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Neuromotor development from kindergarten age to adolescence: developmental course and variability

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Summary

The normal course of neuromotor development is described from 5 to 18 years of age. The data have been collected by use of the Zurich Neuromotor Assessment, a standardized testing procedure in which distinct motor tasks are judged with regard to timed performance and movement quality (associated movements of the contralateral and ipsilateral extremity, face, head and body). In the Zurich Growth and Development Studies, norms for these motor tasks have been established in 662 children and adolescents from middle class families. Neuromotor development is not a phenotypic entity, but evolves from motor functions of different complexity. With regard to timed performance and movement quality developmental course, gender differences and laterality vary considerably over age and among motor tasks. Thus, for a reliable assessment of the neuronotor developmental status in children, a standardized test instrument, well-trained examiners and normative data are required.

Key words: neuromotor development; Zurich Neuromotor Assessment

Introduction

According to epidemiological studies, about 6% of all school-age children are described by experts and parents as uncoordinated in their fine and gross motor skills [1]. Thus, in almost every kindergarten and in every school class there are "clumsy" children. These children have more difficulty than their peers when playing ball outside, as well as with certain fine motor tasks like drawing or writing. For the children concerned this "clumsiness" makes them less capable than their peers and can have manifold consequences. Their well-being and their self-confidence may suffer from the failure and rejection.

The appropriate diagnosis in a presumably "clumsy" child presents a considerable challenge to professionals such as neurologists or paediatricians. These professionals are requested to investigate whether the child's motor performance, quality of movements and posture are still within the normal range, whether they reflect a developmental delay, i.e. comparable to the behavior of a younger child, or indicate frank neurological impairment. While major motor impairments, e.g. cerebral palsy, are easily recognized even by a lay person, the task is difficult in the more frequent, but less obvious minor motor impairments that can rarely be related to a specific neurological disorder. Clinically, minor motor impairments are associated with so-called "soft" or "subtle" neurological signs.

Subtle neurological signs are minor findings that are commonly present in young children [2]. It is only their persistence into later years that makes them "pathological". "The diagnosis of minimal brain dysfunction is based upon findings that are abnormal only with reference to the child's age … had the child been younger, the findings would have been regarded as normal." [3]. Subtle neurological signs serve not only as markers for mild motor impairment, but they have also been related to behavioral disturbances, such as hyperactivity [4], impulsiveness [5], learning disabilities [6], aggressive antisocial conduct and psychotic disorders [7], and even anxiety and depression [8, 9].

A prerequisite for all professionals dealing with normal and developmentally disturbed children is the profound knowledge of normal devel-

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opment. In this article the following questions will be addressed with regard to neuromotor development:

– *How do timed performance (speed) and movement quality develop during childhood?* Up to which age do performance and movement quality improve? When is this developmental process completed: before puberty, in puberty or not until adulthood?
– *How marked is the inter-individual variability of timed performance and movement quality*? How strongly do children of the same age vary in the different age groups with regard to performance and quality of movement?
– *Are there differences between girls and boys?* Is it correct, as most experts and lay people assume, that girls are better coordinated?
– *Do side differences exist?* It is a common assumption that the dominant extremity is always more competent and skillful. Is this true?

Assessment of neuromotor development

During the past 25 years, a number of standardised neurological test instruments have been extensively used in research and clinical practice (Physical and Neurological Examination for Soft Signs [PANESS] [10]; Examination of the Child with Minor Neurological Dysfunction [11]; Neurological Examination for Subtle Signs [NESS] [12]; Movement Assessment Battery for Children [ABC]) [13]. However, for most of these assessments either there are no normative data available or the data are restricted to only a few age groups [14, 15]. More recently the Zurich Neuromotor Assessment has been developed at the Growth and Development Center of the University Children's Hospital, Zurich ([16–18]; detailed information on the assessment can be obtained from the first author). The Zurich Neuromotor Assessment is a standardised testing procedure in which distinct motor tasks are judged with regard to timed performance and movement quality (associated movements of the contralateral and ipsilateral extremity, face, head and body) (table 1). The examination is recorded on video; timed performance and associated movements are assessed from these recordings. The timed performance (speed of movement) is determined with the stopwatch to an accuracy of one tenth of a second. The exact beginning of time measurement and the number of movements to be measured have been established for each motor task.

For the construction of age-specific norms for performance times a skewed distribution of the data had to be taken into account. A logarithmic transformation approximated normally distributed data and achieved constant variability across ages. After log transformation, a quadratic function fitted between age and log times for all tasks. Thus, a quadratic function served as the basis for calculating age-specific norms.

Table 1

Motor tasks of the Zurich Neuromotor Assessment.

Repetitive movements	Foot Hand Finger
Alternating movements	Foot Hand
Sequential movements	Finger
Adaptive performance	Pegboard Dynamic balance
Equilibrium/Balance	Static balance
Posture	Stress gaits

The test instrument assessed movement quality by scoring of associated movements. The less frequent and the less marked the associated movements are, the higher is the quality of the movement. Associated movements are defined as involuntary movements in those parts of the body which are not actively involved in the task. For example, when a child carries out repetitive movements with the right hand, associated movements are the following: Movements of the left hand (contralateral associated movements), movements of the right lower extremity (ipsilateral associated movements), movements of the left lower extremity (contralateral associated movements), movements of the upper part of the body and head, as well as mimic reactions. Associated movements are judged with respect to frequency and degree.

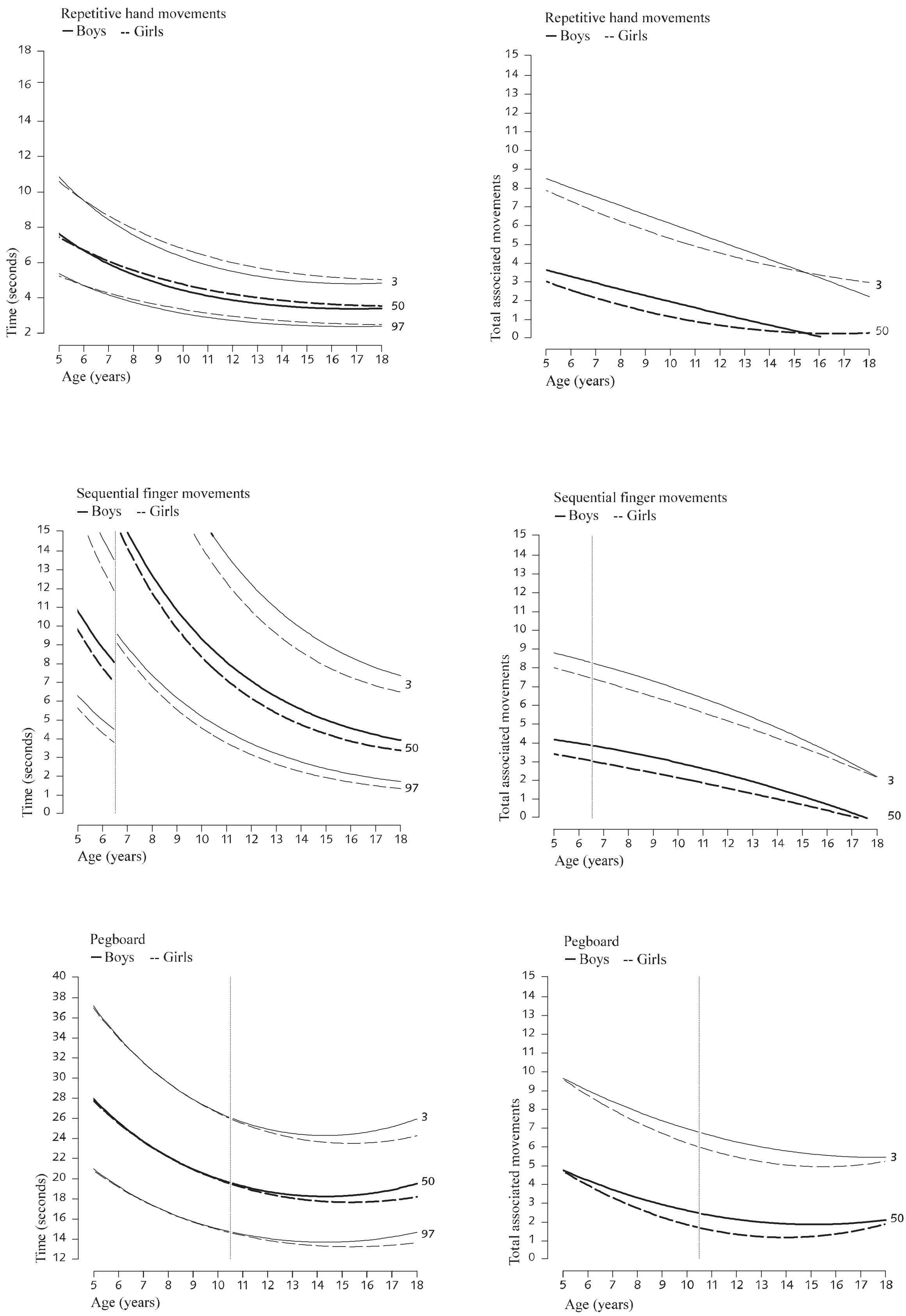
While the active extremity carries out the required number of movements, the frequency of associated movements is noted in tenths of the number of active movements (score ranges from 0 to 10). Example: The child performs repetitive hand movements. During the 20 movements with the right hand, there are associated movements of the left hand four times. The frequency of contralateral associated movements is scored as 2.

For degree, the associated movements which are most pronounced during the task are scored. The evaluation assesses the degree of an associated movement on the basis of the maximal possible movement range for the observed associated movement according to a four-point scale (score ranges from 0 to 3).

Developing a statistically reliable model for normative values of the associated movements proved to be considerably more complicated than for time measurements. From the raw data of frequency and degree of associated movements an index for measuring the "intensity of associated movements" was defined by taking the product of "frequency x degree". The intensity indices of the

Figure 1

Development course and sex differences from 5 to 18 years in three motor tasks. Repetitive hand movements: 20 pats of one hand with the wrist resting on the thigh; sequential finger movements: opposing each finger with the thumb in sequence, i.e., "index, middle, ring, little" comprises a set, <6.5 years: three sets, >6.5 years: five sets; pegboard: <10.5 years: 12 plastic pegs are inserted into the pegboard using one hand, >10.5 years: 12 pins are successively removed from the pegboard, inverted in one hand and then replaced in the pegboard. Left side: timed performance of the dominant extremity; right side: total associated movements of the dominant extremity (total score of frequency and degree of contralateral and ipsilateral associated movements, associated movements of head and upper body, and mimic reactions).



different associated movements (contra- and ipsilateral, head and upper body, and mimic reaction) were summarized in a "total associated movements" score presented in figures 1 and 2. Age-specific norms for the quantity were obtained using the methodology of Gasser and Rousson [19].

In the Zurich Neuromotor Assessment, norms were established from a cross-sectional study of 662 children and adolescents from middle class families. At the time of examination most of these lived in the region of Zurich. Of the total 662 children, 477 were in kindergarten, or the first, third or sixth grades; 202 adolescents were recruited from participants of the Second Zurich Longitudinal Study; 17 children had to be excluded because of serious motor retardation or indetermi-

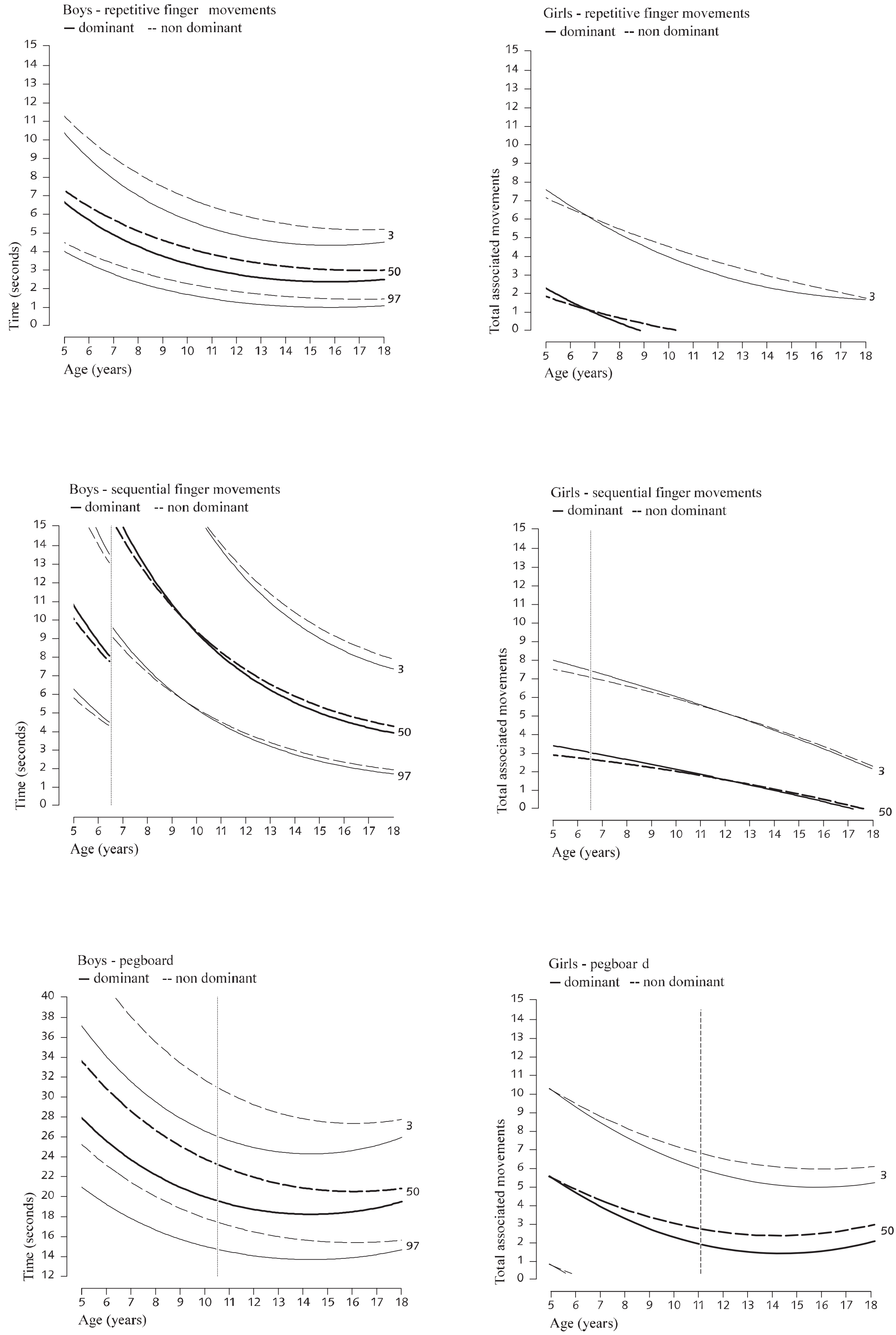


Figure 2

Laterality (dominant versus non-dominant side) from 5 to 18 years in three motor tasks (for details see figure 1). Left side: timed performance in boys; right side in girls: total associated movements (for definition see figure 1).

nate laterality. The children in kindergarten were on average 5.8 years old at the time of the examination, those in the first grade 7.2 years, in the third 9.3 years and in the sixth grade 12.5 years old. In the groups of adolescents and young adults, the average age was 15.0 and 18.1 years.

The socioeconomic status of the families concerned was determined from maternal education and paternal occupation and was on average above the mean for the Swiss population. In the samples investigated, the socioeconomic status of the family had no influence on timed performance or quality of movement.

Neuromotor development from 5 to 18 years

The graphs of Figures 1 and 2 show neuromotor functions between 5 and 18 years of age with so-called percentile curves. The 50th percentile corresponds to a median performance in the norm sample, that means, 50% of all boys carry out the task more slowly and 50% more rapidly than a boy achieving a value exactly on the 50th percentile (e.g. 5.9 seconds for repetitive hand movements at the age of 7 years). Three percent of children lie under the 3rd percentile and a further 3% over the 97th percentile.

Developmental course and variability

Older children obviously perform more efficiently and have less associated movements than do younger children. Developmental changes have been reported for many motor skills, such as hopping or catching or throwing a ball [20, 21]. However, the developmental courses of distinct motor functions are less well documented. With regard to timed performance, Denckla [14, 15] provided some data showing that speed of performance is, as expected, lower in younger children, and reaches a plateau between eight and ten years of age. Wolff et al. [22] essentially confirmed Denckla's findings by reporting age-specific changes in the speed of repetitive, alternating and sequential movements at school age.

In the past, neurological findings such as tendon reflexes or simple motor patterns, like repetitive movements, were regarded as invariable among healthy children of the same age. However, in recent years, there has been a growing awareness that motor functions appear and change not only age-specifically, but they are also highly variable within an age group. Denckla [14, 15] provided mean values and standard deviations for the speed of repetitive, alternating and sequential movements. Wolff et al. [22, 23] reported some data on the age-specific variability of associated movements in these motor tasks.

Timed performance

Our study demonstrated for all neuromotor functions that timed performance improves with age (Figure 1). For the repetitive and alternating hand movements, performance reaches a plateau in the course of puberty. For the sequential finger movements, performance improves beyond the age of 18 years. For these purely motor functions the following applies: the more complicated the task is, the later the plateau is reached. With the pegboard and dynamic balance sidewards, the best performance is already reached at 13 to 15 years of age. In contrast the time to maintain static balance increases up to the age of 18 years.

The distance between the 3rd and the 97th percentiles demonstrates how different the performance of children of the same age can be (inter-individual variability). At the age of seven years, boys display a median time of 5.9 seconds for 20 repetitive hand movements. Three percent of the boys complete the task within less than 4.2 seconds, while another 3% need more than 8.4 seconds. For the pegboard task 10-year-old children accomplish the pegboard task a median time of 20 seconds; 3% of the children require less than 15 seconds, another 3% more than 26.5 seconds.

The Zurich Neuromotor Assessment consists of tasks of varying complexity. The complexity increases from repetitive movements, to alternating movements and sequential movements, and finally to an adaptive task, such as the pegboard. The complexity of the tasks contributes significantly to the differences observed in development and inter-individual variability. A comparison of the developmental change in timed performance across age suggests the following generalised principles for purely motor tasks:
The more complex the task
– the more pronounced the speed increases with age,
– the later the plateau in puberty is reached,
– the greater the inter-individual variability.

Surprisingly, maximal performance with the pegboard, an adaptive task where visual perception has to be integrated into the motor activity, is already reached at about 13 years of age.

Associated movements

From the kindergarten child to the adolescent, the development of associated movements shows a course similar to that of timed performance: i.e. the older a child is, the fewer associated movements are observed.

The associated movements in most of the purely motor tasks gradually decrease with increasing age. For the pegboard the course of associated movements is similar to the course of motor performance in that a plateau is reached during puberty.

For associated movements the largest differences between the individual children are found in kindergarten and the early school years. In these age groups, there are children who carry out a task without or with only a few associated movements, while some of their peers show marked associated movements. The inter-individual variability of associated movements decreases with age to a varying degree depending on the task.

The effect of the varying complexity on associated movements is similar to that on timed performance:
The more complex the task
– the more associated movements will be observed at any age,
– the larger the inter-individual variability will be.

Sex differences

There is a general assumption that females perform faster, particularly in fine motor tasks, and are better coordinated than males. For example, in Denckla's studies [14, 15] successive finger movements and heel-toe alternation were performed faster by females than by males. Our study confirms this assumption only partially.

Timed performance

Boys tend to carry out the simplest motor functions, repetitive movements, more rapidly than girls. It is true that these differences are slight, i.e. not of clinical relevance. With the alternating movements, there are no significant sex differences. In contrast, girls perform complex sequential movements and adaptive tasks on the pegboard more rapidly than boys. Furthermore, girls can stand on one leg longer. Therefore, depending on the task, the sex differences vary in size and direction. These differences do not always turn out to be in favor of the girls; boys carry out certain tasks more rapidly. A few significant differences between females and males were noted, however, given the large inter-individual variation, these sex differences in timed performance are of minor clinical relevance.

Associated movements

Sex differences are more consistent for associated movements than for timed performance. In all tasks, girls show fewer associated movements than boys. In the statistical evaluation of the norm population with several hundred children, these differences are statistically significant. They are, however, small on average and because of the large inter-individual variability are not clinically relevant for the individual case.

The impression that girls are better coordinated than boys is mainly based on two factors:

- Girls carry out movements in complex and adaptive tasks somewhat more rapidly than boys. In general, their performances are not significantly superior to those of males.
- Girls show fewer associated movements during all motor activities and therefore their movements appear more harmonious.

Laterality

In right-handed children, "common sense" suggests a somewhat less stringent set of expectations for the left hand than for the right-hand. However, is a right-handed child only slightly slower with his left hand or very much so? What is a "normal" difference between the dominant and the non-dominant hand? Is there a consistent side difference between the lower extremities? The clinical relevance of these questions becomes evident in developmentally disturbed children. Children with central nervous system dysfunction are reported to display late or weak lateralisation, which is thought to be a reflection of an anomalous cerebral dominance [23]. Annett [25] observed an excess of ambidexterity among children with low IQ levels. In children with minimal brain dysfunction, Martha Denckla [14, 15] found a significant percentage who used either hand. She regarded these children as bilaterally clumsy, rather than ambidextrous. Other children showed mixed lateral preference combinations for the hand, foot and eye. Denckla also reported a higher frequency of children who strictly preferred using their right hand and who were so lateralised that they could not use the left hand in a normal manner, i.e. they were pathologically hyper-lateralised. Reitan [26] observed an excess of preferred hand superiority in handwriting among brain-damaged children compared with normal children. A lack in the quality of left limb coordination in brain-damaged children has also been observed by Rudel et al. [27]. Side differences, e.g. in children with a hemisyndrome, can be reliably assessed only if normative data on lateralisation are available for all age levels. Touwen [11] provided some semi-quantitative data on lateralisation of gross motor skills, e.g. a normal "right-foot" four-year-old child balances and hops only on his right foot; at five years, his left foot catches up and the strength of lateral preference is less pronounced. Denckla [14] reported different degrees of lateralisation in repetitive and successive finger movements. Right hand superiority was noted for speed of repetitive movements, but both hands were equally proficient in successive finger movements. Denckla's findings are supported by other studies demonstrating right side superiority in tasks requiring repetitive movements of fingers, hands and arms [28, 29].

Timed performance

With the simple repetitive movements of the upper extremities, we observed a distinct, and clinically relevant, side difference (Figure 2). Children performed the movements with the dominant extremity more rapidly than with the non-dominant one. These differences decline with the alternating movements, and for the sequential finger movements an age dependent laterality effect was noted. In purely motor tasks, therefore, side differences decrease with increasing complexity of the motor function. Marked differences, however, are found for the pegboard, which represents an adaptive task. For this task the dominant side is considerably quicker.

The following order of lateralisation could be established: pegboard (most lateralised), repetitive finger and hand movements, alternating hand movements, sequential finger movements, repetitive and alternating foot movements (least lateralised). Thus, the lower extremities are much less lateralised than the upper extremities.

Associated movements

Associated movements in the upper extremities showed small side differences for alternating hand movements and the pegboard task (Figure 2). There is a general tendency for fewer associated movements to occur when the dominant hand is active. With the sequential finger movements there are no side differences.

Why are the side differences for associated movements described here considerably smaller than those observed in a routine clinical examination? There are several possible explanations: First, a clinician expects that the non-dominant hand will clearly show more associated movements than the dominant hand. This expectation may influence the observer and lead to the associated movements of the non-dominant hand being perceived more clearly (assessment bias). A second possible explanation is the specific concept of the Zurich Neuromotor Assessment, in which the child is invited to perform the respective task as quickly as possible. In this way the same effort is demanded for both sides. The result is, that although the speed of movement may vary between the two sides, the child is subjected to the same performance stress on both sides. When equally stressed, only slightly fewer associated movements occur with the active dominant extremity than with active non-dominant extremity. In a routine clinical examination, maximum performance is not always demanded from the dominant side. Thus, when performing with the dominant extremity the child is less stressed and, therefore, fewer associated movements are displayed.

In conclusion, our study demonstrated that neuromotor development from kindergarten age to adolescence is not a phenotypic entity, but evolves from motor functions of different complexity. With regard to timed performance and movement quality developmental course, sex differences and laterality vary considerably among motor tasks. Therefore, for a reliable assessment of the neuromotor developmental status in children, a standardised test instrument, well-trained examiners and normative data are required [18].

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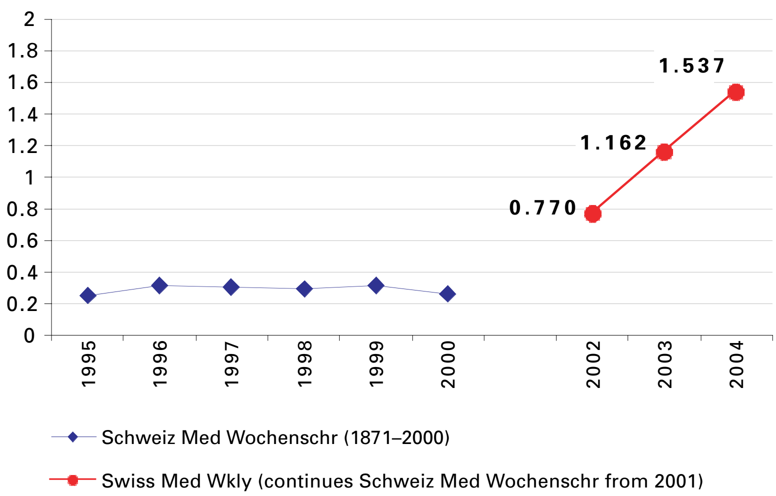

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