquaniti (1981) found some invariant relationships among the joints during a pointing task such as the same time to peak velocities of elbow and shoulder, and equality in the ratios of peak velocity and radial distance that the joints moved suggesting that planning could be in intrinsic coordinates. Rogosky and Rosenbaum (2000) questioned whether space-based motor planning occurs at higher, equal or lower levels of the control system than joint-based motor planning. They based their conclusions on the following prediction: if spatial planning can be learned more quickly than joint planning, then this can be taken to suggest that spatial planning occurs at a higher level of control than joint planning. In contrast, if joint planning can be learned more quickly than spatial planning, then joint planning occurs at a higher level than spatial planning. They asked 32 healthy subjects to reach towards a target while following a visual display, which was distorted with respect to spatial hand displacement (space-based distortion) or with respect to joint angle displacements (joint-based distortion). They found that subjects adapted more easily to space-based distortion. Thus, the result supports the view that space-based planning occurs at a higher level than joint-based planning.

Latash (1993) agreed with the majority of the studies cited above when he wrote that the workpoint, the most important point for executing a task (i.e.: in the case of a reach-to-grasp movement the workpoint is the fingers or the palm of the hand), is the focus of concern of the CNS, because its trajectory is vital for executing the task. However, in his opinion, even the trajectory of the workpoint is not a variable that the CNS uses to control the movement. He points out that if an unexpected perturbation occurs during a movement, the trajectory of all points including the workpoint will change immediately while the central command presumably remains the same, until motor corrections are introduced. This indicates that the central command should stay invariant for some time independently of events in the periphery (Feldman, 1998). Then, the invariant central command may be associated with a control parameter or variable as suggested by Feldman (1986), and others (Latash, 1993, Feldman and Levin, 1995 - the lambda (λ) model).

One of the major questions in motor control is the relationship between the internal movement representation and output trajectories (Archambault et al., 1999). According to Levin (1996) some elements in reaching display invariant behaviors suggesting some principles in motor control. Examples of those behaviors are straightness of trajectories, bell-shaped velocity profiles and distance-scaled acceleration profiles. Studies have suggested that the nervous system controls such invariant characteristics of movement as energy cost (Hatze and Buys, 1977), or smoothness defined by the rate of change in acceleration (Flash and Hogan, 1985), internal models (Kawato, 1999), posture-based planning (Rosenbaum, 2001) and changes in control variables (equilibrium point hypotheses or the lambda (λ) model, Feldman and Levin, 1995). For Feldman and Levin (1995) kinematic and eletromyographic patterns are not programmed but are emergent properties from the interaction among the systems. They proposed that the CNS uses control variables (CVs) to produce voluntary movement. CVs are specified by the nervous system independent of current external conditions. Thus, biomechanical variables are not CVs but are influenced by them. Frames of reference or systems of coordinates are organized by the CNS and movement is produced by shifting the frames in space. The factors that define the frame of reference are derived from the equilibrium point hypotheses or lambda (λ) model. Thus, alpha (α) motoneuron threshold properties, proprioceptive feedback and components of the tonic stretch reflex are factors that define the frame of reference. " *By modifying λ, the CNS specifies* *a new origin point of the positional frame of reference for force generation and neuronal components of the sensorimotor system. In this way, the system is forced to find a steady state that results in a new equilibrium body configuration in the new frame of reference"* (Feldman and Levin, 1995; Feldman, 1998).

Another aspect discussed in motor control and specifically in the control of reaching movement is the redundancy or abundance (Latash, 2000) in the number of degrees of freedom. How does the system choose one way to reach, one combination of joint movement among an infinite number of choices? Studies of rhythmical movements have shown that successive trajectories follow a similar pattern, but not necessarily the same joint coordination (Bernstein, 1967). Based on this findings Bernstein originally suggested some solutions for the problem of redundancy. He proposed that the redundancy problem might be solved by the formation of optimal synergies. Synergies are not created by the nervous system but may emerge naturally from task demands. In a same vein, Turvey et al. (1978) later suggested the formation of coordinative structures as a solution to the redundancy problem. For Levin (1996) interjoint coordination is part of the coordinative structure underlying reaching movements and she suggested that trajectories and interjoint coordination may be associated with functionally different hierarchical levels of motor control as demonstrated in her study with hemiplegic subjects making pointing movements towards visual targets. In spite of the subjects having a disrupted interjoint coordination between elbow and shoulder movements; even those with the most severe spasticity were able to reach into all parts of the workspace with the affected arm, suggesting the integrity of motor planning. Lacquaniti and Soetching (1981), and De Guzman et al. (1997) found an interesting temporal coordination between shoulder and elbow displacements during arm movements. Levin (1996) and Cirstea and Levin (2000) found a spatial coordination between the elbow and shoulder in healthy subjects during pointing movements that was disrupted in hemiplegic subjects. Overall, these studies support the idea that the system organizes coordinative structures to solve the problem of redundancy. Indeed, interjoint coordination can be considered one of these structures in reaching movement. These coordinative structures are constrained by the task or in other words, they are task specific. In the case of reaching as reported by the above studies, the coordination between the shoulder and elbow is necessary to stabilize the hand movement. When this interjoint coordination is not available, i.e.: in the case of hemiplegic subjects, the system compensates with other available synergies (Cirstea and Levin, 2000).

Besides the study of interjoint coordination, the redundancy problem may also be approached by the study of arm and trunk synergies. Most of the studies in reach-to-grasp movement considered reaches that are only made by the arm. However, in many situations, confronted daily, reaching occurs to objects placed beyond the limits of extension of the arm (Wang and Stelmach, 1998). In those situations the motor control system needs to coordinate arm and trunk movement. It has been suggested that arm and trunk motions are governed by different neuromotor synergies (Ma and Feldman, 1995; Kaminski et al., 1995; Saling et al., 1996; Wang and Stelmach, 1998). Ma and Feldman (1995) demonstrated that in reaching tasks, the addition of trunk motion did not affect endpoint trajectory. They also suggested as well as was mentioned before in our text in Pigeon et al. (1999), that reaching in the limits of arm's length involves two synergies: a reaching synergy that consists of moving the arm joints displacing the hand towards the object, and a second synergy that consists of moving the trunk and arm joints without affecting the position of the endpoint (compensatory synergy). Adamovich et al. (2001) also studied reaching movement involving the trunk. Subjects had to make fast arm movements without corrections to the targets while the trunk was free to move or blocked. They found minimal changes in the hand trajectories and velocity profiles of the endpoint in response to trunk arrest, and these few changes were seen only late in the movement. Interestingly, the pattern of interjoint coordination substantially changed during trunk arrest while the hand path was unaffected. This suggested the presence of compensatory joint rotations to minimize deflections in the hand trajectory, independent of whether the trunk was recruited or mechanically blocked. Thus this study corroborated findings Pigeon et al. (2000) that the involvement of the trunk is compensated by appropriate joint rotations. Adamovich et al. (2001) suggested that the integration of additional (in this case: trunk) degrees of freedom into the movement is based on afferent (proprioceptive and vestibular) signals. No central commands are issued for the compensatory arm movements. Instead the control system modulates the degree of compensation by "gating" the afferent signal elicited by the trunk motion. Through this control system an appropriate contribution of trunk motion is provided to the hand transport.

In healthy subjects, when the trunk is involved in reaching, its contribution to the endpoint movement occurs near the end of reach as the hand approaches the target (Rossi et al., 2002). Thus, the healthy nervous system uses a specific strategy to add the trunk movement when reaching is made to targets beyond a critical distance. The threshold for trunk recruitment during such reaching movements is lower in hemiparetic subjects (Levin et al., 2002). They studied reach-to-grasp movements towards targets located at four different distances in 11 healthy and 11 hemiparetic subjects. Although healthy subjects did not use the trunk to reach the closer targets (within arm's length), hemiparetic subjects used considerable trunk motion, corresponding to the amount used by healthy subjects to reach farther targets (beyond arm's length). They suggested that this increased trunk involvement might be due to the need to preserve trajectory smoothness or to limit movement errors, since the ability to extend the arm into extrapersonal space is limited in hemiparetic subjects. Some studies have also demonstrated the presence of temporal coordination between trunk and endpoint (hand or finger) movements in reaching tasks. The movement may be initiated by the trunk, but the trunk continues to move after the end of the grasping phase, thus stopping to move after the endpoint (Kaminiski et al., 1995; Saling et al., 1996; Archambault et al., 1999). The time-to-peak trunk velocity was coupled with the time to peak arm velocity as well as with the time to peak aperture (Wang and Stelmach, 2001).

These studies support the idea that there exists a complex coordination between the arm and trunk movement. A disruption of this coordination can lead to abnormal recruitment of the trunk and/or an impaired interjoint coordination.

1. 2. 2. How do children reach?

Infants learn to reach at about 4-5 months of age. At this time their hand trajectories are jerky and tortuous as in zigzag movements (Von Hofsten, 1979, 1982,1991; Fetters and Todd, 1987; Thelen et al., 1996; Konczack and Dichigans, 1997). Adults are considered skilled reachers compared to infants since they keep the hand moving in a straight and smooth path towards the target. According to Thelen et al. (1996), reaches in young infants are unskilled because their trajectories are still coupled with the energetic and biomechanical constraints of movement execution. In contrast, adults are able to maintain a smooth hand path independent of movement speed, and varying with visual information in different postural contexts and task demands.

Von Hofsten (1979) analysed reach trajectories in five infants aged from 12 to 18 weeks old. He described that reaches could be divided into movement elements or movement units. The definition of a movement unit is based on the velocity profile. Each unit consists of an acceleration and a deceleration phase. When a movement starts to accelerate again, a new unit is defined. Speed valleys mark the borderlines between units.

As was discussed in the previous section, adult reaching movements are characterized by a bell-shaped velocity profile, and thus by one movement unit. With age, children decrease the number of movement units during reaching (Von Hofsten, 1979). In addition, as the number of movement units decreases, the first movement unit occupies a larger proportion of the reach, so that movement is formed by one acceleration and one deceleration. By 2 months of age following the onset of reaching, trajectories become more smooth and fluent, formed basically by one movement unit (Von Hofsten, 1991; Thelen et al., 1993; Konczack, 1995).

Why do infants have such characteristic aspects in their trajectories? For von Hofsten (1979), it is a question of improvement in eye-hand coordination.

For Konczak et al. (1995), it is a question of producing the right pattern of torques. For Feldman (1998), it is the question of the formation and management of appropriate frames of references. For Thelen et al. (1993), it is a question of solving different dynamical and biomechanical problems for each infant. In addition, Thelen et al. (1996) suggested that movement units could be deliberate corrections to the trajectory at a higher level. Thus, the tortuous trajectory could result from the infant's inability to generate a virtual trajectory. Overall, studies suggest that in order to acquire a better performance during reaching, infants must learn several levels of control, which are first the planning level and later, the stabilization of a programming or execution level.

Although infants improve their performance in reaching within the first year of life, the development of coordination in reaching and the stabilization of reaching patterns that leads to stereotyped adult performance is not yet acquired (Konczak et al., 1995). Konczak and Dichgans (1997), with the goal of identifying when infants achieve adult-like consistency of kinematic performance in reaching, studied nine infants longitudinally from the onset of reaching (5 months) up to the age of 3 years and compared these results to those from four healthy adults. The task was to reach a stationary object placed at shoulder height. They found that straightness of the trajectory increased over 90% by 3 years of age with respect to the initial value at the age of 5 months, but still differed from adults. Variability between trials decreased with age but at 3 years old was still higher than adults. Unimodal endpoint velocity (one movement unit) became predominant by 2 years of age. Temporal coordination between shoulder and elbow fluctuated largely during the first year. At 5 months of age, early reaches, showed a pattern of peak velocity of elbow extension preceding shoulder motion. Adult reaching movement was characterized by a temporal pattern of shoulder flexion followed by elbow extension. Only by 24 months of age did infants demonstrate, in the majority of trials, an adult temporal sequencing between shoulder flexion and elbow extension. These authors concluded that endpoint trajectory smoothness emerges with the evolution of interjoint coordination. The underlying synergies, that are the basis of invariant interjoint patterns are not established when infants start to reach, nor were they acquired by three years old but had to be achieved during ontogenesis. They suggested that the developing nervous system employs synergies to reduce both the number of controlled movement parameters and the amount of afferent information necessary to generate and guide movement. The fact that they found an emergent temporal coupling between limb segments is an indication of this constraint used by the CNS. However, their data cannot be conclusive on this issue since they only investigated reaches to a single target distance. In order to determine if this coordination is a general strategy of the CNS, reaches to different target locations should also be investigated.

The majority of the studies about reaching movement in children older than 3 years of age have been concerned with how reaching is planned rather than executed. In general, reaching accuracy and corrections of trajectory have been studied while visual feedback was presented during the entire movement execution or while only the target was seen. The latter condition is visually triggered reaching. In this condition, vision is not present during movement execution so that movement is guided mainly by propioceptive feedback (Hay, 1978, 1979; Von Hofsten and Rösblad, 1987; Fayt, 1992). What such studies have found is that the development of reaching is not linear and that periods of transition (critical periods) or changes in strategy of motor control occur around the age of 6 to 8 years old. In this age range, children make more variable reaches across trials (see Fayt, 1992, Ferrel et al., 2001), visual guidance of reaching is more important and children are more likely to make corrections in their reaches. A more complete sensory motor integration is achieved later around 11 years old.

Overall, these studies reinforce the idea suggested by Konczak et al. (1997) that reaching performance is far from being mature or adult-like at the age of 3 years old. However there is a lack of studies describing kinematic aspects of reaching in children beyond this age. The ages when kinematic aspects such as trajectory straightness, interjoint coordination and intersegment coordination achieve a mature pattern are unknown.

1.3. Rationale

The review of the literature introduced several aspects of the development of coordination in reaching movement including the multicausality of motor development, the acquisition of reaching, and the kinematic characteristics of reaching in adults and in infants. In addition, the review of the literature reveals the lack of data about kinematic aspects of reaching in children older than three years of age. This absence leads to a deficit in the characterisation of the development of reaching movements throughout the childhood years. Thus, since we do not know how coordination of reaching develops throughout healthy childhood, we cannot characterize developmental delays with respect to reaching and manipulation in children with motor disabilities.

Kuhtz-Buschbeck et al. (1998) studied the development of prehension in children aged between 4 to 12 years old, but their study focused on aspects of grasping and coordination between the transport of the hand and the grasp components. They found that the reaching trajectory became straighter and the coordination between hand transport and grip formation improved resulting in smooth and stereotyped kinematic patterns by the age of 12 years. However, they did not compare their results with an adult group nor did they analyse the coordination of the proximal joints, trunk involvement or arm and trunk coordination during reaching. Arm and trunk coordination is an important aspect of reaching, since for most reaches, the trunk is involved.

Levin and Jobin (1998) studied reaching in children with cerebral palsy (CP). They described differences in kinematic patterns between children with CP and an age-matched control group. They analysed kinematic variables such as speed of movement and smoothness of trajectory. They found that children with CP made slower reaches and had more segmented trajectories than healthy children. However, when they analysed trunk involvement (data not published), they noted that young healthy children as well as CP children used more trunk movement when they reached for a target placed within the arm's length than older healthy children and adults. Thus, the fact that CP children used more trunk movement to reach could not be regarded as being abnormal. Why young children use the trunk for reaching and when this usage diminishes were questions that the researchers could not answer.

In clinical practice scales are used to assess motor impairment in order to monitor treatment efficacy. According to Ketelaar et al., (1998) however, the majority of current scales only help to classify developmental disability but they do not provide information about the quality of movement. Knowledge about the development of coordination in reaching can be used to create a database to compare how behaviours deviate from normal and to evaluate the effects of treatment interventions on motor performance.

Aside from the benefits for clinical practice, the study of the development of reaching in children older than three years of age may clarify some questions about motor control. Konczak and Dichgans (1997), in their study of the development of reaching in the first three years of life, proposed that the acquisition of a stereotypic kinematic pattern during ontogenesis may represent the establishment of the control system. Furthermore, the developmental comparison of endpoint and proximal joint motion should clarify some hypotheses about the mechanisms underlying motor planning. According to these authors motor development is a process of continuing calibration of the motor system in the presence of neural and anthropometric growth, but the exact ways in which changes in central structures intertwine with peripheral changes are not known. Thus, the determination of which invariant behaviors result from biomechanical (peripheral) constraints, and which are the result of a neural constraints, require more experiments with older children in which reaching is made to different parts of the workspace.

To answer these questions it is necessary to study the development of reaching in children older than three years of age. In order to characterise the coordination of reaching and different segments, i.e.: between arm and trunk, it is necessary to analyse reaching to different distances that involve different degrees of trunk movement. In addition, to identify when children acquire a mature pattern of reaching, data from a group of adult controls must be used for comparison.

1.4. Objectives and Hypotheses

The continuation of studies in reaching with children aged more than three years old is necessary and important to improve the ability of clinicians to evaluate and treat children with motor impairments. It is also important to gain a better understanding of the development of motor control, in particular by identifying when children acquire mature patterns of reaching.

The general goals of this study are to characterise reaching in children older than three years old and to identify when children acquire mature patterns of reaching. The specific goals are to characterize the kinematic aspects of reaching such as the trajectory, the amount of joint excursion and the coordination among the segments and to identify at what age each kinematic variable component achieves mature characteristics when compared to adults.

We therefore studied the development of reaching using a cross-sectional design in children aged from 4 to 11 years old. They reached to three targets placed at three different distances that did or did not require trunk involvement. Movement was visually-guided and no perturbations were made. Children reached as naturally as possible. We hypothesized that children develop coordination of reaching by mastering the degrees of freedom involved in the task and that the variability of kinematic patterns decreases with age.

Chapter II: Methodology

2.1. Subjects

Thirty-eight healthy children aged from 4 to 11 years and nine healthy adults (55 ± 13.7 years) were recruited from the community to participate in this study. Parents or guardians of the children signed the information and consent form approved by the Ethics Committee of the Rehabilitation Institute of Montreal according to the declaration of Helsinki. Children were included if they had had normal motor development as investigated by a questionnaire inquiring about birth complications and the age of appearance of motor milestones. The questions were elaborated with the help of health professionals experienced with children with developmental delays. Adults were included if they had no current or previous history of orthopaedic or neurological problems affecting the arm and hand. Hand dominance was determined in adults and children over the age of 5 using a handedness questionnaire developed in house at the Montreal Neurological Institute. For younger children, we tested hand dominance by observing which hand was predominantly used when drawing a picture and reaching for an object.

Children were divided into four groups (G1 – G4) according to their age at the time of the study consisting of children aged 4 to 5, 6 to 7, 8 to 9 and 10 to 11 years, respectively. Groups 1 and 2 had nine children and G3 and G4 contained ten children. The adult participants made up Group 5 (G5), (see Table 1 in the article, chapter 3).

2.2. Experimental paradigm

The task chosen was a natural well-learned movement related to self-feeding. It involved reaching towards and grasping, using a full hand (palmer) grasp, a 3.6 cm^3 wood block adequate to the grip size in all groups of children, with the dominant hand and bringing it to the mouth area. Participants sat on an adjustable stool that had no back support. Since seat height and extent of thigh and foot support may affect reaching distance (Chari and Kirby 1986), seat height was adjusted to 100% of lower leg length which was measured from the lateral knee joint line to the floor with the participant standing. The block was placed on a table adjusted to the height of participant's elbow when the arm was alongside the body.

The block was placed in line with the midline of the body at three different distances according to the participant's arm length. Arm length was measured from the medial border of the axilla to the distal wrist crease. Placement of the targets as a function of arm length served to normalize the data for comparison between participants of different sizes. The three target distances were 2/3 (T1), 1 (T2), and 1 2/3 (T3) the length of the arm (Fig. 1A). These three increasing target distances were chosen to evaluate the relationship between segment coordination and target distance. The participants were instructed to move at a natural self-paced speed, and to take the object and bring it to the mouth region as they usually do when taking a drink of water. After two practice trials per target, reaches were initiated on the verbal cue of the experimenter. The order of targets was randomised. Twenty trials were recorded per target for a total of 60 trials per participant. Reaches began from an initial position in which the thumb was positioned 5 cm in front of the middle of the sternum, the hand was relaxed, and the elbow was adducted alongside the trunk. Reaches required extension of the elbow combined with horizontal adduction and minimal shoulder flexion. In addition, reaches to T3 required forward displacement of the trunk. The protocol for adult participants was exactly the same as that used for the children except that they only reached to T2 and T3.

2.3. Data acquisition and analysis

Kinematic data were collected using a three dimensional optical tracking system (Optotrak, Northern Digital, Model 3010) with 8 infra-red emitting diodes (IREDs) placed on the index finger (defined as the movement endpoint), thumb (tip), hand (middle of second metacarpal), wrist (ulnar styloid process), elbow (lateral epicondyle), shoulders (ipsilateral and contralateral acromion processes) and trunk (sternal notch). The movement was recorded for 3 s at a sampling rate of 100 Hz. Detailed anthropometric measures for the children were collected according to Winter (1991; Table 1).

Although the task consisted of reaching, grasping and bringing the object to the mouth, only the reach-to-grasp movement was analysed in this study. Kinetic (force plate) and electromyographic data from six muscles were also recorded, but only kinematic data are reported in this study. The kinematic variables analysed were: endpoint trajectory smoothness, trunk displacement (sternum), timing between arm and trunk movement, joint angular displacements (elbow and shoulder) and interjoint coordination (elbow and shoulder). These variables correspond to those used previously to characterize motor skill acquisition related to reaching (Cirstea and Levin 2000; Hogan and Flash 1987; Kaminski et al. 1995; Levin and Jobin 1998; Ramos et al. 1997).

Kinematic data were filtered with a low–pass cut off frequency of 10 Hz. Two and 3-dimensional endpoint and trunk trajectories were plotted from x, y and z positional data obtained from the index and sternal markers, respectively. Trajectory smoothness was determined by the index of curvature (IC) defined as the ratio of the actual length of the endpoint (index) path to the length of a straight line joining the initial and final positions. Using this measure, a straight line has an index of 1, whereas that of semi-circle has an index of 1.57 (Archambault et al. 1999). Endpoint trajectory consistency was estimated by the coefficient of variability, defined as the ratio between the standard deviation and the mean times one hundred for each subject.

Trunk displacement was measured in centimetres from the movement of the sternal marker in the sagittal plane from start position to grasp. Displacement was expressed as a percentage of the length of the endpoint path to account for differences in arm length between participants. Trunk displacement consistency was also estimated by the coefficient of variability as defined above.

Tangential velocity profiles of the endpoint and trunk were computed from the magnitude of the velocity vector, using time derivatives of the positional data for markers placed on the index finger and sternum, respectively. Movement onsets and offsets were defined as the times at which the tangential velocity surpassed or fell below 5% of the maximum peak velocity, respectively. The differences in the onset and offset times between the endpoint and trunk were computed. The threshold value of 20 ms was found to most reliably distinguish between simultaneous and sequential movements of the endpoint and trunk

(Archambault et al. 1999). Thus, only endpoint-trunk delays at movement onset or offset greater than 20 ms were considered to be significant. Negative delays for movement onset indicated that the trunk started to move before the endpoint and positive values for movement offset indicated that the trunk stopped moving later than the endpoint.

The ranges of angular motion were calculated for elbow flexion/extension and shoulder flexion/extension and shoulder horizontal adduction/abduction. The elbow flexion/extension angle was computed based on the dot product of vectors defined by the coordinates of appropriate markers placed on the wrist, elbow and shoulder. The shoulder flexion/extension angle was defined as the sagittal projection of the angle between two vectors: one defined by the markers placed on the elbow and shoulder and the other defined by the downward vertical projection from the shoulder marker. The shoulder horizontal adduction/abduction angle was measured as the horizontal projection of the angle between two vectors, one defined by the right and left shoulder markers and the other parallel to the humerus between the shoulder and markers on the moving upper arm. For each angular displacement, time series plots were aligned on their onsets. The onset of displacement was determined for each trial as the time at which the angular displacement surpassed 10% of the maximal displacement for that trial. Angle plots were averaged from between 7 and 10 trials per target without amplitude or temporal normalization and curves for the three targets were superposed. Trials were not used for averages if the child failed to complete the reach or dropped the object during the reach. This occurred in less than 2% of trials.

Interjoint coordination between the two angles, elbow and shoulder angles, was characterized qualitatively and quantitatively. Temporal and spatial interjoint coordination have been identified in previous studies as essential characteristics of reaching in this specific task (Levin 1996; Cirstea and Levin 2000). Interjoint coordination was characterized qualitatively by examination of angle/angle diagrams plotted from averaged angular displacement curves for movements to each target. Quantitative analysis consisted of 1) the determination of elbow/shoulder cross correlations at zero time lag and 2) an analysis of the combined variability of the interjoint coordination curves for reaches to all three targets. The analysis of the combined variability was done using a 'loss function' consisting of two variables: Standard Deviation of distance (SDd) and Standard Deviation of targets (SDt). The loss function can be considered as a quantitative measure of the inter- and intra-curve consistency of the three elbow-shoulder interjoint coordination curves across targets. For the SDd variable, inter-curve variability was computed as the sum of the shortest distances between each successive point on one averaged curve and all points on a second curve. This was done for each pair of curves (T1 vs T2, T1 vs T3, T2 vs T3) and the mean was computed. The second variable, SDt, measured inter-target variability. This was computed as the average of the 2D standard deviations of the mean angle/angle plots for all the reaches for the three targets.

2.4. Statistical analysis

We used two-factor (target and group) ANOVAs to determine the effect of age on the six kinematic variables identified above and on three coefficients of variability (IC, trunk displacement and interjoint correlation) when comparing data from the four groups of children. Post-hoc LSD (least significant differences) tests were used to identify the loci of significance for these analyses. Since adult data were from a different set of experiments, these were not included in the ANOVA, but data from adults and children groups were compared using separate Student t-tests. Cluster analysis was used to identify whether variability of interjoint coordination was affected by age. This analysis considered the interaction of the two components of the variability measure (SDd and SDt). The data formed two clusters within the lower and higher boundaries of the 'variability space' formed by plotting SDd against SDt. The frequencies with which members of each age group occurred in each cluster were then calculated.

Chapter III. Article

The development of coordination for reach-to-grasp movements in children

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Abstract

When adults reach to grasp stationary targets, movement kinematics (endpoint trajectories, interjoint coordination) are highly stereotyped and stable. The emergence of an optimal coordination for reaching involves mastering the redundant number of degrees of freedom while the body grows. Reaching has been well studied in healthy children under the age of 3 years. We characterized the development of coordination during reaching in children over the age of 3 years and identified age ranges in which stable patterns emerge. A random sample of 38 healthy children aged 4-11 years and 9 adults participated in the study. They reached from the seated position with the dominant arm and grasped a cone placed at three distances in the forward sagittal plane in front of the body. Kinematic data from markers placed on the arm, head and trunk were recorded at 100 Hz (Optotrak Motion Analysis System). Immature patterns of reaching were characterized by increased variability in younger compared to older children. Hand trajectories became smoother and less variable with age. Interjoint coordination became more consistent, while trunk displacement and variability decreased with age. Only children between 8 and 10 years old had variability similar to adults. Our data suggest that different aspects of movement kinematics mature at different rates. However, our data do not support the idea of a sequential maturation of different biomechanical variables.

Keywords:

Maturation, Motor control, Development, Children, Reaching movement

Introduction

Performance stability and adaptability in response to changing intrinsic and extrinsic conditions are major features in the development of skilled actions throughout the lifespan. An action is considered as being 'learned' when the end result of that action is successful even when environmental conditions are changed. Three approaches to the development of skilled actions have been proposed. In the developmental approach, motor skill acquisition is considered to be a consequence of the maturation of the nervous system and is essentially driven by intrinsic changes in the organism (Gesell 1945, 1946). In the information processing approach, a further emphasis is placed on the interaction of the developing nervous system with newly emerging cognitive processes and the changing properties of the environment (Connolly 1970; Kay 1970). In the dynamic systems approach, the acquisition of new motor skills is driven equally by the developing nervous system and it's interactions with perceptual processes and the environment (Bernstein 1967; Gibson 1966; 1979; Thelen 1988). In the latter approach, the formation of new motor skills is a result of the interaction between these three elements: nervous system maturation, emerging cognitive processes and changing properties of the environment.

The hallmark of dynamical approaches to motor skill acquisition is that variability in performance is an essential characteristic of development. Variability may represent an intermediate state in which the nervous system is in the process of organizing the coordinated control of a large number of degrees of freedom. Motor skill acquisition has been postulated to represent the transition from a state of low organization to one of greater order and stability associated with mastering excessive degrees of freedom (Bernstein 1967; Kugler 1986). Such a state would be characterized by a reduction in performance variability. In the framework of the dynamical systems approach, it has also been suggested that motor development is coupled with the ability to organize and manage different spatial frames of reference for actions in relation to the environment or the body (Feldman and Levin 1995).

The development of reaching and manipulative skills emerges progressively throughout early infancy and childhood, although there are some aspects of reaching that are thought to be innate. For example, the abilities to locate objects in space and to transport the arm are present in a rudimentary form at birth (von Hofsten 1979; 1982). Early reaching attempts, however, are neither precise nor smooth. The first change in reaching occurs by 2 months of age, at which time, infants make arm movements outside of the innate extension synergy and they begin to extend their arm and flex their fingers at the same time. By the age of four months, infants gain more trunk stability and strength in the neck muscles and as a result, reaching becomes more accurate but is still segmented. By the age of 6 months, the amount of segmentation during reaching decreases and accuracy increases. However, reaching dynamics remain different from those in adults. Other aspects of reaching, such as grasping, develop later (6-9 months) in the first year of life (Shumway-Cook and Woollacott 1995).

The precise characterization of reaching and grasping during early and middle childhood has been largely ignored (but see Levin and Jobin, 1998). The majority of research in reaching ability in healthy children has been done in children under the age of 3 years. These studies have focussed on the analysis of movement time, movement segmentation, hand trajectories, temporal aspects of interjoint coordination, head-hand coordination and joint torque (Konczak et al.

1995; 1997; Savelsbergh et al. 1997; Thelen and Smith 1994). Little is known about other elements such as spatial interjoint coordination as described in adults (Cirstea and Levin 2000; Levin 1996), postural adjustments during reaching (Stapley et al. 1998) and the age beyond 3 years by which mature kinematic patterns are acquired. Able-bodied children acquire the ability to co-regulate trunk and arm movements for functional activities over the first 10 years of life and evidence suggests that a developmental transition period occurs between the ages of 4 to 7 years (Dellen and Kalverboer 1984; Hay 1990; Schellekens et al. 1984). Maturation in descending motor tracts may partially explain the development of skilled reaching in childhood. Specifically, changes in the conduction velocity of the corticospinal tract parallels the gradual improvements in motor skills (Forssberg et al. 1991; Lemon et al. 1997; Müller and Hömberg 1992).

To address the issue of when children acquire mature patterns of reaching, the present study was designed to describe the evolution of the coordination of reaching capabilities over the period of early childhood with a particular emphasis on performance variability. Some results of this study have appeared in abstract form (Schneiberg et al. 2000).

Materials and methods

Subjects

Thirty-eight healthy children aged from 4 to 11 years and nine healthy adults (55 ± 13.7 years) were recruited from the community to participate in this study. Parents or guardians of the children signed the information and consent form approved by the Ethics Committee of the Rehabilitation Institute of Montreal according to the declaration of Helsinki. Children were included if they had had normal motor development as investigated by a questionnaire inquiring about birth complications and the age of appearance of motor milestones. The questions were elaborated with the help of health professionals experienced in developmental delays. Adults were included if they had no current or previous history of orthopaedic or neurological problems affecting the arm and hand. Hand dominance was determined in adults and children over the age of 5 using a handedness questionnaire developed at the Montreal Neurological Institute. For younger children, we tested hand dominance by observing which hand was predominantly used when drawing a picture and reaching for an object.

Children were divided into four groups (G1 – G4) according to their age at the time of the study consisting of children aged 4 to 5, 6 to 7, 8 to 9 and 10 to 11 years respectively. Groups 1 and 2 had nine children and G3 and G4 contained ten children (Table 1). The adult participants made up Group 5 (G5).

Experimental paradigm

The task chosen was a natural well-learned movement related to self-feeding. It involved reaching towards and grasping, using a full hand (palmer) grasp, a 3.6 cm^3 wood block adequate to the grip size in all groups of children, with the dominant hand and bringing it to the mouth area. Participants sat on an adjustable stool that had no back support. Since seat height and extent of thigh and foot support may affect reaching distance (Chari and Kirby 1986), seat height was adjusted to 100% of lower leg length which was measured from the lateral knee joint line to the floor with the participant standing. Two-thirds of the length of the thigh was supported on the seat. The block was placed on a table adjusted to the height of participant's elbow when the arm was alongside the body.

Table 1. Anthropomorphic and demographic data for children and adults

Groups	*Age (yrs)*	*Sex* M/F	*Height (m)* (SD)	*Weight (Kg)* (SD)	Trunk/arm length ratio
G1	*4 – 5*	4/5	1.06 (0.04)	44.4 (5.76)	0.76 (0.10)
G2	6 – 7	5/4	1.2 (0.06)	49.5 (8.88)	0.79 (0.08)
G3	8 – 9	5/5	1.3 (0.08)	63.5 (15.86)	0.83 (0.05)
G4	10 – 11	5/5	1.4 (0.05)	92.2 (25.57)	0.88 (0.07)
G5 Mean (SD)	27 - 60 55 (13.7)	5/4			

The block was placed in line with the midline of the body at three different distances according to the participant's arm length. Arm length was measured from the medial border of the axilla to the distal wrist crease. Placement of the targets as a function of arm length served to normalize the data for comparison between participants of different sizes. The three target distances were 2/3 (T1), 1 (T2), and 1 2/3 (T3) the length of the arm (Fig. 1). These three increasing target distances were chosen to evaluate the relationship between segment coordination and target distance. The participants were instructed to move at a natural self-paced speed, and to take the object and bring it to the mouth region as they usually do when taking a drink of water. After two practice trials per target, reaches were initiated on the verbal cue of the experimenter. The order of targets was randomised. Ten trials were recorded per target for a total of 30 trials per participant. Reaches began from an initial position in which the thumb was positioned 5 cm in front of the middle of the sternum, the hand was relaxed, and the elbow was adducted alongside the trunk. Reaches required extension of the elbow combined with horizontal adduction (the movement that brings the arm from the abducted position towards and across the midline) and minimal shoulder flexion. In addition, reaches to T3 required forward displacement of the trunk. The protocol for adult participants was exactly the same as that used for the children except that they only reached to T2 and T3.

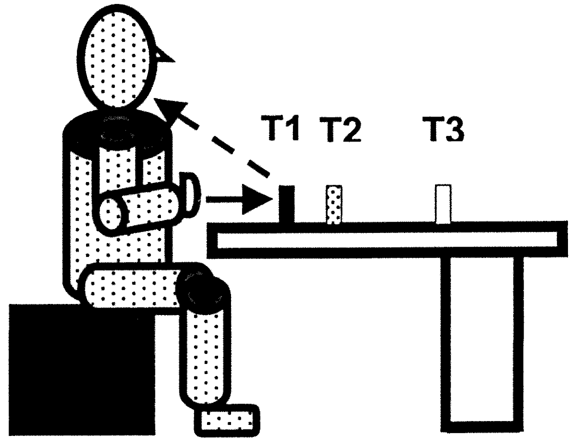

Fig. 1. Schematic diagram of the experimental set up. Targets were placed at arm's length (T2), 2/3 arm's length (T1) and 1 2/3 arm's length (T3). The action was to reach and grasp the object and bring it to the mouth. Only the reach-to-grasp movement was analysed (thick arrow).

Data acquisition and analysis

Kinematic data were collected using a three dimensional optical tracking system (Optotrak, Northern Digital, Model 3010) with 8 infra-red emitting diodes (IREDs) placed on the index finger (defined as the movement endpoint), thumb (tip), hand (middle of second metacarpal), wrist (ulnar styloid process), elbow (lateral epicondyle), shoulders (ipsilateral and contralateral acromion processes) and trunk (sternal notch). The movement was recorded for 3 s at a sampling rate of 100 Hz. Detailed anthropometric measures for the children were collected according to Winter (1991; Table 1).

Although the task consisted of reaching, grasping and bringing the object to the mouth, only the reach-to-grasp movement was analysed in this study. The kinematic variables analysed were: endpoint trajectory smoothness, trunk displacement (sternum), timing between arm and trunk movement, joint angular displacements (elbow and shoulder) and interjoint coordination (elbow and shoulder). These variables correspond to those used previously to characterize motor skill acquisition related to reaching (Cirstea and Levin 2000; Hogan and Flash 1987; Kaminski et al. 1995; Levin and Jobin 1998; Ramos et al. 1997).

Kinematic data were filtered with a low–pass cut off frequency of 10 Hz. Two and 3- dimensional endpoint and trunk trajectories were plotted from x, y and z positional data obtained from the index and sternal markers respectively. Trajectory smoothness was determined by the index of curvature (IC) defined as the ratio of the actual length of the endpoint (index) path to the length of a straight line joining the initial and final positions. Using this measure, a straight line has an index of 1 whereas that of semi-circle has an index of 1.57 (Archambault et al. 1999). Endpoint trajectory consistency was estimated by the coefficient of variability, defined as the ratio between the standard deviation and the mean times one hundred for each subject.

Trunk displacement was measured in centimetres from the movement of the sternal marker in the sagittal plane from start position to grasp. Displacement was expressed as a percentage of the length of the endpoint path to account for differences in arm length between participants. Trunk displacement consistency was also estimated by the coefficient of variability as defined above.

Tangential velocity profiles of the endpoint and trunk were computed from the magnitude of the velocity vector, using time derivatives of the positional data for markers placed on the index finger and sternum, respectively. Movement onsets and offsets were defined as the times at which the tangential velocity surpassed or fell below 5% of the maximum peak velocity respectively. The differences in the onset and offset times between the endpoint and trunk were computed. The threshold value of 20 ms was found to most reliably distinguish between simultaneous and sequential movements of the endpoint and trunk (Archambault et al. 1999). Thus, only endpoint-trunk delays at movement onset or offset greater than 20 ms were considered to be significant. Negative delays for movement onset indicated that the trunk started to move before the endpoint and positive values for movement offset indicated that the trunk stopped moving later than the endpoint.

The ranges of angular motion were calculated for elbow and shoulder flexion/extension and shoulder horizontal adduction/abduction. The elbow flexion/extension angle was computed based on the dot product of vectors defined by the coordinates of appropriate markers placed on the wrist, elbow and shoulder. The shoulder flexion/extension angle was defined as the angle between the sagittal projection of arm and vertical. The shoulder horizontal adduction/abduction angle was measured as the horizontal projection of the angle between two vectors, one defined by the right and left shoulder markers and the other parallel to the humerus between the shoulder and markers on the moving upper arm. For each angular displacement, time series plots were aligned on their onsets. The onset of displacement was determined for each trial as the time at which the angular displacement surpassed 10% of the maximal displacement for that trial. Angle plots were averaged for between 7 and 10 trials per target without amplitude or temporal normalization and curves for the three targets were superposed. Trials were not used for averages if the child failed to complete the reach or dropped the object during the reach. This occurred in less than 2% of trials.

Interjoint coordination between elbow and shoulder angles was characterized qualitatively and quantitatively. Temporal and spatial interjoint coordination have been identified in previous studies as essential characteristics of reaching in this specific task (Levin 1996; Cirstea and Levin 2000). Interjoint coordination was characterized qualitatively by examination of angle/angle diagrams plotted from averaged angular displacement curves for movements to each target. Quantitative analysis consisted of 1) the determination of elbow/shoulder cross correlations at zero time lag and 2) an analysis of the combined variability of the interjoint coordination curves for reaches to all three targets. The analysis of the combined variability was done using a 'loss function' consisting of two variables: Standard Deviation of distance (SDd) and Standard Deviation of targets (SDt). The loss function can be considered as a quantitative measure of the inter- and intra-curve consistency of the three elbow-shoulder interjoint coordination curves across targets. For the SDd variable, inter-curve variability was computed as the sum of the shortest distances between the each successive point on one averaged curve and all points on a second curve. This was done for each pair of curves (T1 vs T2, T1 vs T3, T2 vs T3) and the mean was computed. The second variable, SDt, measured inter-target variability. This was computed as the average of the 2D standard deviations of the mean angle/angle plots for all the reaches for the three targets.

Statistical analysis

We used two-factor (target and group) ANOVAs to determine the effect of age on the six kinematic variables identified above and on three coefficients of variability (IC, trunk displacement and interjoint correlation) when comparing data from the four groups of children. Post-hoc LSD (least significant differences) tests were used to identify the loci of significance for these analyses. Since adult data were from a different set of experiments, these were not included in the ANOVA but data from adults and children groups were compared using separate Student t-tests. Cluster analysis was used to identify whether variability of interjoint coordination was affected by age. This analysis considered the interaction of the two components of the variability measure (SDd and SDt). The data formed two clusters within the lower and higher boundaries of the 'variability space' formed by plotting SDd against SDt. The frequencies with which members of each age group occurred in each cluster were then calculated.

Results

Straightness, smoothness and variability of endpoint trajectories

In all participants, reaches to closer targets were made with curved trajectories such that, at the time of grasping, the hand was moving in the transverse plane. The forearm remained in the 0^{o} position (thumb upward) throughout the reach. To reach targets placed more distally, trajectories were straighter and the hand was oriented more sagittally. The youngest group of children generally produced endpoint trajectories that were more curved and less smooth than in older children and adults for reaches to all three targets (Fig. 2).

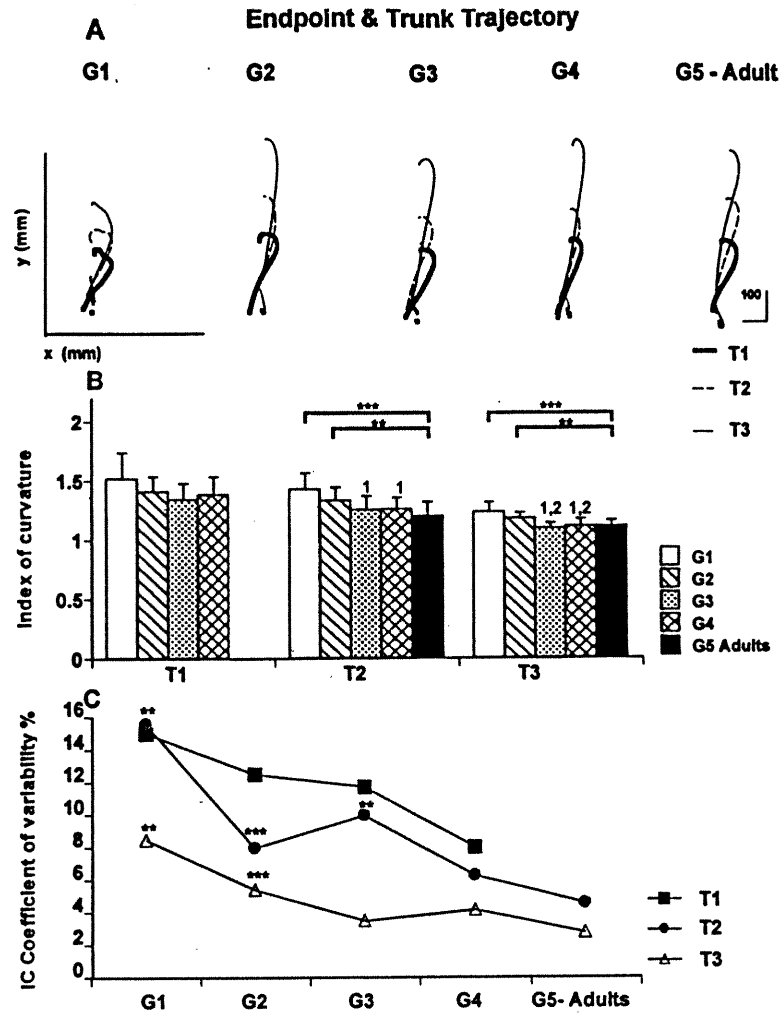

Fig. 2. A) Mean endpoint (hand) trajectories to close (T1, thick traces), middle (T2, thick dashed traces) and far targets (T3, thin traces) for one representative child in each age group (G1- G4) and for T2 and T3 in one representative adult subject. Corresponding trunk trajectories are also shown. B) Mean (SD) endpoint path straightness (Index of Curvature) data for each child group shown for reaches to 3 targets (T1, T2, T3) and for the adult group for T2 and T3 (black bars). Statistical significance between adult and children's groups shown by horizontal lines above bars for T2 and T3. Significant differences between children's groups indicated by numbers above individual bars. For T2, number 1 above third and fourth bars indicates that these means were significantly different from group 1. For T3, numbers 1 and 2 above third and fourth bars indicate that these means were significantly different from groups 1 and 2. C) Coefficient of variability of Index of curvature for each group for three targets. Asterisks indicate that the group mean differed from the adult group mean. ** $p < 0.01$; *** $p < 0.001$.

Endpoint trajectories became straighter with increasing target distance for all age groups (IC, $F_{2,114} = 35.12$, target effect $p < 0.001$). An age effect of trajectory straightness was also observed for T2 and T3 (ANOVA $F_{3,35} = 4.46$, $p < 0.01$ for T2 and $F_{3,35} = 8.73$, $p < 0.000$ for T3; Fig. 2B). For both these targets, post-hoc comparisons of ICs for each group of children revealed differences between G1 and G3-G4 for T2 and T3, and G2 and G3-G4 for T3 only (denoted by numbers on Fig. 2B). T-tests between G5 (adults) and childrens' groups indicated that ICs differed from adults for groups G1 and G2 for both T2 and T3.

In all age groups, curvature variability decreased with target distance (one-way ANOVA, $F_{2,114} = 11.34$, factor = target, $p < 0.000$) In addition, the variability in endpoint trajectories was highest for the youngest group and decreased with age. This difference was significant for T2 and T3 but not for T1 (ANOVA, $F_{3,35} = 3.21$, $p < 0.05$ for T2; Fig. 2C). Trajectory variability for T2 only attained similar values to those seen in adults and in children aged 10-11 (G4). For T3, variability decreased and attained adult levels at a younger age (age 8-9, G3; Fig. 2C).

As compared to younger children, velocity profiles of the endpoint and trunk for all three targets tended to be smoother in older children (Fig. 3) and resembled those of adults. The mean number of peaks in the endpoint tangential velocity was calculated for the children for reaches to T 1-3, and for adults for T2 and T3 only (Fig. 3B). There was a tendency for the number of peaks to decrease with age for all targets but this difference was not significant. Compared to adults, the number of peaks was significantly greater only in G1 for T2 and in G1 and G2 for T3.

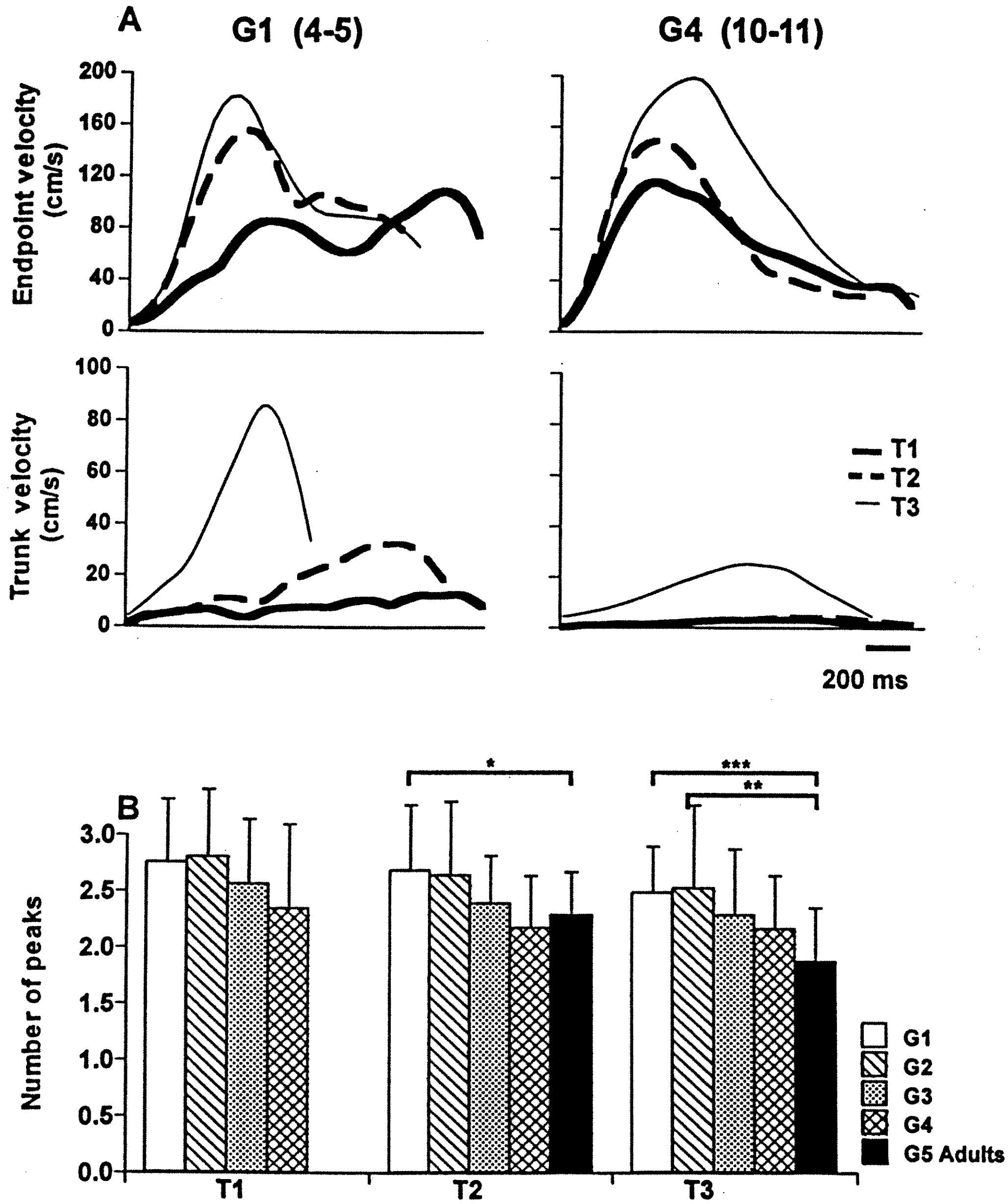

Fig. 3. A) Mean endpoint and trunk velocities for movements to Target 1 (thick line), Target 2 (thick dashed line) and Target 3 (thin line) for representative children in groups 1 (G1) and 4 (G4). B) Mean (SD) number of peaks in the endpoint velocity traces for each group. Groups and significance indicated as in Fig. 2. * $p < 0.05$

Use of elbow and shoulder joint rotations and trunk displacement for reaching

The total range of elbow extension increased with target distance for all groups (ANOVA, $F_{3,37}$ = 87.27, factor target, $p < 0.000$) but did not differ according to age nor in comparison with values in the adult group (Fig. 4 A,B). Since the arm was in an abducted position, requiring mostly horizontal adduction to reach forward, there was minimal pure shoulder flexion (about 15°) and this angle did not vary with age or target (ANOVA $F_{3, 37}$=.489 to 1.514, $p = 0.22$ to 0.69). Thus, shoulder flexion was not analysed further. The range of shoulder adduction also did not vary with age for T1 and T2 but increased with age for T3 (ANOVA $F_{3,38}$ = 6.55, $p < 0.001$, post hoc G1 and 2 < G3 and G4). After the age of six, the range of shoulder adduction used by the children was similar to that in the adult group for T2 while for T3, the range was similar to adults in children over the age of 8. (Fig. 4C).

For closely placed targets (T1, T2) not normally requiring trunk displacement, the youngest children used significant trunk recruitment (Fig. 5). For T1, the amount of trunk displacement used by G1 was almost twice that used by G2-4 (ANOVA, $F_{3,38}$ = 3.38, $p < 0.05$). For the target placed at the length of arm extension (T2), an interesting relationship was observed between age and trunk displacement. Trunk recruitment scaled with age (ANOVA $F_{3,38}$ = 4.98, $p < 0.01$, post hoc G1 > G3 and G4; G2 > G4). The amount of trunk movement used was not different from adults by the age of 10-11 for T2. On the other hand, trunk

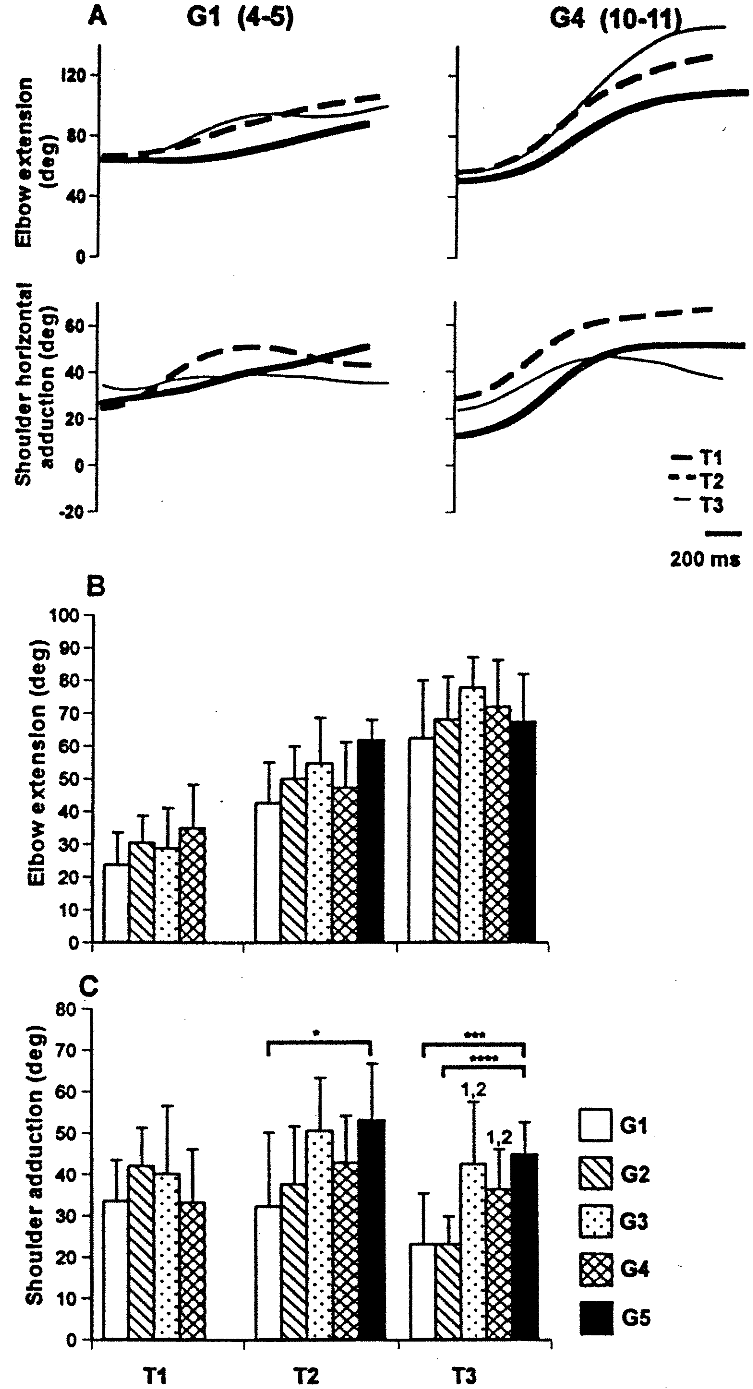

Fig. 4. A) Mean angular displacements of elbow extension (top) and shoulder horizontal adduction (bottom) for same two subjects shown in Fig. 3. Mean (SD) displacements for each group and target are shown for elbow extension in B) and shoulder adduction in C). Groups and significance indicated as in Fig. 2. **** $p < 0.0001$

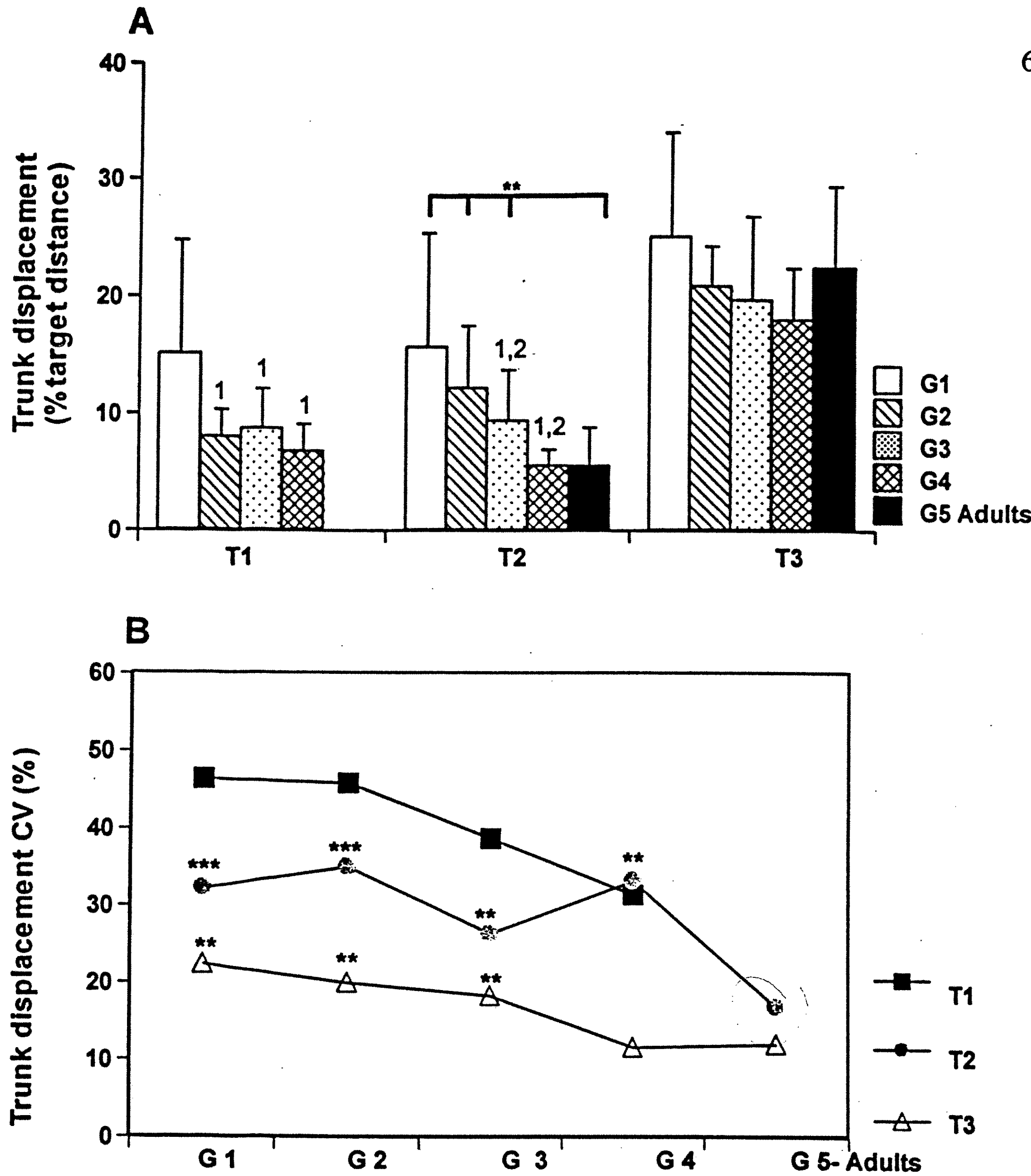

Fig. 5. A) Mean (SD) trunk displacement for all groups and targets expressed as a percentage of target distance. B) Coefficient of variation of trunk displacement for each group and target. Groups and significance are indicated as in Fig. 2.

displacement was necessary to reach T3 and there was no difference in trunk usage between groups for this target (Fig. 5A).

The variability in trunk use was significantly higher in all childrens' groups compared to adults for T2 (t-tests, $p < 0.01$-0.001) and up to age 8-9 for T3 (t-tests, $p < 0.01$) while a similar comparison was not possible for T1. On the other hand, the variability was consistently high within all children's groups for the three targets without significant differences (Fig. 5B).

Development of interjoint coordination pattern occurs with age

Interjoint coordination (IJ) between shoulder adduction and elbow extension movements was analysed. The degree of overlap in IJ patterns between these two movements for the three targets increased with age, such that more variability or less consistency of the three patterns was observed in younger children (Fig. 6A).

Temporal and spatial coupling between movements of the elbow (extension) and shoulder (horizontal adduction) were analyzed separately. Temporal coupling, measured by cross correlation analysis between the elbow and shoulder, was greater than $r = 0.80$ for all targets in all age groups and did not vary with age for any of the three targets (Fig. 6B). In general, coupling was higher for reaches to the closer two targets than for T3 (ANOVA, $F_{2,105} = 12.22$ target effect, $p < 0.000$). For this target, differences in coupling were seen in G1 and G4 as compared to the adult group (t-tests, $p < 0.01$). Thus, for T3, the angles were less temporally coupled than for T1 and T2.

There was no age effect on the variability of the cross correlation coefficient (ANOVA (T1) $p = 0.40$, (T2) $p = 0.33$, (T3) $p = 0.86$; Fig 6C). However, the variability in the cross correlation coefficient was higher in all children compared to the adults for reaches to T2 and T3 (t-tests, $p < 0.05$ to 0.01).

To analyse the spatial variability of interjoint correlation throughout the reach, we examined the degree of overlap between the IJ patterns of reaches to the three targets (SDd measure) and their total inter-trial variability across targets (SDt measure). High values of both measures reflected inconsistency in IJ patterns. For both measures, younger children (G1 and G2) had higher SDd and SDt values than G4 (t-test; $p< 0.05$, Fig. 7A,B). To determine at what age children started to optimize the IJ coordination pattern across the targets, data were compared to the adult group. Significant differences were found between the adult group and childrens' groups G1 and G2 for the SDd measure (t-test, $p < 0.05$; Fig. 7A) and for all childrens' groups for the SDt measure (t-test, $p< 0.001$; Fig. 7B).

Cluster analysis revealed that the data could be divided into two clusters (Fig. 8). Cluster 1 was composed of 24 points, the majority of which was obtained from children less than 8 years old (approximately 67% of the total number). This cluster was characterized by higher values of SDd and SDt representing more variability in IJ coordination. In contrast, Cluster 2 consisted of 23 points representing low IJ variability. Seventy-five percent of this cluster was composed of points obtained from older children (10-11 yrs) and adults. Data from children aged 8-9 (G3) were more equally distributed between the two Clusters.

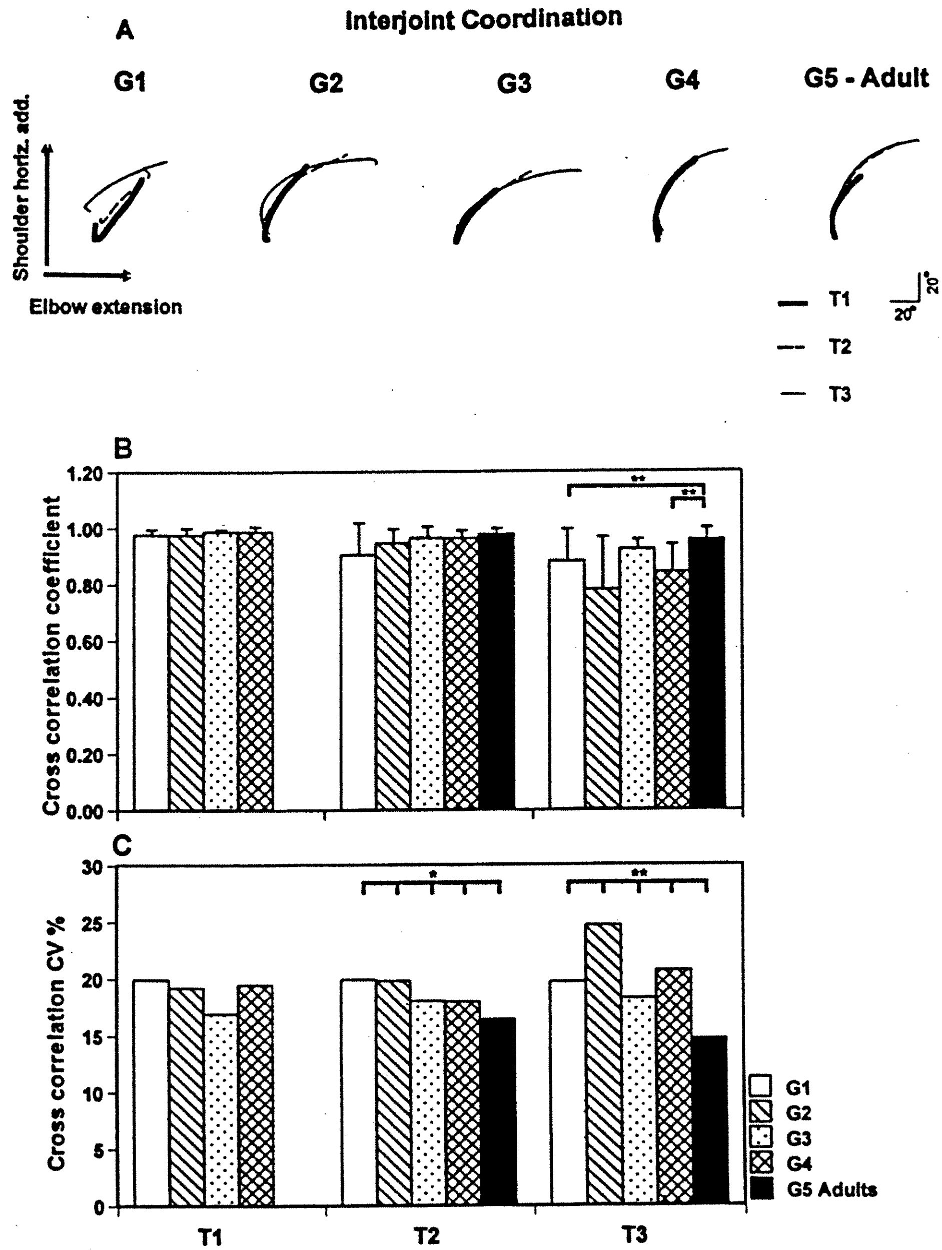

Fig. 6. A) Mean interjoint coordination between shoulder horizontal adduction and elbow extension for the same representative subjects in each group as shown in Fig. 2. Thick line (Target 1), dashed line (Target 2), thin line (Target 3). Mean (SD) coefficients of correlation (B) and variability of correlation (coefficient of variability; C) for each group and target. Groups and significance indicated as in Fig. 2.

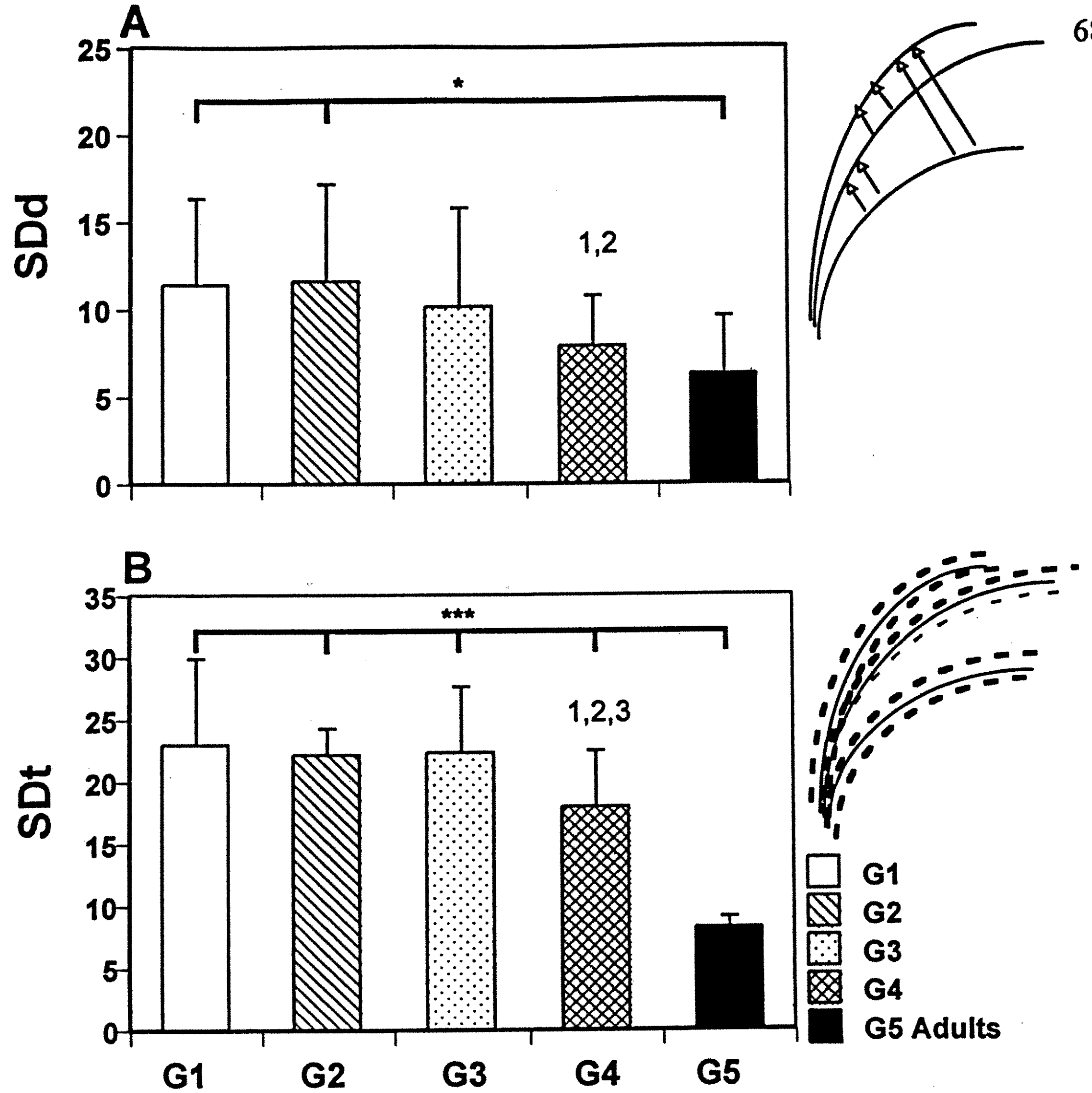

Fig.7. Mean (SD) inter-target (SDd, A) and intra-target (SDt, B) variability of elbow-shoulder interjoint coordination for each group. Variabilities are summed across targets. SDd is a measure of the distance between mean coordination patterns (inset A) and SDt sums the variability of movements to each target (inset B).

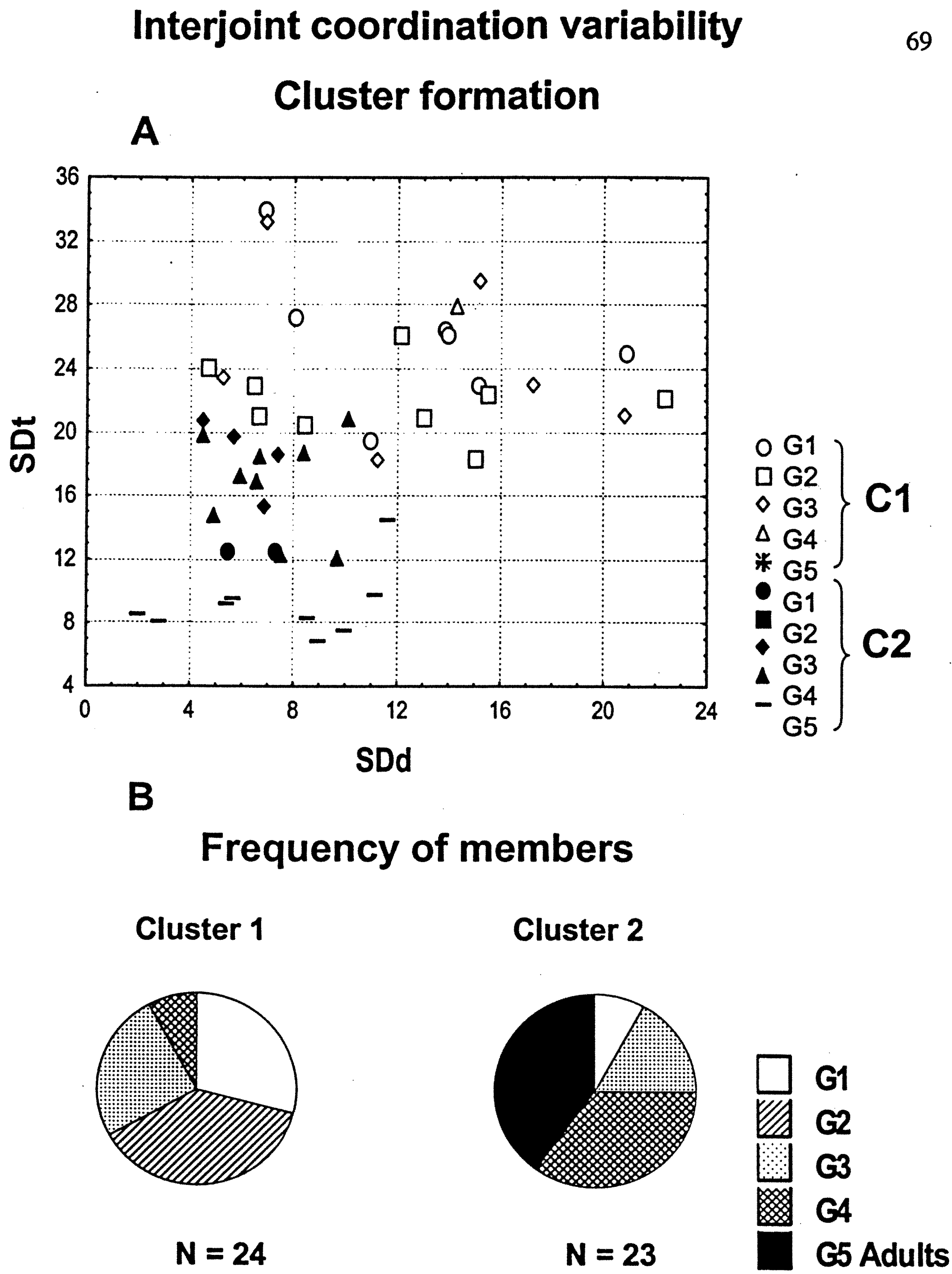

Fig. 8. Results of cluster analysis of interjoint coordination variability. A) shows the cluster formation considering the interaction of the two components (inter-target, SDd and intra-target, SDt variability). B) Distribution of children and adults in each cluster.

Temporal arm-trunk coordination

We analysed the temporal coordination between trunk and endpoint for T2 and T3, when trunk involvement was present in all groups of children. Similar to adults at the onset of reach, all the children started to move the trunk before the endpoint and at the offset they stopped moving the trunk after the endpoint had stopped. This sequence was well organized without any significant differences across the groups (Fig. 9).

Discussion

We described the development of coordination for sagittal reach-to-grasp movements in young children and identified when adult-like kinematic patterns were acquired. In order to characterize coordination between different limb and trunk segments during reaching, we asked the children to reach to different distances from the body, such that the first two targets did not, and the third did require trunk displacement.

We evaluated movement variables reflecting several aspects of reaching kinematics characterizing motor execution. These variables were grouped into four catagories: those characterizing endpoint trajectory, joint excursions, trunk involvement and coordination (Table 2). To facilitate discussion, age-related differences for each variable are summarized according to target distance. The table also shows at what age mature patterns emerge for each movement variable based on a comparison with healthy adults.

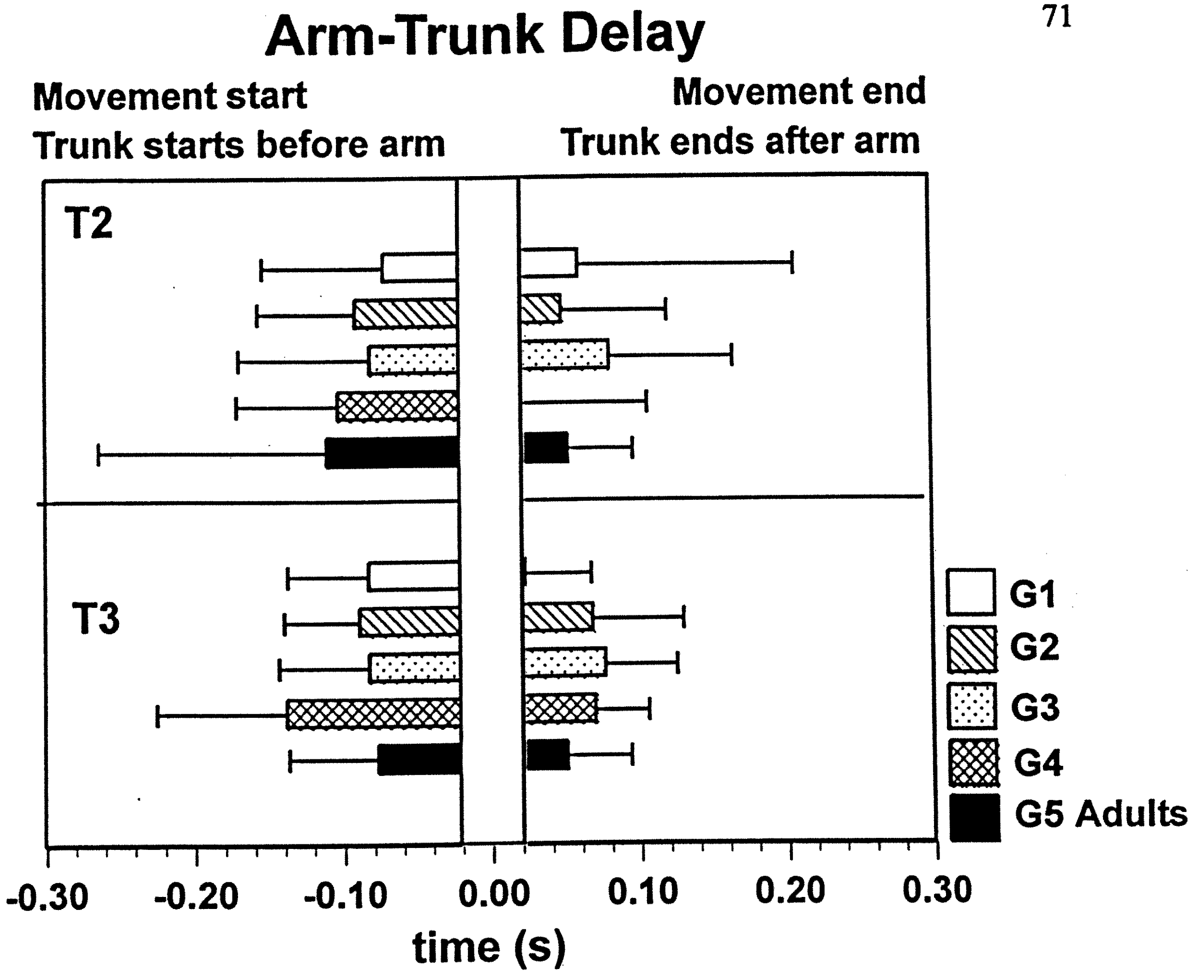

Fig. 9. Temporal arm-trunk coordination for reaches to Targets 2 (T2) and 3 (T3) in four children's groups and one adult group. Horizontal bars to the left indicate that the trunk started moving before the arm at the beginning of the reach. Horizontal bars to the right show that the trunk stopped moving after the arm at the end of the reach. Delays were considered significant if the difference between arm and trunk onset surpassed +/- 20 ms (indicated by the centre white section).

Table 2. Summary of Results, X indicates presence of the effect. Age of acquisition and older ages are filled in black. X* indicates that the age at which mature patterns emerge is less than 4 years old. T1, Target 1; T2, Target 2; T3, Target 3.

Variable Measured	Presence of differences due to age			Age of appearance of mature pattern									
	T1	T2	T3	T2					T3				
Age group (yrs)				4-5	6-7	8-9	10-11	>11	4-5	6-7	8-9	10-11	>11
I. Endpoint Trajectory													
Straightness		X	X			X					X		
- variability		X	X				X				X		
Smoothness					X						X		
II. Joint Excursions													
Elbow ext				X*					X*				
Shoulder add			X		X						X		
III. Trunk Involvement													
Displacement	X	X					X		X*				
- variability								X				X	
- timing				X					X				
IV. Interjoint Coordination													
Cross-correlation				X									X
- variability								X					X
SDd		X				X					X		
SDt		X						X					X

Our data suggest that different aspects of movement kinematics mature at different rates. This is consistent with other studies measuring the maturation of different arm and handtasks in children. Depending on the task studied, the attainment of mature movement patterns or behaviours is reported to occur around age 8 for the coordination of grip and load forces during precision lifting (Forssberg et al. 1991; Kuhtz-Buschbeck et al. 1998), age 10 for postural control (Dietz 1992; Shumway-Cook and Woollacott 1985) and age 12 for rapid repetitive hand motions (Müller and Hömberg 1992). However, no study to date has made a detailed quantification of kinematics pertaining to reach-to-grasp movements in children over 3 years old. Our analysis of the change in kinematic variables with age suggests that the maturation of some features of movement (joint excursions, timing of arm and trunk recruitment) generally occurs before others and that the differences depend on the amount of upper body movement involved in the task. Stated in other terms, our results suggest that movements requiring the coordination of a greater number of degrees of freedom take longer to mature.

Endpoint trajectories

Spatio-temporal features of endpoint trajectories in reach-to-grasp movements have been studied in Konczak et al. (1995) and Konczak and Dichgans (1997). They demonstrated that for targets located close to the body, endpoint trajectory straightness increased dramatically over the first 9 months of age and then had a slower time course of improvement. By the age of 3 years, there was still a significant difference in path straightness compared to adult trajectories.

Although improvements in endpoint straightness were somewhat less dramatic in our sample of older children, our data nevertheless show continued improvements in trajectory straightness with age in agreement with Kuhtz-Buschbeck et al. (1998). Endpoint trajectories become straighter with age such that children younger than 7 years old had more curved trajectories than older children and adults for T2 and T3. At the same time, all children preserved the tendency to decrease trajectory curvature with target distance, as in adults (Roby-Brami et al. 1997; Michaelsen et al. 2001). Trajectory curvature is related to the final configuration of the hand for grasping, the hand being more frontally oriented and involving more lateral movement for closer targets and being more sagittally oriented and requiring more planar movement for farther targets (Roby-Brami et al. 1997). Previous studies in adults suggest that endpoint trajectories for grasping are planned in terms of the initial position of the hand and the configuration and placement of the object to be grasped (de Guzman et al. 1997). The spatial coordinates of target location and orientation are transmitted via visual signals to areas of the parietal and frontal cortices. In these brain areas, visual and other sensory signals are then integrated and movements are planned within spatial frames of reference or systems of coordinates (Paillard 1991; Soechting and Flanders 1992; Feldman and Levin 1995; Andersen et al. 1997; for review see Burnod et al. 1999).

It has been suggested that reaching movements are planned within task-specific frames of reference associated with external space (Soechting and Flanders 1992; McIntyre et al. 1998; Ghafouri et al. 2002). The origin of the reference frames may be shoulder- (Soechting and Flanders 1989), head- (Flanders et al. 1992) or eye-centered (Medentorp et al. 1999) depending on the task.

According to Feldman and Levin (1995) and Ghafouri et al. (2002), active movements result from shifts in the origin of appropriate spatial frames of reference. They also argued that rather than being associated with a particular point on the body, the origin of the reference frame used for pointing is a particular (referent) configuration of the whole body to which the current, actual body configurations are compared. In a previous study in children ranging from 5 – 36 months of age, Konczak and Dichgans (1997) suggested that vertical reaches may be planned in a shoulder-centered frame of reference since only shoulder but not elbow joint paths decreased in length and variability during development. Our data cannot be directly compared to those of Konczak and Dichgans (1997) since our task involved reaching in a horizontal rather than vertical direction. Indeed, our reaching task required less than half the shoulder flexion amplitude used in their study.

If one assumes that a stereotypic kinematic response is a sign of an established control system, the fact that one variable becomes stable or consistent before another may mean that the nervous system prioritizes the control of this variable. In our task, trajectory variability decreases earlier than interjoint coordination (age of 8-9 compared to age 11 or older), supporting the hypothesis that movements are planned in end-effector rather than joint-space (Morasso 1981; Abend et al. 1982; Georgopoulos et al. 1982; Flash and Hogan 1985). The differences in results between horizontal reaching in our study and vertical reaching in that of Konczak and Dichgans (1997) also supports the idea of task-specific frames of reference. The issue of the origin of the frame of reference for reaching would be better addressed in a study in which target location and distance in the external workspace are systematically varied requiring different combinations of elbow and shoulder joint movements.

Joint excursions and trunk involvement

By the age of 4, children used the same proportion of elbow extension as adults for reaching to close and far targets. This was also true for the amount of trunk excursion when reaching towards the distant target. Also for the distant target, when trunk recruitment was necessary, the pattern of temporal coordination of arm and trunk recruitment was already similar to that observed in adults reaching to targets beyond the reach (Kaminski et al. 1995; Wang and Stelmach 2001). The presence of a mature pattern of temporal coordination of arm and trunk movement by age 4 is consistent with previous studies on the emergence of feedforward control in young children. Anticipatory control strategies are reportedly present in 4-year-old children during bimanual load-lifting tasks (Schmitz et al. 1999), the production of isometric forces for precision grip (Forssberg et al. 1992) and during posturokinetic tasks (Haas et al. 1989; Hay and Redon 1999; 2001; Assaiante et al. 2000). Although patterns may be *acquired* by this age, further *refinements* in anticipatory postural adjustments occur during childhood for tasks such as jumping (McKinley and Pelland 1994), obstacle avoidance during locomotion (McFadyen et al. 2001) and forearm stabilization and timing of muscle activation during bi-manual unloading (Schmitz et al. 2002). Thus, our finding of the acquisition of an adult-like timing in arm and trunk recruitment during reaching by age 4 does not preclude the possibility that further refinements take place during development in other movement elements not measured in this study such as the timing of agonist and antagonist muscle activation or coactivation.

Although elbow and shoulder joint kinematics and temporal coordination between reach and grasp have been investigated in other studies (e.g. Konczak and Dichgans 1997; Konczak et al. 1997, Kuhtz-Buschbeck et al. 1998), the characteristics of arm-trunk coordination have not been previously described in children. Our results showed that for more closely located targets, younger children used excessive trunk displacement and this tendency continued up until the age of 10, remaining more variable than in adults even after this age. In healthy adults, the target distance at which the trunk is recruited into the reaching strategy corresponds to a distance equal to approximately 90% of the length of the arm (Mark et al. 1997). This target distance was reduced in children up to age 10. It has been suggested that, for reaching, arm and trunk motions are governed by different neuromotor synergies (Ma and Feldman 1995; Saling et al. 1996; Wang and Stelmach 1998; Kaminiski et al. 1995). Ma and Feldman (1995) demonstrated that when moving the trunk while reaching to objects placed within the anatomical limits of the arm, the addition of trunk motion did not affect the endpoint trajectory. They suggested that to stabilize the endpoint trajectory, two synergies were necessary: a reaching synergy that consisted of moving the arm joints so that the hand is displaced towards the object, and a second synergy that consisted of compensatory rotations of the arm joints so that trunk movement does not affect the position of the endpoint (compensatory synergy). Adamovich et al. (2001) further demonstrated that the hand trajectory remained invariant even if the trunk movement was arrested in randomly selected trials. They suggested that trunk movement was "gated" by vestibular and proprioceptive inputs that activated compensatory arm movements diminishing the influence of trunk flexion on the hand movement to the target. The central commands that determine the contribution of the arm and the trunk to the transport of the hand may be generated sequentially, since the trunk did not begin to contribute to the hand displacement until the time of peak hand velocity (Rossi et al. 2002).

Based on findings of arm-trunk coordination in adults, several explanations for the increased involvement of the trunk for near reaches in younger children may be suggested: 1) Young children may not be able to make appropriate or coordinated joint rotations to minimize trunk involvement due to the lack of maturation of cortical areas involved in sensorimotor integration (Kostović et al. 1995; Paus et al. 1999). This is supported by evidence of an increased dependence on vision in young children (4 years old) for precision grasping (Kuhtz-Buschbeck et al. 1998), and reported in other studies by Hay (1979), von Hofsten and Rönnqvist (1988) and Ferrel et al. (2001). Hay and colleagues found that a critical period for perceptuo-motor function, particularly for visually-guided reaching, does not occur until about age 8 (Hay 1979; 1990; Fayt et al. 1993). 2) The selection of an appropriate motor strategy for reaching from the vast repertoire of possible strategies occurs with practice (Sporns and Edelman 1993). It is possible that in younger children, the trunk and arm synergies are not completely separated and only after years of practice, is this compensatory strategy established. 3) Another explanation may be the absence of mature feedforward control (discussed above) during reaching so that displacement of the trunk is not adequately prevented when the arm is raised to reach the object (Schmitz et al. 2002).

Interjoint coordination

Studies of rhythmical movements such as hammering have shown that while successive hammer trajectories follow similar patterns, these patterns are not necessarily accomplished by the same interjoint coordination in every cycle (Bernstein 1967). The system, having a redundant number of degrees of freedom or joint motions to produce a particular hand trajectory for example, optimizes but does not entirely limit the interjoint coordination patterns used for the task. The optimization of coordination patterns may be accomplished by the formation of synergies, emerging naturally from task demands (Gelfand and Tsetlin 1971; Turvey et al. 1978). Despite more than 10 degrees of freedom in the arm-trunk system, adults can maintain the invariance of the trajectory and the consistency of interjoint coordination when reaching to well defined targets. The optimization of interjoint coordination patterns for reaches to the three targets occurred slowly up until the age of 8 years, when mature patterns emerged, while inter-trial variability remained greater than adults in children aged up to 11 years or more (Table 2).

Acquisition of optimal trajectory formation occurs progressively during development and is linked to both neurological and biomechanical factors. Consideration of biomechanical factors has led to the re-assessment of some traditional theories about motor development (Kamm et al. 1990) that had considered the maturation of the central nervous system as playing the most important role. Jensen and Bothner (1993, 1998) proposed that successful force management is critical for the emergence of specific developmental behaviours such as independent stance and gait. In the case of reaching, it has been suggested that the development of interjoint coordination between the shoulder and elbow is necessary to stabilize the end effector (hand) trajectory (de Guzman et al. 1997; Morasso 1981). However, during development, the problem confronted by the nervous system is two-fold: the minimisation of excessive degrees of freedom (i.e. trunk movement during reaching) and the search for a task-appropriate pattern of interjoint coordination. Our data do not support the idea that maturation of one biomechanical variable must necessarily precede another. While anthropomorphic measures indicated that growth occurred linearly with age (Table 1), endpoint trajectory straightness, smoothness and variability attained adult levels in children aged 6 for T2 and 8 for T3 while evidence of increased variability in interjoint coordination patterns persisted in children as old as 11 for both targets. The persistence of a high variability in interjoint coordination despite adult-like endpoint trajectories suggests instead that the system prioritises movement smoothness using other available movement segments such as the trunk. This phenomenon, preservation of endpoint path smoothness, has also been observed in adults with hemiparesis due to stroke-related brain damage in whom interjoint coordination between the elbow and shoulder is disrupted (Levin 1996). Our data suggest that younger children optimize trajectory smoothness by integrating the movement of arm and trunk body segments. The decrease in variability in interjoint coordination with age indicates that during growth and development, children learn to master the redundant number of degrees of freedom of the motor apparatus. Thus, it can be suggested that maturation of movement patterns pertains to the learning of stable coordinative structures or combinations of degrees of freedom leading to the desired result.

It has been suggested that the increased variability seen in children and during learning of new movement skills may reflect the system's attempts to search for optimal kinematic solutions during development and learning (Thelen and Smith 1984). The high variability during development of skilled movement also supports the idea of an innate repertoire of motor strategies suggested by the theory of neuronal group selection. During development, synaptic connections between existing populations of neurons are reinforced or eliminated according to patterns of use. This selection process occurs through maturation of the CNS and training (Sporns and Edelman, 1993). The decrease in variability related to age may reflect the reinforcement of synaptic connections between groups of neurons and our data suggest that, aside from trajectory straightness, the process of learning is not complete within the first decade of life.

Clinical implications

A major problem encountered in the rehabilitation of arm and hand function in children with neurological disorders is the assessment of the efficacy of treatment interventions aimed at improving motor function. Current clinical assessment scales mainly characterize gross motor function (usually of bilateral manual tasks) according to developmental milestones in normal children (Folio and Fewell 1983; Ottenbacher et al. 1996). Although helpful in *classifying* the developmental disability, such scales provide no information about the quality of movement and are therefore less sensitive in the assessment of the motor consequences of therapeutic interventions (Ketelaar et al. 1998). Previous research has shown that children with CP have problems with movement speed, coordination and postural adjustments during reaching (Utley and Sugden 1998). By improving our knowledge about the development of reaching and grasping in healthy children, particularly for children over the age of 3 years, we will have a database allowing us to compare behaviours that deviate from normal and to evaluate the effects of therapeutic interventions on motor performance.

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Chapter IV: Discussion

This study described the development of coordination for reach-to-grasp movement in children aged 4 to 11 years old and identified when children acquire a mature or an adult-like pattern of reaching for certain kinematic variables. Reaching movements were characterized for three different distances, which did or did not involve the recruitment of the trunk segment. This approach allowed us to analyse, in addition, the coordination of arm and trunk movement.

The results suggested that, in order to acquire coordinated reaching movement children face one major problem: mastering the redundant degrees of freedom required by the task. This conclusion is based on the observation that most of the differences in the kinematic variables analysed were due to the amount of upper body movement involved in the task, and the upper body movement represents an additional degree of freedom.

Optimization of interjoint coordination and the decrease of unnecessary trunk involvement, are results that reflect the search for a coordinated structure. The inverse linear relationship between kinematic variability and age suggests that the acquisition of coordination occurs through exploration and practice until a stable pattern is learned. This process can occur in parallel with but may not necessarily be dependent on the maturation of CNS structures. The results suggest that different aspects of movement kinematics mature at different rates, supporting the idea that instead of being monotonic, motor development is marked by periods of evolution and regression (Kamm et al., 1990).

In order to organize the discussion in Chapter III, the kinematic variables analysed were grouped into four categories: those characterizing endpoint trajectories, joint excursion and trunk involvement, and interjoint coordination (Chapter III, Table 2). In this section, the results of the study will be discussed with respect to theories of motor development such as dynamic system's theory and the theory of neural group selection. Finally, the limitations of the study will be discussed as well as its clinical implications.

4.2. Development of coordination in reaching: a question of mastering the redundant degrees of freedom and achieving stereotypic kinematic patterns

4.2.1. Mastering the redundant degrees of freedom

During the first months after the onset of reaching, infants dramatically change the kinematic aspects of their trajectories and this process continues to evolve as suggested by Von Hofsten (1979, 1982, 1991); Fetters and Todd (1987); Thelen et al. (1996); Konczak and Dichgans (1997). Konczak and Dichgans (1997) demonstrated that in the first three years of life after the onset of reaching, hand trajectory straightness, as well as shape and velocity of the selected trajectories vary greatly. During development, infants reduce their between-trial variability but they still do not acquire an adult pattern of reaching. However, no study to date has analysed coordination (i.e. interjoint coordination, arm-trunk coordination) in reach-to-grasp movement in children over three years old.

Our results demonstrated that endpoint velocity or trajectory smoothness reached a mature pattern in children older than 6 years old. In addition, trajectory straightness continued to improve with age, which is in agreement with Kuhtz-Buschbeck et al. (1998). Indeed, endpoint trajectory straightness and variability reached a mature pattern around 8 years of age. What mechanisms lead children to produce smoother and straighter trajectories?

The dynamical system in motor development proposes that behavior is an emergent property of the interaction of multiple subsystems, and the system itself can be said to be self-organizing (Kamm et al., 1990). Thus, development of coordination in reaching is a product of the components or subsystems involved in the task; such subsystems have their own ontogeny trajectory (Fig. 10). In this way, development can be represented as a layered system that consists of multiple parallel developing components.

The increase of smoothness of the trajectory with age might be explained by the fact that the brain directly controls the direction of the endpoint trajectory through continuous comparisons between the actual and intended trajectory or by minimizing the irregularities in the path of the hand (Morasso, 1981; Hogan, 1984). This may be done by calculation of the correct pattern of joint angles in order to move the hand correctly in space (Soechting and Ross, 1984), or by the relative timing of the activation of the limb agonist and antagonist muscles (Gottlieb and al., 1989).

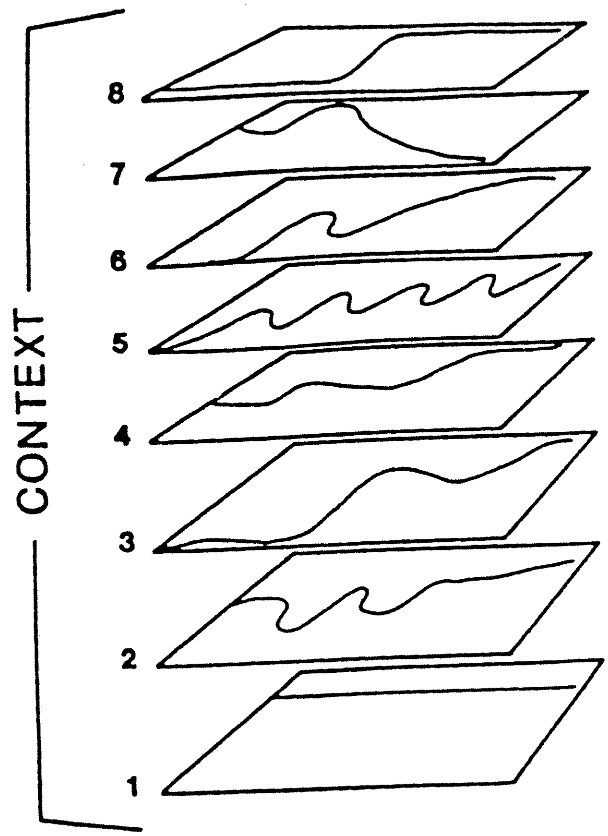

Fig. 10. Development represented as a layered system where multiple parallel developing components have asynchronous trajectories. At any point in time, the behavior outcome is a product of the components within a context. Copied from: "Motor development – A new synthesis" by E. Thelen, 1995, American psychologist, 2, p.82.

However, the dynamical system's theory does not consider that development can be explained by models that consider trajectory, joint excursion or muscle patterns to be controlled variables. The dynamical system approach suggests that the CNS controls the dynamic and ensemble characteristics of the entire controlled limb rather than its movement pathway or the firing pattern of the muscles. Specifically, the dynamical approach supports the idea that development occurs with the formation and appropriate management of frames of references (Thelen and Smith, 1994). According to Thelen (1995), early infant movements are dominated by biomechanical and dynamic factors without external frames of reference. Thus, in early reaches, the dynamics of trajectory generation as a succession of frames of reference might be coupled to the dynamics of intrinsic and extrinsic loads. The load consists of interaction, centripetal and inertial forces, stiffness and viscoelastic properties of the musculoskeletal system. The establishment of a frame of reference in a developing system is related to the acquisition of appropriate sensorimotor integration (Feldman and Levin, 1995; Feldman, 1998).

The system integrates all the sensory and visual information to make spatial transformations and create movements in a frame of reference (Soechting and Flanders, 1992; Feldman and Levin, 1995). It has been suggested that planning of reach-to-grasp movement is based on hand position and the position and configuration of the object to be grasped (de Guzman et al., 1997). The hand position and the object location are integrated via proprioceptive and visual information in the parietal and frontal cortices (Kalaska, 1996). Visual tracking has been observed as early as a few hours after birth (Greenman, 1963; Trevarthen et al., 1975), and it changes from saccadic to smooth during the second month (White et al., 1964). Coordinated head and eye movements can be observed in an irregular form just after birth (Trevarthen et al., 1975). This neonatal tracking and orienting activity shows that the relationships among ocular motricity, labyrinthine sensitivity, and neck proprioception are prewired at birth. However, eye-head-hand coordination seems to continue to be refined during the first decade of life, as suggested by Hay (1990). In younger children the visual control of movement occurs mainly after and not during the action. At 7 years of age an ongoing control begins to predominate. Between 7 and 11 years of age, visual control is reduced at the terminal phase of movement, which requires a reorganization of motor programming (Hay, 1979). The segmented velocity profile observed in our study in children younger than 6 years old may be explained by deliberate corrections to the trajectory originating at a higher level. Thus, the decrease in the number of movement units in the velocity profiles could be due to the increase in the ability or efficiency to generate a virtual trajectory or a referent position of the endpoint, which is dependent on the correct integration of afferent information.

Trajectory curvature is related to the final configuration of the hand for grasping, the hand being more frontally oriented and involving more lateral movement for closer targets and being more sagittally oriented and requiring more planar movement for farther targets (Roby-Brami et al. 1997; Jeannerod, 1984). In spite of the fact that the object used in this study was the same for all groups of children, there was an age related difference with respect to the curvature of the trajectory. Younger children had more curved trajectories than older ones. The increased curvature may be explained by the fact that younger children used an additional degree of freedom not necessary to the task – the trunk. Although children used the same excursion of elbow extension as adults by the age of four years old, shoulder horizontal adduction increased with age, assuming the adult amount of excursion around 6 years old. Our target was located at the midline of the subject's body. If one considers that the major function of the shoulder adduction is to bring the hand to the midline this would allow the hand to be positioned more sagitally. One should also consider that shoulder horizontal adduction is minimized when the trunk is involved in the transport of the hand. With less shoulder adduction, the hand is oriented more frontally to the target. Because younger children used more trunk than older ones they positioned their hand more frontally towards the target, and had more curved trajectories. Thus, smoothness and straightness of the trajectory are emergent properties of the development of multiple systems, including neuronal, biomechanical, and contextual factors.

Although excessive trunk movement for closer targets explains the more curved trajectory in children, it raises another question of why these children use the trunk at all for close targets. Bard and Hay (1993) studied reaching movement in which an additional head movement was imposed while children reached to a target. They reported that when a hand movement toward a target is accompanied by an orienting head movement, the speed of the hand movement increases only in children older than 8 years of age. In younger children, the hand movement time was found to be shorter when the child's head was kept fixed during the aiming movement, as if the head orienting movement interfered with the hand approach.

Studying reaching movement in adults, Adamovich et al. (2001) suggested that the integration of an additional (in this case, the trunk) degree of freedom depends on afferent (proprioceptive and vestibular) signals. For them, no central commands are issued for the compensatory arm movements. Instead control systems modulate the degree of compensation of arm joint rotations by "gating" the afferent signal elicited by the trunk motion. Through this control system, an appropriate contribution of trunk motion is provided to the hand transport.

Our results show that young children use an additional trunk degree of freedom in conditions in which adults do not. Young children may use such excessive trunk movement because they may not be able to make appropriate or coordinated joint rotations to minimize trunk involvement due to the lack of maturation of cortical areas involved in sensorimotor integration (Kostović et al., 1995; Paus et al. 1999). This is supported by evidence of an increased dependence on vision in young children (4 years old) for precision grasping (Kuhtz-Buschbeck et al. 1998), and reported in other studies by Hay (1979), von Hofsten and Rönnqvist (1988) and Ferrel et al. (2001). Hay and colleagues found that a critical period for perceptuo-motor function, particularly for visually guided reaching, does not occur until about age 8 (Hay 1979; 1990; Fayt et al. 1993). Interesting the corticospinal conduction time does not achieve the same speed as adults before the age of 10 years. In addition, a study conducted by Myklebust and Gottlieb (1993), about the development of the stretch reflex in the newborn suggested that reciprocal excitation and reflex irradiation is a functional pathway of all newborn infants, that is eliminated during the normal course of development of motor skills. During childhood, stretch reflexes become more focused, and reflex irradiation is suppressed. However, reciprocal excitation persists as a recognised pattern until 4 to 6 years of age, while reflex ratios (agonist /antagonist) fall significantly during the first year of life. The findings that children do not achieve a mature sensorimotor integration before 11 years old, and that properties of the stretch reflex only acquire mature patterns around 4 to 6 years old (Hay, 1990; Myklebust and Gottlieb 1993), lead us to suggest that young children use excessive trunk movement for reaching since they may not be able to generate a mature referent configuration.

The selection of an appropriate motor strategy for reaching from the vast repertoire of possible strategies occurs with practice (Sporns and Edelman 1993). It is possible that in younger children, the trunk and arm synergies are not completely separated and only after years of practice is this compensatory strategy established. The theory of neuronal group selection (TNGS) emphasizes the importance of the somatic selection of neuronal groups into maps for the progressive transformation of a primary movement repertoire into a set of motor synergies and adaptive action patterns (Sporns and Edelman 1993).

Another explanation may be the absence of mature feedforward control during reaching so that displacement of the trunk is not adequately prevented when the arm is raised to reach the object (Schmitz et al., 2002). In general, all the previous explanations of trunk involvement have certain similarities and may indeed be complementary. All of them propose that the trunk involvement will decrease with practice and experience, parallel to neural maturation, and better sensorimotor integration. What they fail to explain however is what is the "attractor", or in other words, the mechanisms that make children decrease their trunk motion with age?

Bernstein (1967) defined motor coordination as the process of mastering redundant degrees of freedom of the moving system. He proposed that the motor apparatus is functionally organized into synergies or classes of movement patterns. Based on this assumption, in a mature system, if one additional degree of freedom is added (or sometimes eliminated i.e. paralysis or amputation), there is an immediate spontaneous use of other degrees of freedom that had not been previously associated with the performance of the action. In other words, self-organization of the system occurs to priorize the movement goal (Kamm et al., 1990). From this point of view, the optimization of coordination patterns may be accomplished by the formation of synergies emerging naturally from task demands (Gelfand and Tseltlin, 1971; Turvey et al., 1978).

Based on our results, we suggest that the development of interjoint coordination is associated with the decrease in trunk involvement, since the lack of appropriate or the presence of an immature pattern of interjoint coordination demands the involvement of the trunk to produce an optimal endpoint trajectory. The attractor is the final configuration of the workpoint, which in the case of reach-to-grasp movement, is the hand. This phenomenon, preservation of endpoint path smoothness by inclusion of trunk movement when reaching, has also been observed in adults with hemiparesis due to stroke-related brain damage in whom interjoint coordination between the elbow and shoulder is disrupted (Levin 1996, Levin et al., 2002).

Our data suggest that younger children optimize trajectory smoothness by integrating the movement of arm and trunk body segments. The decrease in variability in interjoint coordination with age indicates that during growth and development, children learn to master the redundant number of degrees of freedom of the motor apparatus. Thus, it can be suggested that maturation of movement patterns pertains to the learning of stable coordinative structures or combinations of degrees of freedom leading to the desired result.

What our results do not support is that acquisition of one biomechanical variable must necessarily precede another as suggested by other theories of motor development such as the maturational theory. For example, development of trunk and interjoint coordination are linked, but we cannot determine which one leads the other. They can be concurrent.

4.2.2. Achieving stereotypic kinematic patterns

Variability is often interpreted as a reflection of reduced stability of a system. In general, stability of a system is related to the ability to accommodate perturbations. Outcome variability is reduced as a function of practice and increments of skill. The role of variability has been widely discussed in the study of motor control (Newell and Corcos, 1993). According to Sporns and Edelman (1993), during development, behavior is *selected* from a wider number of possibilities rather than *imposed*. For them, multimodal exploration is a key process for acquiring new skills. Creation and manipulation of variability are elements of this skill acquisition process.

Our results demonstrated that for most of the kinematic variables analysed, variability decreased with age, achieving adult values around 8-9 years old, specifically for endpoint trajectories and standard deviation of distance (SDd) in interjoint coordination (Table 2). Cluster analysis based on the variability of interjoint coordination revealed two groups, one characterized by high variability, consisting of younger children and the other characterized by low variability, formed by the older children and adults. Indeed, children aged 8-9 years old were present in both clusters, suggesting once more that this age group is characterised by a transitional or critical period (Hay, 1978,1979; Fayt, 1992). In other kinematic variables analysed, (trunk involvement, SDt; Table 2), variability did not reach an adult value suggesting that stereotypic patterns for these variables probably occur after 11 years old.

The theory of neuronal group selection (TNGS; Sporns and Edelman, 1993) as in the traditional Darwinian theory, proposes that a selectionist view of development requires a source of diversity and variability from which adaptive patterns can be chosen. The TNGS further proposes that the development of sensorimotor coordination occurs in three steps: 1) The spontaneous generation during development of a variety of movements forming a basic movement repertoire; 2) Development of the ability to sense the effects of movements in the environment, then guiding neural selection; and 3) The actual selection of movements. Selection in the nervous system is mediated by synaptic change, resulting in the stabilization of brain circuits that support the specific goal-directed movements. In other words, somatic selection in the nervous system results from the competitive strengthening of neural connections (synapses) involved in the generation of successful movements (Sporns and Edelman, 1993). Thus, if motor development is interpreted by the traditional theories, as guided from neuromaturation, it is difficult to understand how the motor command adapts to changes in the peripheral structures. In contrast, development through selection accounts for individual variability and changes in the activity level, body proportion, neural growth and task environments (Thelen, 1995).

Sporns and Edelman (1993) have demonstrated this selectionist process with the schematic diagram shown in Fig. 11. The diagram shows a developing movement repertoire. They assume that a movement such as reaching is characterized by values of a set of *n* joint variables ϕn. The set of all possible combinations of these *n* joint variables thus forms an *n*-dimensional movement space **M** ($n = 2$ in Fig. 11). Initially, the subset of movements is only constrained by the mechanisms of its motor ensemble and pre-existent motor structures, and is unconstrained by the experience of the environment. Each pattern is shown as a dot on the diagram in a movement space, **M**, specified by two variables, $\phi 1$ and $\phi 2$, where the variables can be joint angles or positions of the hand in space. The density of the dots represents the frequency that movements with a particular configuration are performed. At time 1, infants have a specified set of patterns. With growth and changing environmental demands at Times 2 and 3, the shape and density of the movement repertoire changes. New patterns emerge and some old patterns lose stability. Hatched regions are associated with positive value and are positively strong and stable. For example, some movements will help to accomplish a task better than others. They form one or more subsets of θ within the movement space **M.** Because of individual variations in the biomechanics of the motor system, their progressive structural and dynamical change during development and the unpredictable environmental demands, these areas may also evolve and change (Sporns and Edelman, 1993; Thelen 1995).

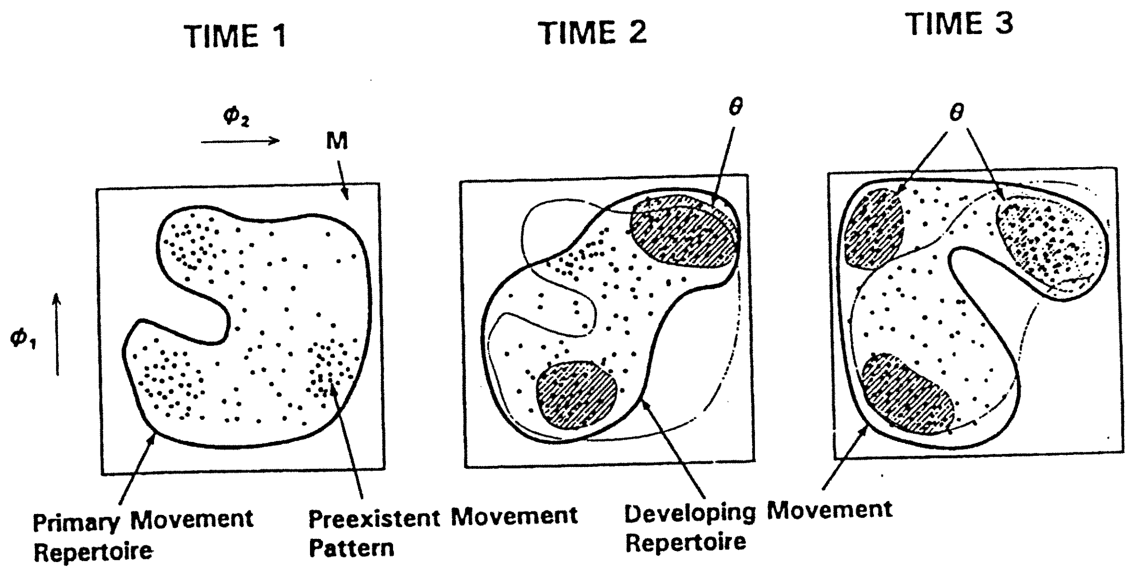

Fig. 11. Schematic diagram of selection in movement repertoires. M is the movement space specified by a certain combination of movement variables, ϕ1 and ϕ2. Each dot is a movement , and the density of dots signifies the frequency of movement in the space. The three frames show changes over time. The frame at the left shows the primary movement repertoire. The repertoires evolves with time to include previously unoccupied regions of M and to exclude others. Hatched regions indicate movement regions that correspond to a given task, as they emerge from the primary repertoire. Copied from: "Motor development – A new synthesis" by E. Thelen, 1995, American psychologist, 2, p.91.

For example, a dense area representing the reaching arm-trunk synergy may become less dense with age and may be replaced by other forms of reaching only involving arm joints.

The specific details of cortical representations of the distributed selective responses of cortical neurons are established and are continually remodelled by experiences throughout life (Thelen and Smith, 1994).

Considering the TNGS, we can explain our results of reduced variability with age as an exploration of different patterns of coordination in reaching movement through development. As suggested by Bernstein (1967) the possibilities for correct realisation of a task become progressively reduced as the system settles on an efficient solution. Thus, before an efficient solution is chosen, the system should explore all possibilities, and continue to adapt these possibilities with body growth, neural maturation, and different task demands. The fact that the age of 8 years old has been found in our study and in others to be a transition period, can be explained as these children changing a previous established subset θ to a new one, due to neuronal and biomechanical changes.

4.3. Limitations of the study

The goal of this study was to characterize the development of coordination for reaching movements in children. Both longitudinal and cross-sectional studies can be done in motor development. In the longitudinal design, one can follow changes in an individual or a group with age for the entire length of the period of interest. The disadvantage of this design is that since the periods are years or decades, researchers may be able to complete only a few of this studies in their lifetimes. Another way to learn more about motor development in a shorter time is through the use of cross-sectional study designs. In a cross-sectional study, researches select individuals or groups of specific ages. In our study, we used a cross-sectional design for convenience. The disadvantage of this approach, is that age-related difference are inferred from groups made up of different individuals and we can mistakenly assume that observed differences are caused only by developmental changes (Haywood and Getchel, 2001). In our study, all the kinematic outcomes were proportional to the antropometric measures of each child.

Reaching movement can be realized in different planes. In our study reaching was limited to the sagittal plane with one movement in the transverse plane, since our targets were located in the body midline. One of the issues debated in the development of reaching is which variable becomes stereotypic first, joint excursion or endpoint trajectories (Konczak and Dichgans, 1997). In order to more completely address this question, we would have had to study reaches in different parts of the workspace with different combinations of shoulder and elbow joint movements. We chose horizontal instead of vertical reaches because horizontal reaches are most common in functional activities such as self feeding.

We suggested that most of the differences found with age were due to concurrent changes in biomechanical and neuronal maturation. In spite of collecting all the anthropometric information, we did not make any perturbations to the system, such as blocking vision, to analyse differences in accuracy, nor did we control movement time to analyse differences in speed due to maturation of corticospinal efferents. We also did not study the effect of arresting trunk movement during reaching. These manipulations would provide more concrete data to substantiate different arguments.

Postural adjustments are essential to the emergence of coordinated reaching. Although we collected data from some muscles involved in postural adjustment and also centre of pressure data, we did not report the results in this study. These findings would complement the present results.

Most of the limitations cited above were due to an impossibility to collect a large amount of information in only one study due to the limited time. However, in general, this study did provide essential characteristics of the development of reaching in children older than three years.

4.4. Clinical Implications

The evaluation of motor impairments is necessary to plan rehabilitation treatment. For a physiotherapist, it is important to know ***why*** a motor action is not accomplished. However, most of the evaluations available in children with motor disorders mainly characterize whether or not a task is performed. They characterize gross motor function according to developmental motor milestones in healthy children (Folio and Fewell 1983; Ottenbacher et al. 1996). Although such scales are helpful in classifying the developmental motor disability, they do not provide information about how the movement was performed. Those scales that do provide more information about the quality of movement, such as the QUEST (Quality of upper extremity skills test, DeMatteo et al., 1992), fail to analyse the movement within the context of a functional task such as reaching and grasping an object.

We believe that with the results presented in this study, more evaluations focusing on motor performance can be elaborated by physiotherapists. With better evaluations, treatment planning can be facilitated and as a result treatment efficacy can be improved. Through our results, clinicians will be aware of the evolution of the development of coordinated reaches, kinematic variability and improvement with age. Clinicians can develop scales that measure the quality of motor performance such as the amount of trunk displacement, straightness and smoothness of the hand trajectory, and variability during the trials. Such a clinical scale (RPSS), based on the kinematic analysis of reaching in healthy adults and in adults with stroke has been developed by Levin et al., 2002. The normative data provided by this study may also be used for comparison with data from children with motor impairments such as CP to develop similar clinically relevant motor assessment scales.

Chapter V : Conclusion

The development of coordination for reaching movements is in continual evolution from birth and beyond three years of age. Children acquire mature kinematic patterns of reaching at different ages depending on the variable analysed. In the search for the coordinated pattern, children have to solve the problem of the redundant degrees of freedom. Young children used excessive trunk displacement to reach targets located close to the body, an aspect not observed in older children and adults. At the same time young children do not use optimal interjoint coordination patterns, a fact illustrated by the lack of consistency in interjoint coordination patterns when reaching across the targets. Due to the addition of one more degree of freedom, unnecessary to the task, together with the immature pattern of interjoint coordination, trajectories in younger children are not as smooth or straight as in older children and adults. Variability of kinematic variables decreases with age, consistent with Bernstein's (1967) suggestion that before an efficient solution is chosen, the system explores all the possibilities.

We suggest that children acquire a coordinated pattern of reaching when they are able to form and manipulate correct frames of reference in space. This can only happen when children are able to make correct sensorimotor transformations and integration in motor planning. Until this integration occurs, motor execution is not the same as adults. In addition, motor execution, or the central command, should be continuously updated due to anthropometric changes.

Coordination of reaching occurs through the contribution of multiple subsystems. Moreover, some aspects of reaching are innate or prewired at birth, but with age and practice children select the best pattern to accomplish the task. Selection is only possible because of diversity and variability that exists in the system.

The aspects of reaching described in this study could allow a better characterization of abnormal patterns of reaching with a developmental perspective in children with motor disabilities. The fact that is normal that young children use more the trunk than older children and adults Thus, therapists can create new evaluations that will help to improve treatment efficacy.

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