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RESEARCH ARTICLE

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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 characterised 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 nine 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 characterised 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

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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 its 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 organising 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 organisation to one of greater order and stability associated with mastering excessive degrees of freedom (Bernstein 1967; Kugler 1986). Such a state would be characterised 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 organise 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 4 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 characterisation 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 focused 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 and 7 years (van 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 years 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 4–5, 6–7, 8–9 and 10–11 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

Table 1 Anthropomorphic and demographic data for children and adults

Group	Age (years)	Sex, M/F	Height (m), (SD)	Weight (kg), (SD)	Trunk/arm length ratio
G1	4–5	4/5	1.1 (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	27–60	5/4	–	–	–
Mean (SD)	55 (13.7)				

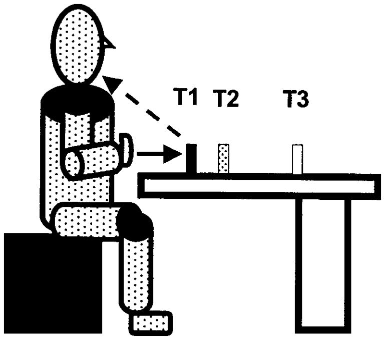

Fig. 1 Schematic diagram of the experimental set up. Targets were placed at arm's length (T2), two-thirds arm's length (T1), and one and two-thirds arm's length (T3). The action was to reach and grasp the object and bring it to the mouth. Only the reach-to-grasp movement was analysed (*thick arrow*)

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 normalise the data for comparison between participants of different sizes. The three target distances were two-thirds (T1), one (T2), and one and two-thirds (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.

Data acquisition and analysis

Kinematic data were collected using a three-dimensional optical tracking system (Optotrak, Northern Digital, Model 3010) with eight infrared emitting diodes 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 characterise 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 three-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 a semicircle 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 100 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 seven and ten trials per target without amplitude or temporal normalisation 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 characterised qualitatively and quantitatively. Temporal and spatial interjoint coordination have been identified in previous studies as essential characteristics of reaching in this specific task (Cirstea and Levin 2000; Levin 1996). Interjoint coordination was characterised 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 intracurve consistency of the three elbow–shoulder interjoint coordination curves across targets. For the SDd variable, intercurve 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 intertarget variability. This was computed as the average of the two-dimensional 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* 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° 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).

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). The *t*-tests between G5 (adults) and children's 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 in children aged 10–11 years (G4). For T3, variability decreased and

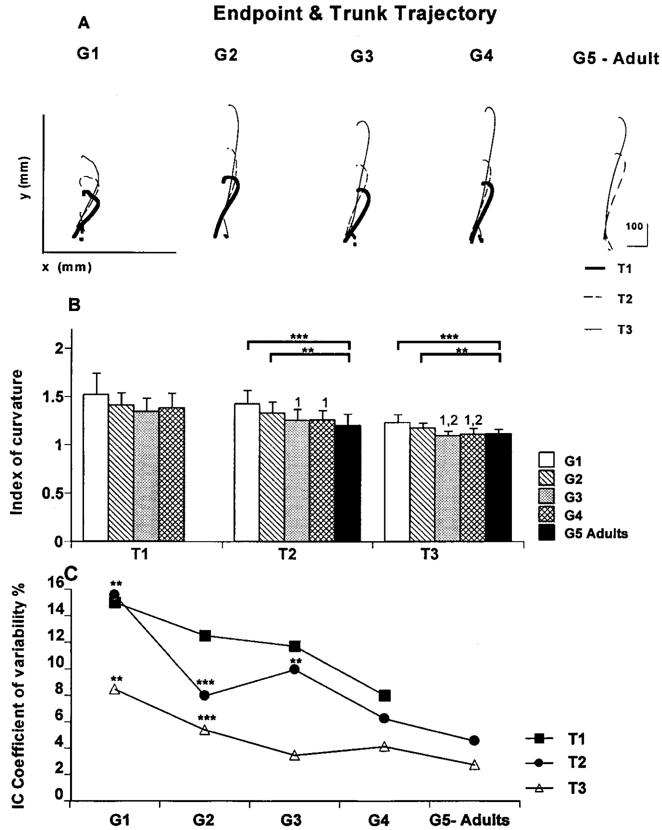

Fig. 2 A Mean endpoint (hand) trajectories to close (T1, *thick traces*), middle (T2, *thin dashed traces*) and far targets (T3, *thin traces*) for one representative child in each age group (G1–G4) and for T2 and T3 in one representative adult subject. Corresponding trunk trajectories are also shown. **B** Mean (SD) endpoint path straightness (index of curvature) data for each child group shown for reaches to three 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 (*IC*) for each group for three targets. *Asterisks* indicate that the group mean differed from the adult group mean. ** $P<0.01$; *** $P<0.001$

attained adult levels at a younger age (age 8–9 years, 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 T1–3, 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.

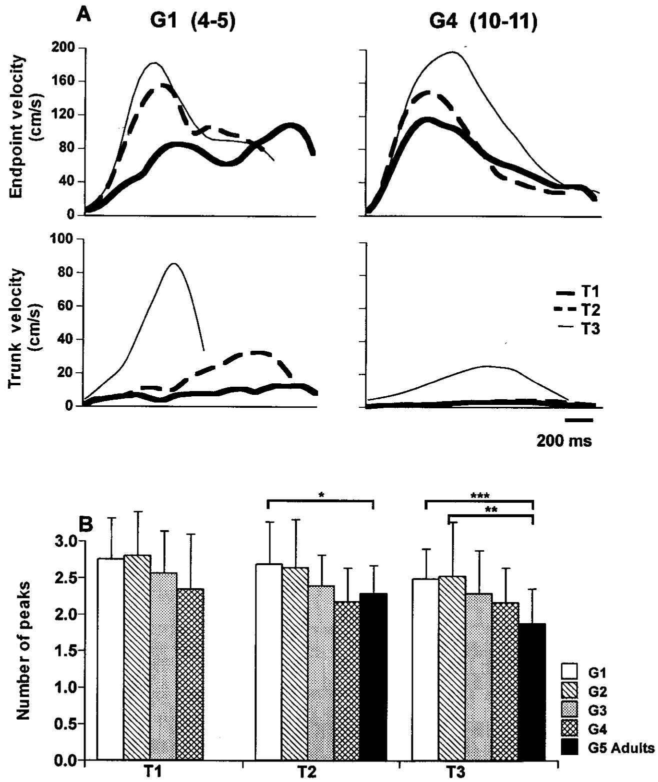

Fig. 3 **A** Mean endpoint and trunk velocities for movements to T1 (*thick line*), T2 (*thick dashed line*) and T3 (*thin line*) for representative children in groups 1 (*G1*) and 4 (*G4*). **B** Mean (SD) number of peaks in the endpoint velocity traces for each group. Groups and significance indicated as in Fig. 2. * $P<0.05$

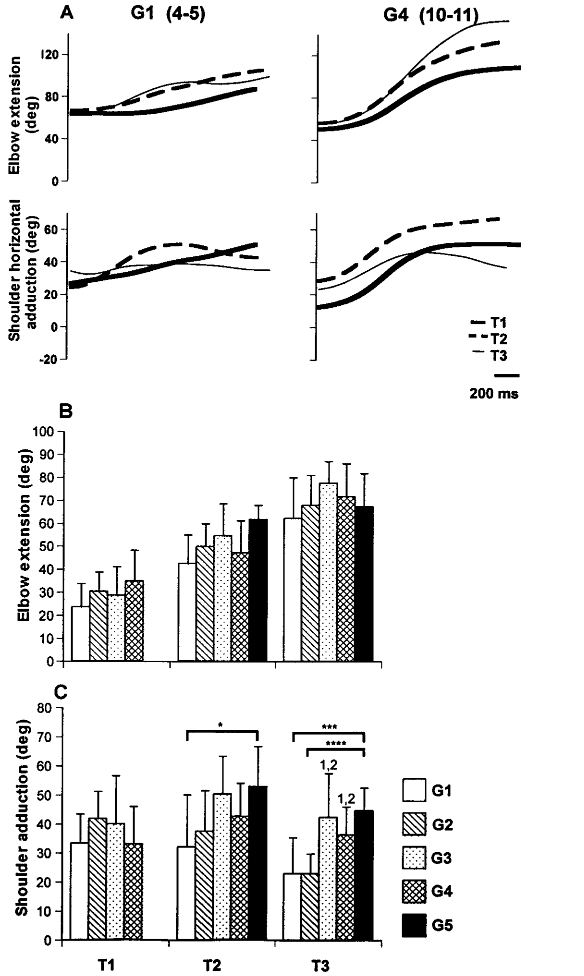

Fig. 4 **A** Mean angular displacements of elbow extension (*top*) and shoulder horizontal adduction (*bottom*) for same two subjects shown in Fig. 3. Mean (SD) displacements for each group and target are shown for elbow extension in **B** and shoulder adduction in **C**. Groups and significance indicated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

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. 4A, 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 $F(3,37)=0.489$–1.514, $P=0.22$–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 years (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 years for T2. On the other hand, trunk 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 children's groups compared to adults for T2 (*t*-tests, $P<0.01$–0.001) and up to age 8–9 years 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).

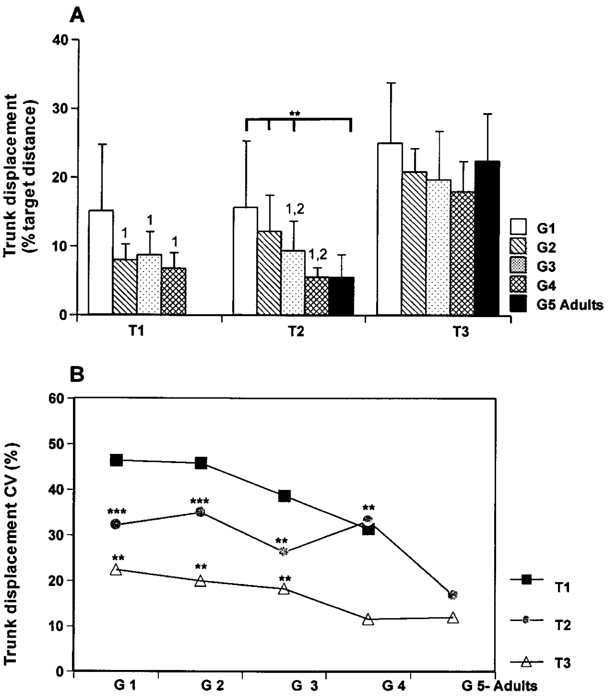

Fig. 5 A Mean (SD) trunk displacement for all groups and targets expressed as a percentage of target distance. B Coefficient of variation (*CV*) of trunk displacement for each group and target. Groups and significance are indicated as in Fig. 2

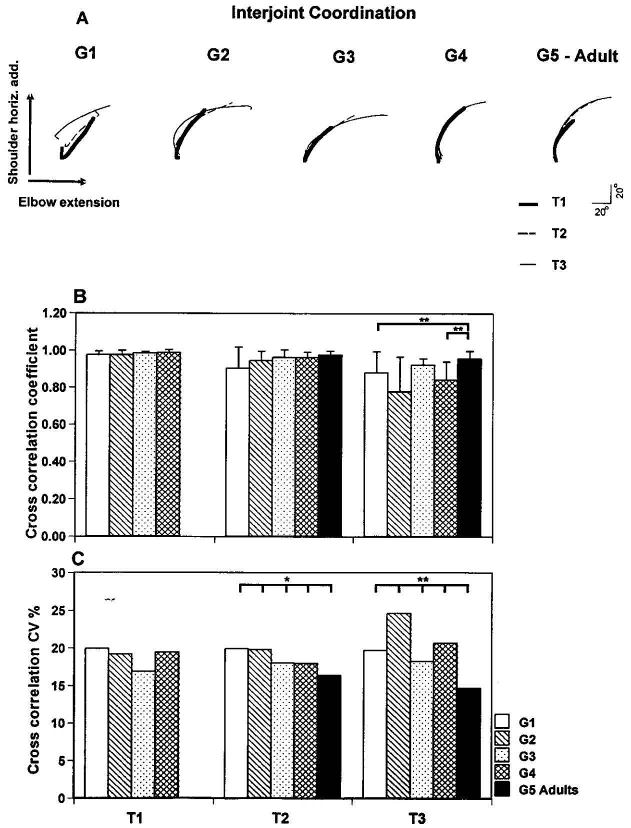

Fig. 6 A Mean interjoint coordination between shoulder horizontal adduction and elbow extension for the same representative subjects in each group as shown in Fig. 2. *Thick line* T1, *dashed line* T2, *thin line* T3. Mean (SD) coefficients of correlation (**B**) and variability of correlation (coefficient of variability; **C**) for each group and target. Groups and significance indicated as in Fig. 2

Development of interjoint coordination pattern occurs with age

Interjoint coordination between shoulder adduction and elbow extension movements was analysed. The degree of overlap in interjoint coordination 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 analysed 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, $P<0.05$–0.01).

To analyse the spatial variability of interjoint correlation throughout the reach, we examined the degree of overlap between the interjoint coordination patterns of reaches to the three targets (SDd measure) and their total intertrial variability across targets (SDt measure). High values of both measures reflected inconsistency in interjoint coordination 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 optimise the interjoint coordination pattern across the targets, data were compared to the adult group. Significant differences were found between the adult group and children's groups G1 and G2 for the SDd measure (t-test, $P<0.05$; Fig. 7A) and for all children's 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 characterised by higher values of SDd and SDt representing more variability in interjoint coordination. In contrast, cluster 2 consisted of 23 points representing low interjoint coordination variability. Seventy-five percent of this cluster was composed of points obtained from older children (10–11 years) and

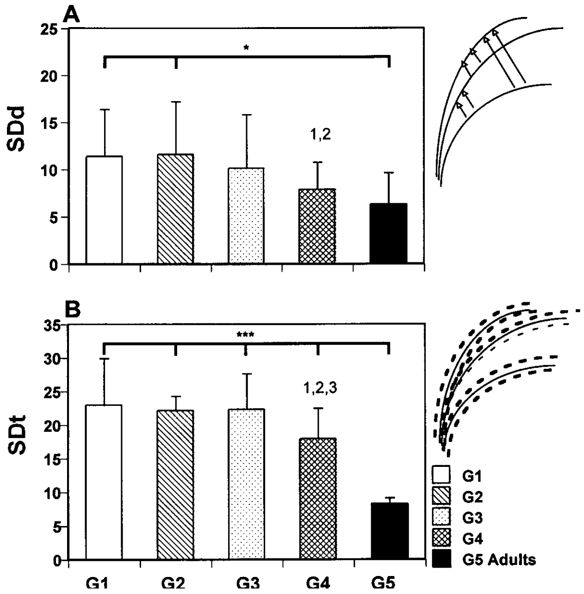

Fig. 7 Mean (SD) intertarget (*SDd*; **A**) and intratarget (*SDt*; **B**) variability of elbow–shoulder interjoint coordination for each group. Variabilities are summed across targets. SDd is a measure of the distance between mean coordination patterns (*inset* **A**) and SDt sums the variability of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

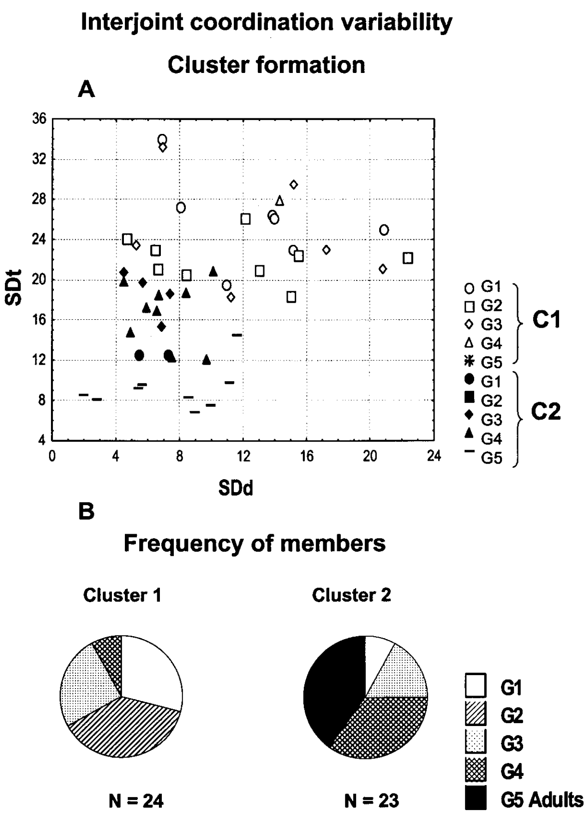

Fig. 8A, B Results of cluster analysis of interjoint coordination variability. **A** The cluster formation considering the interaction of the two components (intertarget, SDd and intratarget, SDt variability). **B** Distribution of children and adults in each cluster

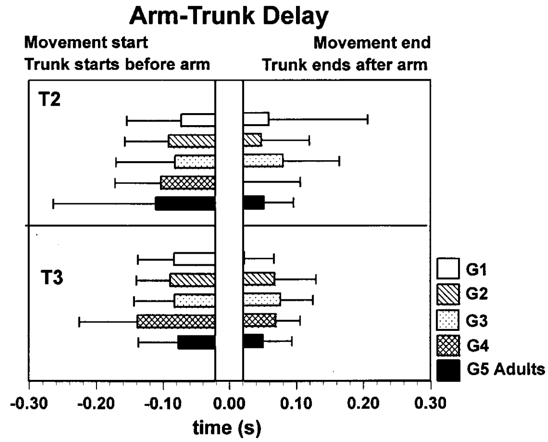

Fig. 9 Temporal arm–trunk coordination for reaches to T2 and T3 in four children's groups and one adult group. *Horizontal bars to the left* indicate that the trunk started moving before the arm at the beginning of the reach. *Horizontal bars to the right* show that the trunk stopped moving after the 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*)

adults. Data from children aged 8–9 years (G3) were more equally distributed between the two clusters.

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 organised 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 characterise 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 characterising motor execution. These variables were grouped into four categories: those characterising endpoint trajectory, joint excursions, trunk involvement and coordination (Fig. 10). To facilitate discussion, age-related differences for each variable are summarised according to target distance. The figure also shows at what age mature patterns emerge for each movement variable based on a comparison with healthy adults.

Fig. 10 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

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 hand tasks in children. Depending on the task studied, the attainment of mature movement patterns or behaviours is reported to occur around age 8 years for the coordination of grip and load forces during precision lifting (Forssberg et al. 1991; Kuhtz-Buschbeck et al. 1998), age 10 years for postural control (Dietz 1992; Shumway-Cook and Woollacott 1985) and age 12 years 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

Spatiotemporal 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 (Michaelsen et al. 2001; Roby-Brami et al. 1997). 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 (Andersen et al. 1997; Feldman and Levin 1995; Paillard 1991; Soechting and Flanders 1992; 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 (Ghafouri et al. 2002; McIntyre et al. 1998; Soechting and Flanders 1992). The origin of the reference frames may be shoulder- (Soechting and Flanders 1989), head- (Flanders et al. 1992) or eye-centred (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 to 36 months of age, Konczak and Dichgans (1997) suggested that vertical reaches may be planned in a shoulder-centred 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 prioritises the control of this variable. In our task, trajectory variability decreases earlier than interjoint coordination (age of 8–9 years compared to age 11 years or older), supporting the hypothesis that movements are planned in end-effector rather than joint-space (Abend et al. 1982; Flash and Hogan 1985; Georgopoulos et al. 1982; Morasso 1981). 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 years, 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 years 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 (Assaiante 2000; Haas et al. 1989; Hay and Redon 1999, 2001). 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 stabilisation and timing of muscle activation during bimanual 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 years 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 (see, for example, 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 years, 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 years. It has been suggested that for reaching, arm and trunk motions are governed by different neuromotor synergies (Kaminiski et al. 1995; Ma and Feldman 1995; Saling et al. 1996; Wang and Stelmach 1998). 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 stabilise 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 minimise trunk involvement due to the lack of maturation of cortical areas involved in sensorimotor integration (Kostoviæ

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 years (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, optimises but does not entirely limit the interjoint coordination patterns used for the task. The optimisation 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 ten 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 optimisation of interjoint coordination patterns for reaches to the three targets occurred slowly up until the age of 8 years, when mature patterns emerged, while intertrial variability remained greater than adults in children aged up to 11 years or more (Fig. 10).

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 stabilise the end effector (hand) trajectory (de Guzman et al. 1997; Morasso 1981). However, during development, the problem confronted by the nervous system is twofold: 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 years for T2 and 8 years for T3 while evidence of increased variability in interjoint coordination patterns persisted in children as old as 11 years 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 optimise 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 1994). 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 characterise gross motor function (usually of bilateral manual tasks) according to developmental milestones in normal children (Folio and Fewell 1983; Ottenbacher et al. 1997). 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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