Neuromotor development from 5 to 18 years. Part 1: timed performance

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Timed performance in specific motor tasks is an essential component of a neurological examination applied to children with motor dysfunctions. This article provides centile curves describing normal developmental course and interindividual variation of timed performances of non-disabled children from 5 to 18 years. In a cross-sectional study (n=662) the following motor tasks were investigated: repetitive finger movements, hand and foot movements, alternating hand and foot movements, sequential finger movements, pegboard, and dynamic and static balance. Intraobserver, interobserver, and test–retest reliability for timed measurements were moderate to high. Timed performances improved throughout the entire prepubertal period, but differed among various motor tasks with respect to increase in speed and when the 'adolescent plateau' was reached. Centile curves of timed performance displayed large interindividual variation for all motor tasks. At no age were clinically relevant sex differences noted, nor did socioeconomic status significantly correlate with timed performance. Our results demonstrate that timed motor performances between 5 and 18 years are characterized by a long-lasting developmental change and a large interindividual variation. Therefore, a well standardized test instrument, and age-specific standards for motor performances are necessary preconditions for a reliable assessment of motor competence in school-age children.

By definition, a clumsy child has no formal neurological signs, and motor difficulties are not explicable by demonstrable neurological disease or general developmental delay (Hall 1988). Clumsy children show two characteristics in their motor behaviour: first, their performance in fine and gross motor activities, such as handwriting or running, is not age appropriate and may be variably impaired; second, poor quality of movements and so-called subtle or soft neurological signs are noted. According to Deuel and Robinson (1987), the latter are minor findings commonly present in young children. It is only their persistence into later years that makes these soft neurological signs 'pathological'. The diagnosis of minimal brain dysfunction is based upon findings that are abnormal with reference to the child's age only. If the child had been younger, the findings would have been regarded as normal (Kinsbourne 1973). From a neurobehavioural perspective, clumsiness ought best to be regarded as a developmental phenomenon, namely as a variable expression of performance and movement quality.

In the evaluation of somatic growth and intellectual performance a development-oriented approach taking into account age-specific changes and interindividual variation has been a well-accepted practice for many years. This has not been, and still is not the case when assessing neuromotor development. During the past 25 years a number of standardized neurological test instruments have been extensively used in research and clinical practice: e.g. Examination of the Child with Minor Neurological Dysfunction (Touwen and Prechtl 1979); and Neurological Examination for Subtle Signs (NESS; Denckla 1985). However, for most of these assessments either no data or normative data that is restricted to a few ages are available (Denckla 1973, 1974). This article provides centile curves of timed performance from 5 to 18 years for distinct motor tasks. Data were collected using the Zurich Neuromotor Assessment (ZNA), a test instrument developed at the Growth and Development Centre, University Children's Hospital, Zurich. During the development of the ZNA, we investigated the motor tasks described in various neuromotor assessments (Abercrombie et al. 1964; Connolly and Stratton 1968; Touwen and Prechtl 1979; Denckla 1985; Wolff 1983, 1985; Henderson and Sudgen 1992). In the initial phase, only tasks were chosen which showed sizeable age-specific changes and were variably confounded by non-motor variables of perception, memory, training, or social-rearing conditions (Neuhauser 1975). In the second phase, tasks of different complexity, such as repetitive, alternating, or sequential movements, were selected to set up a test instrument. After three versions of the assessment had been tested, a highly standardized testing procedure that provided reliable results was finally achieved.

The objective of this article is to describe the developmental course and interindividual variation for timed performance of 10 distinct motor tasks of variable complexity between the ages of 5 and 18 years. In a subsequent article duration and degree of associated movements will be discussed (Largo et al. 2001b).

Method

PARTICIPANTS

Table I provides the numbers of females and males of the six age groups, and means and standard deviations (SDs) of the ages at testing. In a cross-sectional study on neuromotor development, 477 children were recruited in kindergarten,

first, third, and sixth grade in the city of Zürich: mean age and SD of testing age, 5.8 (SD 0.42); 7.2 (SD 0.35); 9.3 (SD 0.39); and 12.5 (SD 0.44), respectively. The school classes were randomly chosen and all children recruited were initially included. Based on the test results and information obtained from parents and teachers, 17 children had to be excluded because of major deviations in age, obvious neurodevelopmental disturbances, such as cerebral palsy (CP), or unclear laterality. In all children a neurodevelopmental examination was carried out. The 202 participants examined at the ages of 15.0 (SD 0.05) and 18.1 years (SD 0.23) participated in the Zürich longitudinal study (Largo et al. 1996; 91.5% of the participants were right-handed and 8.5% were left-handed).

The majority of the children lived in the Zürich area and came from families with middle-class characteristics. Their mean socioeconomic status (SES; see below for definition) was significantly higher than that of the general population (Wilcoxon test; $p<0.05$).

ZÜRICH NEUROMOTOR ASSESSMENT (ZNA)

The ZNA is a standardized testing procedure in which distinct motor tasks are assessed with regard to timed performance, duration, and degree of associated movements of the contralateral and ipsilateral extremity, face, head, and body (Table II). Most motor tasks have been described previously by Denckla (1973, 1974), Wolff (1985), and Henderson and Sudgen (1992). Tasks were modified to reach the highest possible level of standardization for examination procedure, time measurement, and scoring of associated movements. Children's performances were videotaped. Informed consent was obtained from children and their parents after the testing procedure and the goals of the study had been fully explained.

The testing procedure is briefly described below (a manual with detailed instruction is available from the first author upon request).

Handedness

Handedness was verified by a hand-preference inventory consisting of four unimanual tasks. Children were asked to show the examiner how they write and draw with a pencil, cut with scissors, and brush their teeth. Children performing all four activities with one hand were included in the study and defined, respectively, as right- or left-handed. The preferred hand was subsequently called the dominant, and the non-preferred, the non-dominant hand.

Repetitive, alternating, and sequential movements

Children wore a minimum of clothing and rubber-soled socks or were barefoot. They sat in a chair facing the examiner, and were instructed to bring their legs into a position where hip, knee, and ankle joints are flexed at a 90° angle.

For each task, the examiner gave verbal instructions while demonstrating the expected performance to ensure that the child understood the instruction. Brief, untimed practice followed without specifying which side the child should try first. No effort was made during the practice or timed trials to control whether the child looked at their own performing limb or spoke during the activity. To measure the task at full exertion, after practising with both extremities the examiner said, 'When I say "go", do the same thing as fast as you can until I stop you'.

The time needed to perform the required number of movements, first for the dominant, then for the non-dominant side, was recorded for the following six motor tasks: (1) Repetitive finger movements – 20 taps between index finger and thumb while arms are held up sideways, shoulders and elbows are flexed at a 90° angle. (2) Repetitive hand movements – 20 pattings of one hand with the wrists resting on the thighs and the palm of the inactive hand held down. (3) Repetitive foot movements – 20 taps of the forefoot while the heel of the foot remains on the floor. (4) Alternating hand pronation–supination – 10 pairs of alternating movements of one hand with the wrists resting on the thighs and the palm of the inactive hand held up. (5) Alternating foot movements – 10 pairs of heel–toe alternations in a rocking motion, with one part of the foot always on the floor. (6) Sequential finger movements – opposing each finger with the thumb in sequence, i.e. 'index, middle, ring, little' comprises a set. Arms are held up as in repetitive finger movements. Younger than 7 years, three sets; older than 7 years, five sets.

The stopwatch was started by the examiner, not on the word 'go', but on the third tap, the second set, or the second alternating pair for each task, and stopped at the conclusion of the required number of movements.

Pegboard

The child sat at a table; the pegboard with 12 holes, fixed

Table I: Study population and mean ages at testing (n=662)

	Age at testing, y mean (SD)	*Females (n)*	*Males (n)*
n		336	326
Kindergarten	5.8 (0.42)	54	52
First grade	7.2 (0.35)	62	60
Third grade	9.3 (0.39)	57	57
Sixth grade	12.5 (0.44)	60	58
Longitudinal study	15.0 (0.05)	49	48
Longitudinal study	18.1 (0.23)	54	51

Table II: Motor tasks of the Zurich Neuromotor Assessment

Repetitive movements	Fingers
	Hand
	Foot
Alternating movements	Hand (pro-/supination in sitting position)
	Diadochokinesis[a] (pro-/supination in standing position)
	Foot (heel–toe alternation)
Sequential movements	Fingers
Pegboard	
Dynamic balance	Side-to-side jumping
	Forward jumping
Static balance	
Stress gaits[a]	Walking on toes
	on heels
	on outer soles of feet
	on inner soles of feet

[a] Items without timed performance are not presented in this article.

onto a plastic plank, was placed in front of the child. The child was given one practice attempt with each hand, i.e. completing one row of four holes. First the dominant hand was tested, and then the non-dominant. The inactive hand was placed in a relaxed position beside the pegboard.

The following two age-specific versions of the pegboard are applied: (1) For children aged 5 to 10.5 years, 14 plastic pegs were laid in a small plate beside the pegboard. The plate with the pegs was subsequently transferred to the other side of the board for the non-dominant hand. At the word 'go', the child began to pick up the pegs, and place them in any hole on the board. The pegs may be picked up in any order, but only one at a time. No transfer of a peg from one hand to the other is allowed. Timing was started when the child picked up the first peg and is stopped when he releases the last peg. (2) For children older than 10.5 years the pegboard was filled with 12 brass pegs whose ends are marked differently. At the word 'go', the child picked up the pegs, one at a time, inverted them so that the other end is showing up and put them back in their holes. The stopwatch was started when the child picked up the first peg and was stopped when the last peg is placed back in its hole.

Dynamic balance

An elastic cord was fixed 20 cm above the floor between two metal poles placed 4 metres apart from each other. For each trial the child has one practice attempt.

The first trial was side-to-side jumping. The child was asked to stand beside the cord and to jump back and forth over the cord sideways while keeping the feet together. At the word 'go', the stopwatch was started and then stopped when the child finished the last jump. For children younger than 10.5 years: 10 jumps; older than 10.5 years: 15 jumps.

The second trial was forward jumping: the child stood beside the cord next to one of the poles. The child was then asked to jump sideways over the cord six times while moving forward toward the second pole. The child turned around to perform another six jumps while returning to the first pole. At the word 'go', the stopwatch was started and stopped when the child had finished the last jump. For children younger than 10.5 years: two times six jumps; older than 10.5 years: three times six jumps.

Static balance

With the child standing, the examiner gave the instruction 'Choose one leg and stand on it for as long as you can'. The stopwatch was started when the child lifted one foot off the floor. It was then stopped when the child returned the lifted foot to the floor, or when a time limit of 60 seconds (s) was reached. The same procedure was repeated for the other foot. For children younger than 11.5 years, with stretched arms they hold a 30 cm long stick over their heads; and for those older than 11.5 years, the lifted leg is bent at the knee and the foot is held with both hands.

EXAMINERS' INSTRUCTIONS

The examiners were instructed by a detailed manual, pictures, and video sequences demonstrating precisely the testing procedure (e.g. how to place the child on the chair), time measurement, and scoring systems. During the training period, they tested normally developed children as well as those with neurological impairment, and during the study, they were regularly supervised by means of video recordings. In the cross-sectional study the children were tested by authors FH and KM, and in the longitudinal study by JAC and AAM.

ESTIMATION OF RELIABILITY

Intraobserver reliability was assessed by one examiner (AAM). Within an interval of 8 weeks, all motor tasks were timed twice using video recordings of 30 children. Interobserver reliability was assessed by two examiners (AAM, JAC). JAC took time measurements during the neuromotor testing, AAM timed the motor tasks from videotapes. Test–retest reliability was also assessed by two examiners (JAC, KM); each of them tested 11 seven-year-old children. One week after initial testing, they retested these children.

SOCIOECONOMIC STATUS

SES was estimated by means of a 6-point scale for both paternal occupation and maternal education; the lowest combined SES score was 2 (signifying the highest SES), the highest 12 (Largo et al. 1989).

Table III: Intraobserver, interobserver, and test–retest reliability for timed performance calculated by Spearman correlation coefficients

Motor task	*Reliability*		
	Intraobserver	*Interobserver*	*Test–retest*
n	30	30	11/11
Repetitive finger movements	0.90	0.90	0.32/0.51
Sequential finger movements	0.99	0.98	0.69/0.95
Repetitive hand movements	0.94	0.96	0.30/0.74
Alternating hand pro-/supination	0.98	0.91	0.92/0.94
Pegboard	0.99	0.99	0.77/0.61
Repetitive foot movements	0.99	0.99	0.15/0.82
Alternating foot movements	0.99	0.95	0.89/0.90
Side-to-side jumping	0.99	0.98	0.91/0.79
Forward jumping	0.99	0.99	0.62/0.62
Static balance	0.99	0.99	0.77/0.25

For all intraobserver and interobserver correlations: $p<0.001$; for test–retest correlations $p<0.05$: $r>0.62$; $p<0.01$: $r>0.75$; $p<0.001$: $r>0.90$.

STATISTICAL ANALYSIS

For the establishment of normative values, only data from right-handed participants were used. Time measurements showed a skewed distribution with an age-dependent variance. A log transformation achieved an approximately normal distribution with a nearly constant variance. For all timed performances a quadratic polynomial was found to model the relation between mean log time and age satisfactorily. Age-dependent centiles on the log scale were obtained by mean age + (c × SD), with the multiplier c from tables of the normal distribution. The SD was estimated as the median absolute deviation of the residuals from the fitted mean multiplied by the constant 1.4826. Centiles on the ordinary time scale were obtained by back transformation via exponentiation.

Spearman's correlations of the time measurements of the dominant extremity were used to estimate intraobserver, interobserver, and test–retest reliability.

Results

Data on reliability are presented first, then centile curves describing developmental course and interindividual variation for timed performance are provided. (Centile curves and normative data tables from 5 to 18 years are available from the first author upon request).

RELIABILITY

For comparison with previous studies, intraobserver, interobserver, and test–retest reliability are expressed by Spearman's rank correlations (Table III). Intraobserver and interobserver reliability were found to be very high (r=0.90 to 0.99, and 0.90 to 0.99, respectively). Test–retest reliability turned out to be lower, and varied considerably in both examiners (r=0.15 to 0.92, and 0.25 to 95, respectively). The low correlation coefficients of repetitive finger and foot movements were due to low variance of the time measurements (relative to measurement error) and correlations for static balance were low because of a ceiling effect.

DEVELOPMENTAL COURSE AND INTERINDIVIDUAL VARIATION

For the sake of brevity, only centile curves of the dominant extremity are presented. Among the various motor tasks they differed variably from those of the non-dominant extremity. Centile curves of timed performance for the motor tasks of the upper extremities are shown in Figure 1.

Timed performance of all motor tasks improved steadily throughout the entire prepubertal period. However, the annual increase in speed differed considerably among motor tasks. Between 7 and 18 years, the 50th centile for repetitive finger movements decreased from 6.2 to 4.2 s, while the 50th centile for sequential finger movements did so from 14 to 5.5 s. Timed performance of the various motor tasks also reached a plateau at different ages during adolescence. Repetitive movements levelled off at 15 years, and alternating movements did so at 18 years, while sequential movements had not quite reached a plateau by 18 years. Timed performance of the pegboard stopped improving already by the onset of puberty. This finding needs to be taken with caution because the testing procedure changed at 10.5 years.

Comparable observations were made for the lower extremities (Fig. 2). Repetitive movements improved on average by 3.2 s between 7 and 18 years and levelled off by 13 years, while alternating foot movements increased speed by 5.4 s and reached a plateau by 16 years. Timed performances of forward and side-to-side jumping increased up to 15 years and decreased slightly thereafter. An improvement up to the age of 18 years was noted for static balance.

Interindividual variation of timed performance was considerable among all motor tasks. At the age of 7 years, sequential movements were carried out by males, on average, in 14.2 s; 10% of the males needed more than 18.2 s, and another 10% less than 10.2 s. Interindividual variability decreased variably with age, although it was nearly constant on the log scale. Little change was noted in repetitive movements, while alternating and sequential movements showed a major reduction.

In the lower extremities interindividual variation decreased in all motor tasks with age, but remained large. At the age of 7 years females needed, on average, 10.2 s for 10 alternating foot movements; 10% of the females performed this task in less than 6.7 s and another 10% required more than 13.8 s. Dynamic and static balance showed large interindividual variation at all ages.

With regard to sex differences, females performed slightly faster than males in all motor tasks of the upper extremities between 5 and 7 years (see Fig. 1). Thereafter, females were slightly faster only in sequential movements, while males tended to be faster in repetitive finger and hand movements. Both sexes performed about equally fast in alternating hand pronation–supination and on the pegboard. With regard to the lower extremity, males performed again slightly faster than females in repetitive movements, and both sexes performed equally well in alternating foot movements, dynamic and static balance.

SOCIOECONOMIC STATUS

The mean SES of the study population was significantly higher than that of the general population (Wilcoxon test; $p<0.05$). Although the children of families of low SES were under represented, a statistical analysis of the impact of SES on timed performance was still possible. No significant correlation (Spearman) between SES and timed performance was noted for any of the motor tasks.

Discussion

Clumsiness in school-age children may substantially impair their academic performance and competence in other developmental areas, such as communication and social interaction with peers, and thus, clumsiness profoundly influence feelings of well-being and self-esteem (Polatajko 1999). Mild-to-moderate motor dysfunction is a significant epidemiological problem, occurring in up to 6% of the children in the general population (American Psychiatric Association 1994). In spite of the numerous articles published on this subject, the assessment of motor dysfunction has remained a controversial issue mainly for two reasons: questionable test reliability and lack of normative data.

How reliable are timed measurements of motor performances? Only a few studies validating the reliability of the most widely used assessments (Touwen and Prechtl 1979, Denckla 1985) have been published. Denckla (1973) analysed test–retest reliability of timed performance in school-age children 3 weeks after the initial testing. Correlation coefficients between trials were 0.69 for repetitive and 0.80 for successive movements. Vitiello and coworkers (1989) estimated interobserver and test–retest reliability of neurological subtle signs in

54 psychiatric patients and in 25 normally developing children, aged 5 to 17 years, using the revised version of the NESS. An acceptable interrater reliability (kappa coefficient ≥0.50, intraclass correlation coefficient ≥0.70) was found for 40 of 64 items tested. This was particularly true for continuous variables, such as time needed to perform 20 consecutive movements.

In our study intraobserver and interobserver reliability of

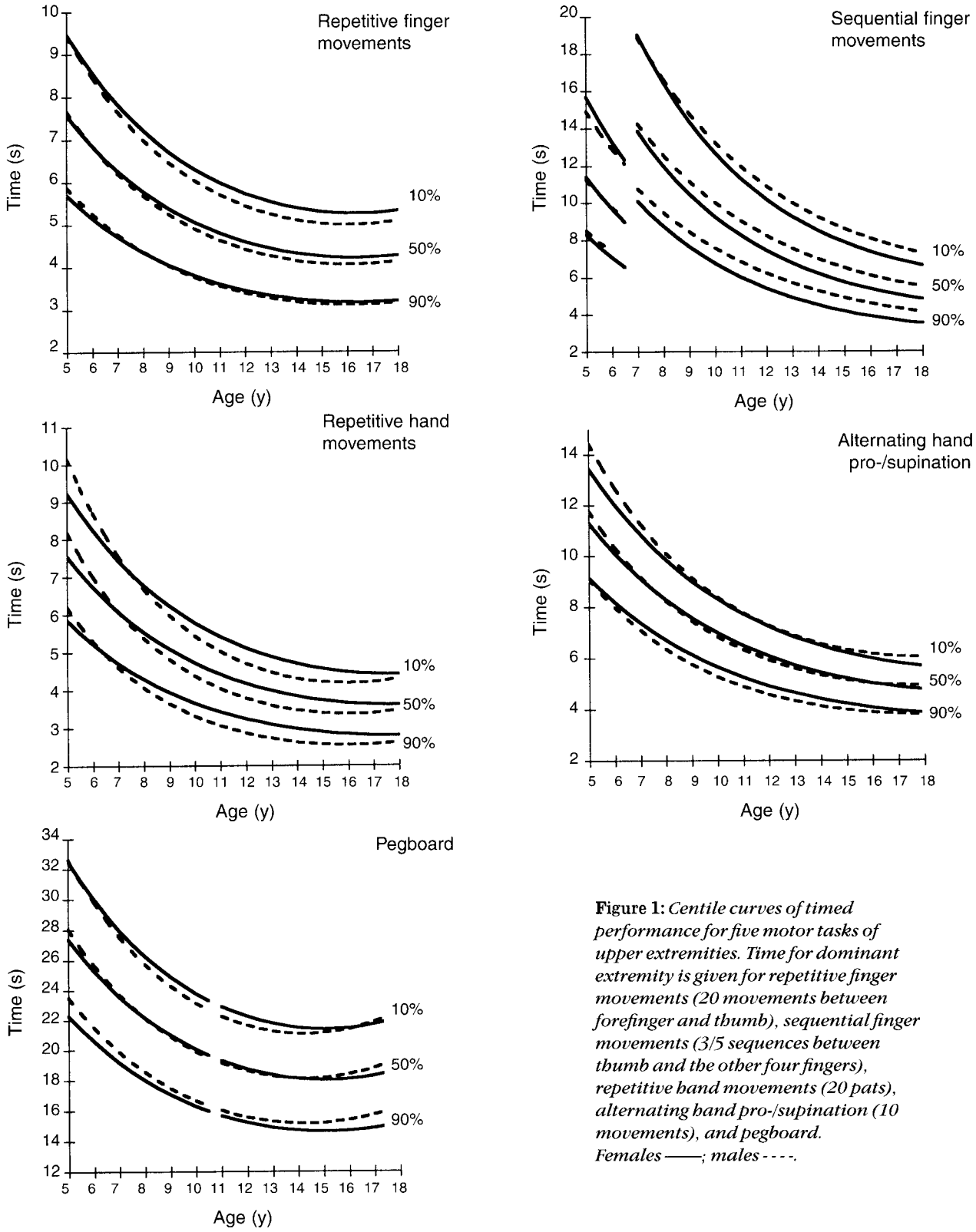

Figure 1: *Centile curves of timed performance for five motor tasks of upper extremities. Time for dominant extremity is given for repetitive finger movements (20 movements between forefinger and thumb), sequential finger movements (3/5 sequences between thumb and the other four fingers), repetitive hand movements (20 pats), alternating hand pro-/supination (10 movements), and pegboard. Females ——; males - - - -.*

timed performance was found to be very high (Spearman's rank correlations >0.90), while test–retest reliability was lower. Moderate correlations between trials most likely reflected the intraindividual variability of the children, whose daily performance depends on their actual physical and mental fitness, mood, and motivation. To determine the clinical relevance of timed performances a detailed analysis of the various aspects of reliability and validity of the ZNA is currently

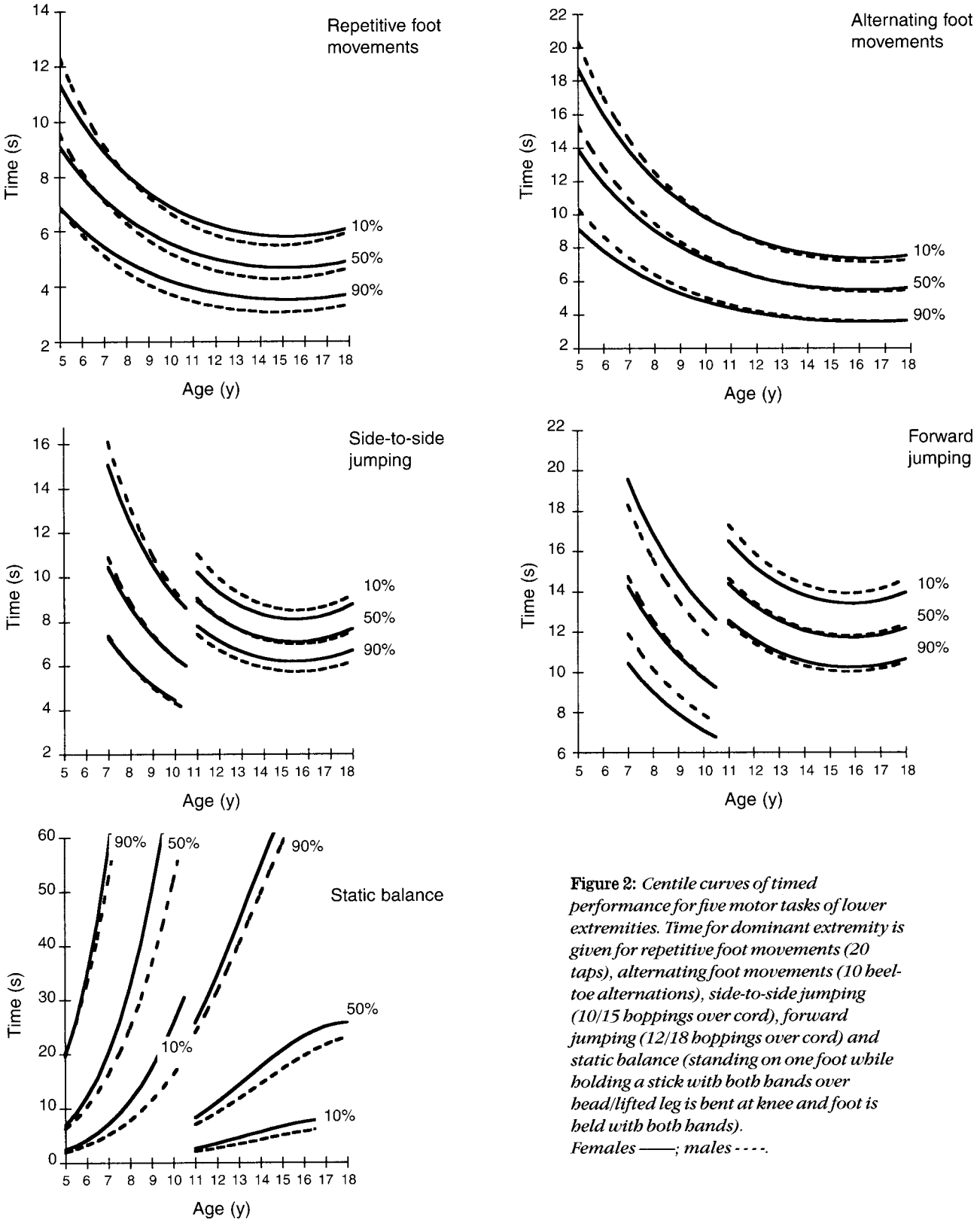

Figure 2: *Centile curves of timed performance for five motor tasks of lower extremities. Time for dominant extremity is given for repetitive foot movements (20 taps), alternating foot movements (10 heel-toe alternations), side-to-side jumping (10/15 hoppings over cord), forward jumping (12/18 hoppings over cord) and static balance (standing on one foot while holding a stick with both hands over head/lifted leg is bent at knee and foot is held with both hands).*
Females ——; *males* - - - -.

being carried out in children with and without neurological disabilities. Preliminary results indicate that timed performances of various motor tasks are not equally affected by neurological disturbances. For example, performance profiles appear to differ between children with spastic and those with dyskinetic CP.

Age-specific normative data have been collected for motor-behavioural assessments used in educational settings, using for example, the Movement Assessment Battery for Children (Henderson and Sugden 1992). In these tests, the child is asked to carry out complex motor tasks, such as throwing and catching a ball or cutting paper with scissors. The test results provide useful information about how the child is functioning in daily life. However, because the child's performance relies heavily on non-motor functions, such as visual and tactile–kinesthetic perception as well as on previous experience, the results reflect motor competence, per se, to a limited extent.

Normative data for distinct motor tasks, used in clinical settings and research, are rarely provided. Denckla (1973, 1974, 1985) published age-specific normative values for timed performance for early school age, i.e. mean values and SD for the speed of repetitive, alternating, and sequential movements. She demonstrated that performance speed is, as expected, lower in younger children, but reaches a plateau between 8 and 10 years of age. Wolff and colleagues (1983, 1985) essentially confirmed her findings. In a recent article Fietzek and his coworkers (2000) reported on developmental changes of central conduction times and motor performance tests from the first to the third decade.

Our results clearly demonstrate that timed performance in all motor tasks studied improved throughout the entire prepubertal period. However, the increase in speed differed considerably and appeared to be a function of the complexity of the movement pattern. Repetitive movements improved less than alternating and sequential movements. The age at which a specific motor task reached a plateau seemed also to be related to the complexity of the movement pattern. Repetitive movements levelled off as early as 12 to 15 years, while alternating and sequential movements improved up to the age of 18 years. Speed in pegboard and dynamic balance increased up to 15 years, and started to decrease again thereafter. Our centile curves of timed performance not only displayed long-lasting, age-specific changes, but also showed large interindividual variations for all motor tasks.

There is a general assumption that females perform faster than males, particularly in fine motor tasks. However, previous studies on sex differences provided mixed results. In Denckla's studies (1973, 1974), successive finger movements and heel–toe alternation were performed faster by females, while males tapped faster. In the pegboard task, Annett (1970) observed that females were slightly faster than males with the right hand, while males were slightly faster than females with the left hand. In the Zürich studies, females tended to be faster than males in all motor tasks between 5 and 7 years. Thereafter, in agreement with Denckla, females still performed better in sequential movements, while males were slightly faster in repetitive movements. Both sexes did equally well in alternating movements, pegboard, and dynamic balance. In a forthcoming paper on timed performance and associated movements we will report in detail on the significance of sex as well as laterality and handedness.

One of the most important variables affecting intellectual development is SES (Dunn 1987, Largo et al. 1989). With respect to motor performance, correlational analysis revealed no significant relation between time measurements of any motor task at any age and SES. Thus, motor performance in normally developing children does not seem to be substantially influenced by either genetic endowment or the environmental influences that may be deduced from SES. The centile curves presented are applicable to children of all social classes.

In conclusion, our results demonstrate that timed motor performance between 5 and 18 years is characterized by a long-lasting developmental change and large interindividual variation; both change and variation are a function of the complexity of the motor task. Therefore, for a reliable assessment of motor competence in school-age children, a well standardized test instrument, and age-specific standards for motor performances are necessary preconditions.

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