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RESEARCH ARTICLE

Head, arm and trunk coordination during reaching in children

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Abstract During postural and locomotor tasks, the orientation of the head with respect to space is maintained in order to serve as an egocentric reference value for maintaining balance. In young children during locomotor tasks, task difficulty determines the coordination of movements between head–trunk segments: the more difficult the task, the more the child limits the head on trunk movement ("en bloc") rather than letting the head move freely in space. For reaching tasks, however, there are no data about the development and maturation of coordination between the head and trunk movements and when the pattern of coordination is considered mature. The goal of this study was to characterize the development of head–trunk coordination during reaching from a sitting position in typically developing children. Forty-four typically-developing (TD) children aged from 2.8 to 11.8 years and six healthy adults participated. Children were divided into five groups (G1–G5) according to their age: 2–3, 4–5, 6–7, 8–9 and 10–11 years old. The task involved reaching towards and grasping a piece of food in the younger group or a wooden block in the older children and adults with the dominant hand, adequate to the grip size of each participant, and returning it to the mouth area to simulate self-feeding. The object was placed in line with the midline of the body at three different distances from the trunk according to the participant's arm length (two within and one beyond arm's length). Rotational movements of the head and trunk in three planes; yaw, roll and pitch, were recorded using three-dimensional tracking systems (Optotrak, Northern Digital, Model 3010 or Ariel Performance Analysis System). The variables analysed were relative head and trunk angle, absolute head and trunk angle, the anchoring index (AI) and initial direction of head and trunk rotation (direction index: DI). Patterns of head–trunk coupling were different along different axes of rotation and across groups. For the AI, a head-stabilized-on-trunk (HST) or "en bloc" pattern was observed with approximately the same frequency as a head-stabilized-in-space (HSS) pattern in the youngest children in the yaw plane for reaches within arm's length. In all other planes and for reaches of all distances, a HSS pattern was evident in the youngest children and remained consistent across the groups of children. Compared to the children, adult reaching was characterised by fixed head–trunk coordination (HST) in the roll plane at all reach distances, and greater decoupling in yaw plane motion for the two closest distances. There were no age-related differences in the pitch plane strategy which was mainly HSS. The DI patterns matured by 2–3 or 4–5 years of age, except for reaches to T1 in the pitch plane. In addition, in the roll plane, there was evidence of a two-step maturation that was not complete until adulthood. Maturation of strategies used to stabilize the head and trunk

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relative to each other and to the reaching arm differ across movement planes for a seated reaching task. Our data suggest that different aspects of head and trunk coordination during reaching movement mature at different rates, like for locomotor tasks previously described, and that the maturation follows a non-chronological and protracted course. These results can serve as a comparative database with which to contrast head and trunk coordination in children with movement disorders. However, in terms of typical development, these data should be considered specific for the task studied and may not reflect general principles of motor development.

Keywords Motor control · Reaching · Grasping · Head trunk coordination

Introduction

The coordination between head, trunk and arm movements during purposeful reaching in children is important for the performance of many everyday activities, including self-feeding. Mastery of reaching and manipulation is predicated on adequate postural control (Bertenthal and von Hofsten 1998). While postural adjustments of the head and trunk have been well-characterized in typically-developing (TD) infants (van der Fits et al. 1999a, b; van der Heide et al. 2003) and for older children during locomotor tasks (e.g., Assaiante and Amblard 1993, 1996; Assaiante et al. 1997; Breniere and Bril 1998; Assaiante 1998; Vallis and McFadyen 2005), little information exists for TD children older than 2 years of age for the further maturation of postural stability and the coordination of the head and trunk related to functional reaching (but see van der Heide et al. 2003). This may be because the focus has been on the time of appearance of a specific behavior in infancy, with the assumption that this posturo-kinetic behavior is mature by the beginning of the toddler years. For example, van der Fits et al. (1999b) found that by 15 months of age, when reaching to objects placed at arm's length, the temporal sequence of activation of muscles of the head and trunk was similar to that of adults, and was characterized by a dorso-ventral and cranio-caudal order of postural muscle recruitment. Thelen and Spencer (1998), using the criterion of achievement of a midline head position for 50% of reaches, established that the onset of head stability had occurred in infants by 9–15 weeks of age, which was on average 4.7 weeks before reaching onset. Leaning forward to grasp an object was observed to be coincident with the ability to sit independently (Rochat 1995), while anticipatory preparation of trunk muscles prior to the reach may (Von Hofsten and Woollacott 1989; Casimiro and Sveistrup 2001) or may not (van der Fits and Hadders-Algra 1998) be present at 9 months of age, depending on task goals and constraints. These results are consistent with the finding that by 8 months of age, infants effectively use leaning to extend their range of reach and grasp (McKenzie et al. 1993). By 3 years of age, children are able to distinguish between objects within versus beyond reach (Rochat 1995). Thus, previous studies have suggested that by the age of 3, several aspects of purposeful reaching appear to be well-developed.

The optimal coordination between head, trunk and arm movements during reaching involves the mastery of a redundant number of degrees of freedom while the body grows (Bernstein 1967; Thelen and Spencer 1998). Previous studies have shown that interjoint and intersegment coordination of the arm and trunk during a reach and grasp task continues to develop even into late childhood (Dellen and Kalverboer 1984; Hay 1990; Schellekens et al. 1984; Schneiberg et al. 2002). During childhood, changes occur in the variability of grasping (Deutsch and Newell 2004) and manipulating objects (Elliott and Connolly 1984), and in the application of forces and the timing of grasping and lifting for uni-manual (Forssberg et al. 1991) and bi-manual (Schmitz and Assaiante 2002; Schmitz et al. 2002; Roncesvalles et al. 2005) tasks. Changes in arm trajectory variability in reaching also occur over this period (Schneiberg et al. 2002). As well, a developmental transition period for coordination of hand and eye movements during pointing tasks occurs between the ages of 4–7 years (Hay 1990), while perception of the location of an object in space is different between 5- and 7-year-old and 9-year-old children (Huttenlocher et al. 1994). Similarly, the ability to coordinate the head and trunk in an articulated (head stable in space) rather than in an 'en bloc' or strapped-down (head stable on trunk) strategy appears to be a task dependent process during locomotor activities, and matures slowly and non-linearly with age (Assaiante and Amblard 1993).

The development of postural adjustments accompanying arm's length reaching movements in children between 2 and 11 years of age was characterized by examination of anticipatory muscle activation and postural adjustments for reaches in the sagittal plane with the pelvis in the neutral, anterior or posterior tilt position (van der Heide et al. 2003). For anticipatory adjustments, the head gradually became the dominant frame of reference and up until 18 and 24 months of age, children had a preference for an "en bloc" strategy. However, this analysis focused on postural muscle activity and was not specifically related to the anchoring index (AI) of Assaiante and Amblard (1993), which may be useful as a comparative index across experimental paradigms. As well, van der Heide et al. (2003) did not examine reaches to different distances or discuss head–trunk coordination in different planes. As trunk involvement during reaching appears to be both a function of age and object distance (Schneiberg et al. 2002), and the "en bloc" configuration may vary in the three planes (sagittal, frontal, transverse) for a given movement in adults and children (Assaiante et al. 1997), an understanding of the maturation of reaching should include these factors.

Thus, the purpose of this study was to characterize the coordination of the head and trunk movements during seated reaches to objects placed at distances less than, equal to and greater than the length of the arm in TD children between the ages of 2 and 11 years. A better characterization of head–trunk coordination may serve as a normative database for the comparison of the behavior in children with developmental delays or cerebral palsy, and to evaluate the effects of therapeutic interventions such as trunk restraint on motor performance for similar tasks. Preliminary data have appeared in abstract form (Levin et al. 2003; Schneiberg et al. 2003, 2004).

Methodology

Subjects

This is a cross-sectional study of 44 healthy children aged from 2.8 to 11.8 years and six healthy young adults, who were recruited from the community. Adults and parents/guardians of the children signed an information and consent form consistent with the declaration of Helsinki that was approved by the Ethics Committee of the Rehabilitation Institute of Montreal and the Research Ethics Board of the University of Ottawa. Children were included if they had experienced typical motor development as verified by a questionnaire about birth complications and the appearance of motor milestones. The questions were developed in conjunction with health professionals experienced in developmental delays. Hand dominance was determined in children over the age of 5 using the Handedness questionnaire (Crovitz and Zener 1962). For younger children, hand dominance was tested by observing which hand was predominantly used when drawing a picture and reaching for an object. The adults were healthy without any orthopaedic or neurological impairments affecting reaching.

Data from children were divided into five groups according to the child's age at the time of the study: Group 1 (G1) consisted of six children aged 2 and 3 years; Group 2 (G2) was made up of nine children aged 4 and 5 years; Group 3 (G3) included nine children aged 6 and 7 years; Group 4 (G4) included ten children aged 8 and 9 years; Group 5 (G5) included ten children aged 10 and 11 years; and Group 6 (G6) included six adults aged 22–32 years old.

Experimental paradigm

The task was a natural, well-learned movement related to self-feeding. It involved reaching with the dominant hand towards and grasping a food item or wooden block (2–4 cm^3) adequate to the grip size in all groups of children and adults, and returning it to the mouth area. Participants sat on an adjustable stool that had no back support. According to Crosbie et al. (1997) and Chari and Kirby (1986), seat height and extent of thigh and foot support may affect reaching distance. Thus, seat height was adjusted to 100% of lower leg length, which was measured from the lateral knee joint line to the floor with the participant standing. The participant sat with 1/3 of the thigh extending beyond the seat of the stool. The target was placed on a table adjusted to the height of each participant's elbow when the arm was alongside the body.

The target was placed in line with the body midline at three different distances according to the length of the participant's arm. Arm length was measured from the medial border of the axilla to the distal wrist crease. Placement of the targets as a function of arm length served to normalize the data for comparison between participants of different sizes. The three target distances were 67% (T1), 100% (T2), and 167% (T3) of arm's length. Reaching movements to targets placed at greater distances from the body were used to investigate the relationship between coordination of the body segments with increasing involvement of the trunk. The participants were instructed to reach at a natural self-paced speed, to grasp the target and bring it to the mouth region and self feed or imitate self-feeding. A task with a functional goal was chosen because performing reaches in a functional context favors more natural movement (Ada et al. 1994). After two to three 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 with the hand in an initial position with the thumb positioned approximately 5 cm in front of mid-sternum, the hand was relaxed and the elbow was adducted alongside the trunk. Reaches required extension of the elbow combined with shoulder flexion and horizontal adduction. In addition, reaches to the farthest target (T3) required forward displacement of the trunk (Fig. 1a).

Data acquisition

Kinematic data were collected using a three-dimensional optical tracking system (Optotrak, Northern Digital, Model 3010) for G2–G6 and a three-dimensional video tracking system for G1 (Ariel Performance Analysis

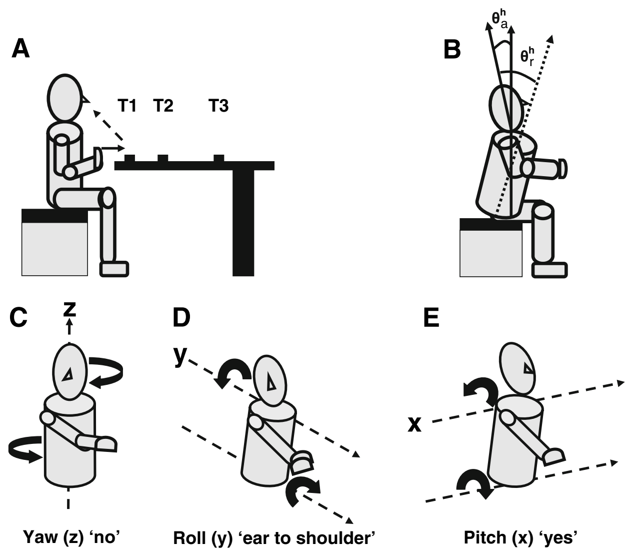


Fig. 1 **a** Schematic diagram of the experimental set up. Targets were placed at 66% (T1), 100% (T2) and 167% (T3) of arm's length. The action was to reach and grasp the object and bring it to the mouth. Only the reach-to-grasp movement was analyzed (*solid arrow*). **b** Illustration of the absolute (position in Cartesian coordinates of the room: $\theta^{\mathrm{h}}_{\mathrm{a}}$) and relative (position relative to the trunk: $\theta^{\mathrm{h}}_{\mathrm{r}}$) angle of the head in the pitch plane. **c**–**e** Absolute and relative rotation of the head and trunk were calculated in the yaw, roll and pitch planes

System). Video tracking was used for the youngest children since they were less tolerant of adhesive markers and wires used in the Optotrak system. Head and trunk movements were measured from the rigid bodies formed by groups of three non-colinear markers made up of either infrared emitting diodes (IREDs for G2–G6) or reflective balls for G1 and placed on the forehead and the trunk. For measurements of the trunk movements, all markers were placed on the ipsilateral and contralateral acromion processes and on the mid-sternum. In addition, movements of the arm endpoint were recorded by a marker placed on the index finger. Data were recorded for 3 s at a sampling rate of 100 Hz. Although the task consisted of reaching, grasping and bringing the object to the mouth, only data recorded during the reach-to-grasp movement was analysed in this study.

Data analysis

Data were low-pass filtered with a three-point Butterworth filter (cut-off frequency of 10 Hz). We determined the movements of the head and trunk segments in space (absolute yaw, roll and pitch) and with respect to each other (relative yaw, roll and pitch; Fig. 1b–e). Absolute rotations were determined by computing angles relative to rotations about the horizontal, sagittal and vertical axes in Cartesian coordinates of the room. In addition, pitch, roll and yaw rotations of the head in a body-centred reference frame were computed relative to movements of the trunk segment. Angles were assumed to be positive if the corresponding rotations were in a counterclockwise direction and negative if they were in a clockwise direction.

To characterize the stability of the head movement during reaching movements to each target, we computed the Anchoring Index (AI; Assaiante et al. 1997). The AI compares the behavioural strategy for stabilization of a given segment (head) with respect to both external space and to the inferior anatomical segment (trunk). It is defined as the ratio of the difference between the standard deviation of the relative head–trunk and absolute head angular distributions to their sum:

$$\text{Anchoring index} = \frac{\sigma(\theta^h_r) - \sigma(\theta^h_{\mathrm{a}})}{\sigma(\theta^h_r) + \sigma(\theta^h_{\mathrm{a}})}$$

where $\sigma(\theta^h_{\mathrm{r}})$ is the standard deviation of the angular distribution of the head movement relative to the trunk and $\sigma(\theta^h_{\mathrm{a}})$ is the standard deviation of the absolute angular distribution of the head movement in space (with respect to external axes). A positive value of AI would indicate a better stabilization of the head in space than on the trunk ("head-stabilization-in-space strategy"; HSS), whereas a negative value would indicate a better stabilization of the head on the trunk than in space "head-stabilization-on-trunk strategy" head-stabilized-on-trunk (HST; Fig. 2a–c). AIs were calculated for individual trials for each participant in each plane of rotation (yaw, roll and pitch).

While the AI describes the variability of head movement with respect to space and to trunk movement, it does not directly specify the direction of movements of either head or trunk segments. To do this, we coded the direction of the head and trunk movements with respect to the reaching arm (left or right) in each trial for each subject. For this direction index (DI), four patterns of head and trunk movement were identified (Fig. 2d, e): pattern 1: movements of the head and trunk were both made towards the moving arm; pattern 2: movement of the head was towards the reaching arm and the trunk was away from the arm; pattern 3: movement of the head was away from the arm and the trunk was towards the arm; and pattern 4: movements of both the head and trunk were away from the reaching arm. For each subject, the number of trials in which each pattern occurred in each child was calculated for each target (T1, T2, T3) and each direction (yaw, roll, pitch) and were expressed as a percentage of the total of number of trials and then averaged for each group. Note that unlike the AI, the DI does not take into consideration if there is a time lag between movements of the head and trunk. Thus, although the measure indicates that the two segments move in the same direction, movements of the segments may be dissociated in time.

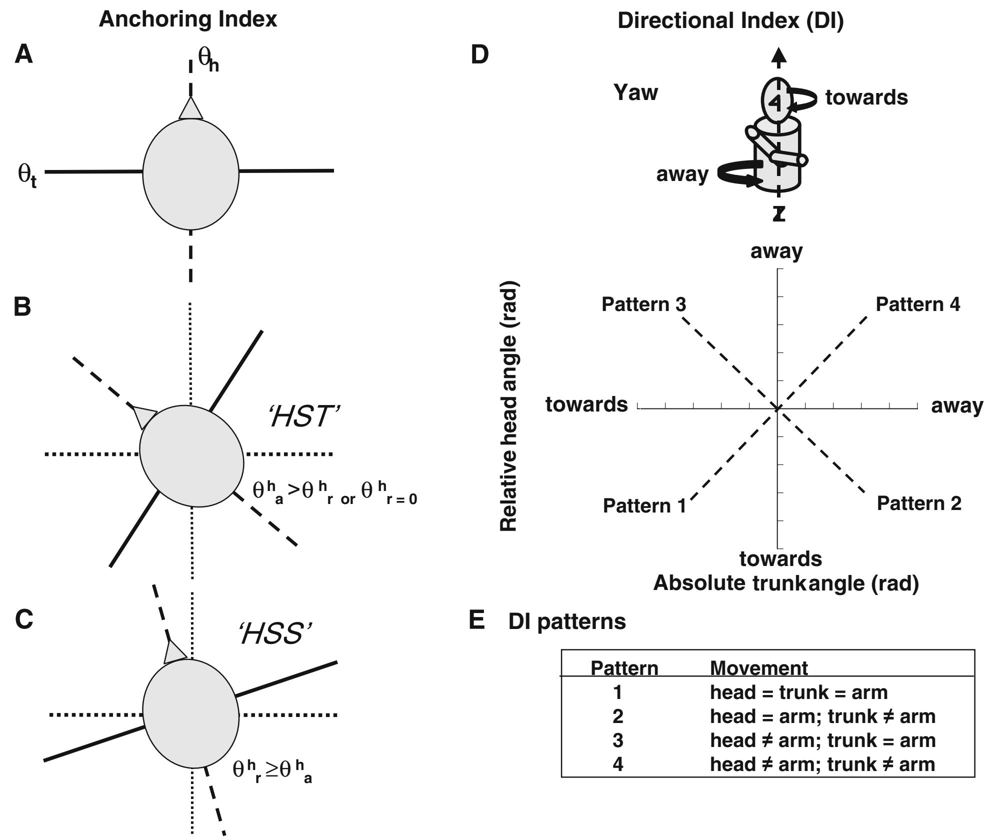


Fig. 2 Illustration of the relationship between the head and shoulder segments (*thick solid* and *dashed lines*) for calculation of the anchoring index (AI) in the sagittal plane (Yaw). The starting position (**a**), the relationship between the two segments for the head-stabilized-on-trunk (HST) strategy (**b**) and the head-stabilized-in-space (HSS) (**c**) strategies are shown. **d**, **e** The initial pattern of movement direction (directional Index: DI) for the head and trunk in the Yaw plane. In panel **d**, pattern 2 is shown in which the head is moving away from the reaching right arm while the trunk is moving towards the arm

Statistical analysis

Separate one-way analyses of variance (ANOVAs) were performed for each target and each plane of rotation, with AI and DI as the dependent variables, and age group as the independent variable. Post hoc least significant difference tests were used to identify the loci of the differences between individual age groups and the adult group. A significance level of $P < 0.05$ was used for each comparison. A coefficient of variability (CV), defined as the ratio between the standard deviation and mean of the AI, was computed for each subject for each trial at every target and for each plane of rotation. Individual subject mean CVs were then averaged to obtain group means and standard deviations. Separate ANOVAs were performed for each target by age group.

Results

General description of movement

As previously reported in adults (Michaelsen et al. 2001) and in children (Schneiberg et al. 2002), reaches to closer targets were made with trajectories that were more curved such that, at the time of grasping, the hand was moving in the transverse plane. The forearm remained in the neutral position (thumb upward) throughout the reach. To reach targets placed more distally, trajectories were straighter and the hand became more sagittally oriented. Children, up to the age of 7 years, produced endpoint trajectories that were more curved and less smooth than older children and adults for reaches to targets placed at arm's length and beyond (Fig. 3). The ranges of angular movement of the head and trunk were similar across groups for all directions and targets. There were no developmental trends in either amplitude or variability. Not surprisingly, the range of movement in all directions increased with target distance. For example, in the

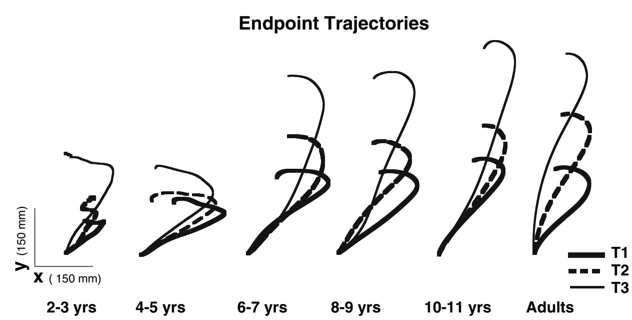
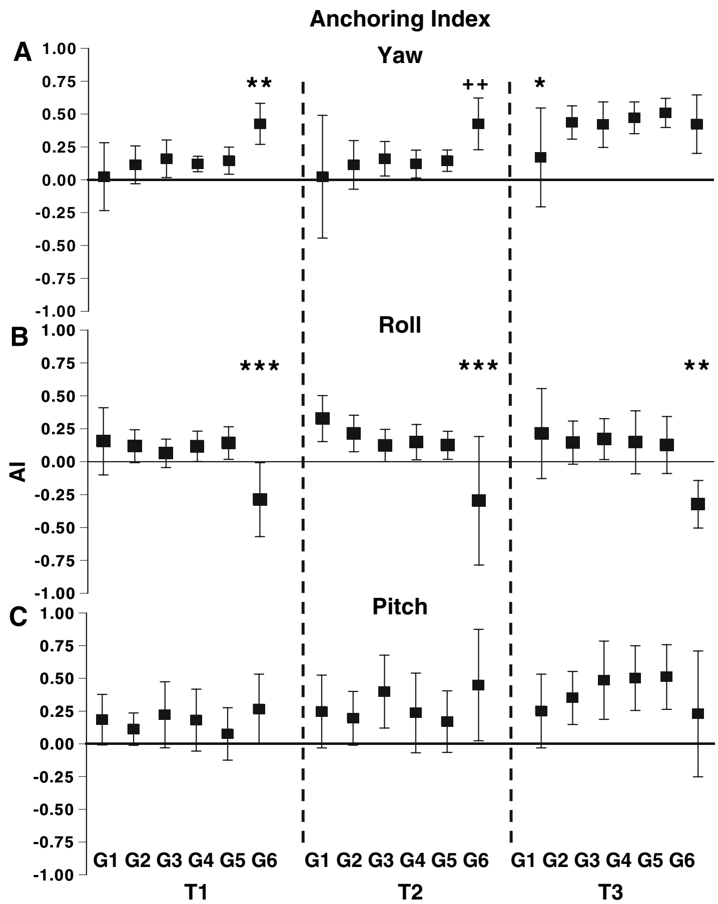


Fig. 3 Mean endpoint (hand) trajectories to close (T1, *thick solid lines*), middle (T2, *dashed line*) and far targets (T3, *thin solid lines*) for one representative subject in each age group



Group	Age
G1	2-3
G2	4-5
G3	6-7
G4	8-9
G5	10-11
G6	adults

Fig. 4 Mean (SD) head anchoring index (AI) for all groups and targets in the **a** Yaw, **b** Roll and **c** Pitch planes. Subject ages indicated in years. *Symbols* indicate that the group mean differed from the mean of all the other groups. $*P < 0.05$; $**P < 0.01$; $***P < 0.001$; $++P < 0.01$ for G6 compared to G2–G5

pitch plane, head and trunk rotations were between approximately 2–8° and 10–40° for T1 and T3 respectively.

Anchoring index (AI)

AIs for yaw, roll and pitch are illustrated in Fig. 4 for all age groups. There were three distinct features of the AI. First, in the yaw plane, the 2–3 year olds were the only group in whom the AI and its standard deviation crossed the zero line at all three target distances, indicating that this age group used both "HST" and "HSS" strategies whereas all other groups used primarily the HSS strategy. This difference was most pronounced for reaches towards the farthest target (T3) where the AI for the 2–3 year olds was significantly different from all others ($F_{5,43} = 2.66$, $P < 0.05$). The adult values were significantly more positive than all other groups for T1 ($F_{5,43} = 4.66$, $P < 0.01$). However for T2, the ANOVA was not significant because of the variability of G1. When the ANOVA was repeated without G1, the value of the adult group was different from the remaining groups (G2–G5; $F = 4.29_{4,37}$, $P < 0.01$). These results indicate higher dissociation of movement between the head and trunk in the adults in yaw at the close and middle reach distances. Second, the AI was significantly different in the roll plane for adults (T1, T2: $F_{5,43} = 5.85$ and 6.24, respectively; $P < 0.001$; T3: $F_{5,43} = 4.37$, $P < 0.01$) as compared to all other age groups across the three reach distances. In this case, the adult values were consistently negative indicating a HST strategy as compared to positive values for all other groups. Lastly, in the pitch plane, there were no significant differences between age groups, and all the AI values were positive indicating use of the HSS strategy. Interestingly, however, was that for the adults reaching to the farthest target (T3), the standard deviation extended below zero, suggesting the use of both strategies.

Variability of the AI

There were no significant differences in the CV of the AIs between groups for either direction or distance.

Direction index (DI)

Head and trunk movements during reaches to the three targets in representative subjects are shown in Fig. 5 for the yaw direction (A: pattern 1 in a young child; B and C: pattern 4 in an older child and an adult). The proportions of

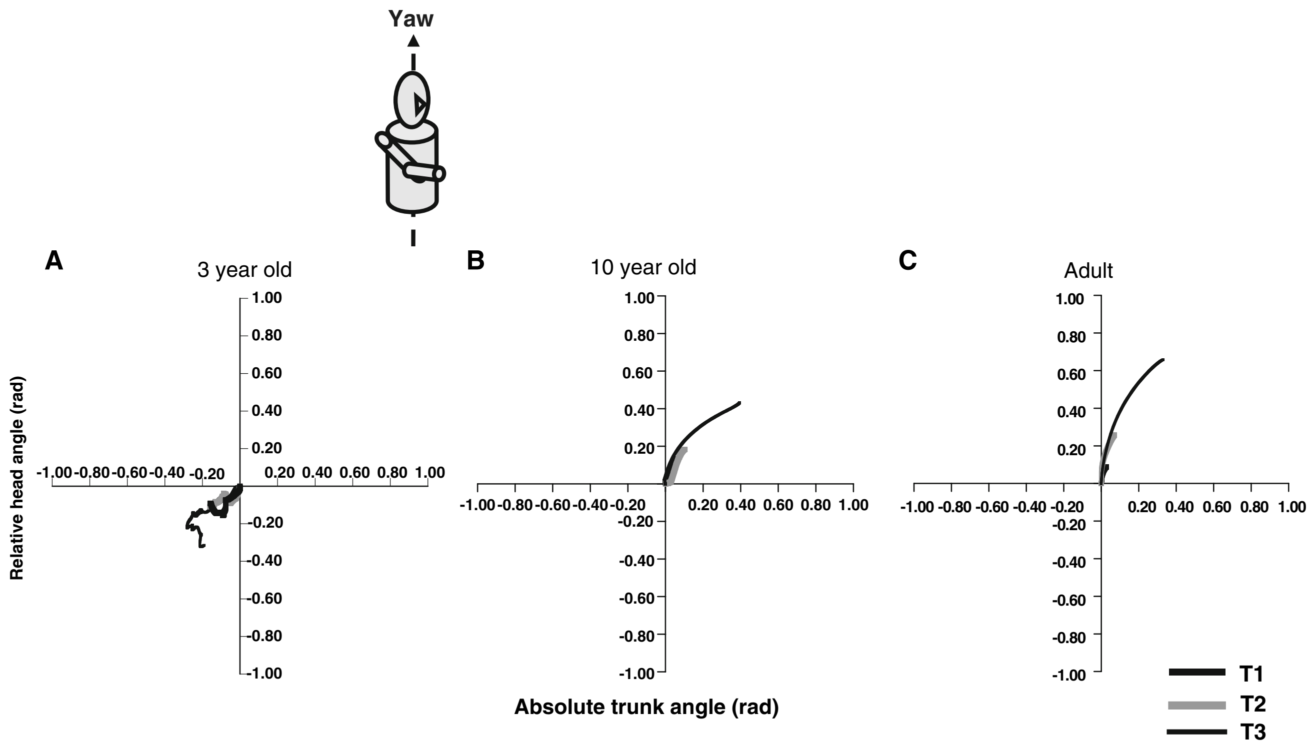


Fig. 5 Illustration of the head and trunk movements in the Yaw plane during reaches to close (T1, *thick black lines*), middle (T2, *grey lines*) and far targets (T3, *thin black lines*) for one representative subject in the **a** youngest group of children, **b** the oldest group of children, and **c** adult group

each DI pattern used by each group to reach each of the targets is summarized in Fig. 6 for all three directions.

Yaw

In the youngest children (Fig. 6a), the head and trunk or trunk alone predominantly moved toward the arm (patterns 1 and 3), while in the older children and adults, the head and trunk tended to move away from the reaching arm (patterns 2 and 4). This tendency increased with target distance. Strikingly, pattern 4 was absent in the youngest children for all targets in whom patterns 1 (head and trunk towards the target) and 3 (head away from and trunk towards the target) were present.

Roll

Movements were more variable in the roll direction compared to the other directions. In children older than 3, the most predominant patterns were those in which the trunk moved away from the arm while the head moved in either direction almost equally (patterns 2 and 4). However, the ratio of pattern 2:4 changed for the adults, who predominantly used pattern 4. In contrast, the youngest children had a greater tendency to move the trunk and the head towards the arm (pattern 1) for all three targets.

Pitch

Pattern 3 became more predominant across groups for T1 indicating extension of the head away from and trunk flexion toward the reaching arm. For the closest target (target 1), the younger groups used all patterns including those where the trunk extended while the arm reached forward (patterns 2 and 4). Early maturation was apparent for T2 and T3 where the patterns were similar across all age groups.

Emergence of mature patterns

Age-related differences for each movement variable are summarized according to target distance (Fig. 7). The figure also shows at what age mature patterns emerged for each movement variable based on a comparison with healthy adults. Our data show that the maturation of strategies used to stabilize and coordinate the head, trunk and arm differed across movement planes and reach distances. The AI for yaw matured by adulthood for T1 and T2 and by 4–5 years of age for T3. The DI for yaw had adult-like features for T1 and T2 from 4 to 5 years onwards. The patterns used for reaching beyond arm's length (T3) changed throughout childhood. In the roll plane, AI maturation was delayed until adulthood and while maturation of DI may be a two-step process: the

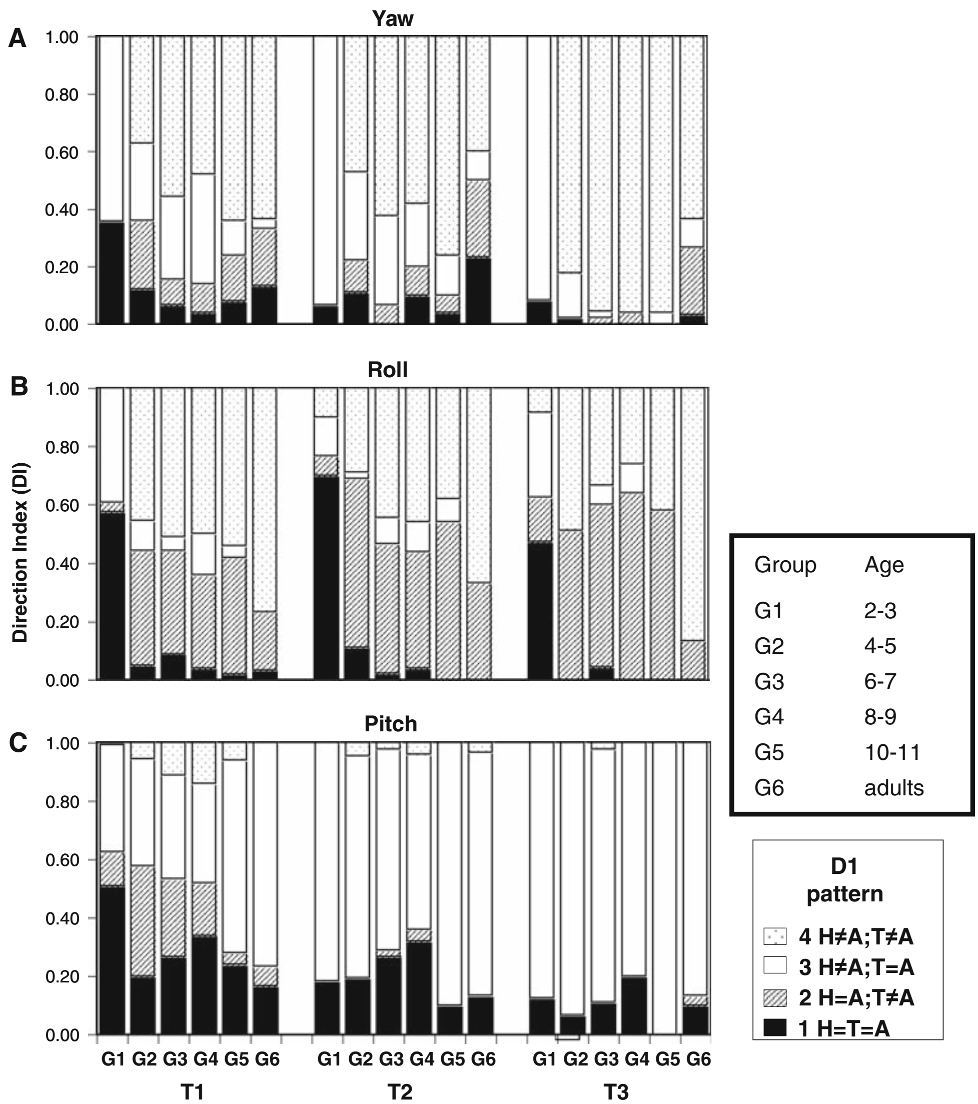


Fig. 6 Percentage of reaches within each group (age ranges for G1–G5 as per Fig. 4) characterized by different initial patterns of movement (DI) for the **a** Yaw, **b** Roll and **c** Pitch planes. Reaches to close (T1), middle (T2) and far targets (T3) are shown from left to right for each plane. Pattern 1: movement of head (H) and trunk (T) was towards the reaching arm (A); pattern 2: movement of the head was toward the reaching arm and the trunk was away from the arm; pattern 3: movement of the head was away from the arm and the trunk was towards the arm; pattern 4: movement of the head and trunk were away from the reaching arm

Fig. 7 Summary of results. *X* indicates presence of the adult pattern. Age of acquisition and older ages are *filled in grey*

Variable Measured	Presence of differences due to age			Age of appearance of mature pattern																	
	T1	T2	T3	T1						T2						T3					
Age group				G1	G2	G3	G4	G5	G6	G1	G2	G3	G4	G5	G6	G1	G2	G3	G4	G5	G6
I. Anchoring Index																					
Yaw	X	X	X						X						X		X				
Roll	X	X	X						X						X						X
Pitch				X						X						X					
II. Direction Index																					
Yaw	X	X	X		X						X										X
Roll		X	X		X						X						X				
Pitch	X							X		X						X					

predominance of patterns 2 and 4 as seen in adults emerged by 4–5 years of age but the ratio of patterns 2:4 remained different from adults in 10–11 year old for all three targets. Movements in the pitch plane were mature by 2–3 years of age for the AI at all distances and DI (except for T1 reaches).

Discussion

We described the development of head and trunk coordination patterns relative to the reaching arm during functional reaching in the sagittal plane in TD children and compared them with patterns used by adults. Head–trunk–

arm coordination for reaches to targets at different distances were characterized using the AI (Assaiante and Amblard 1993) and the DI that were significant even in the absence of developmental changes in movement amplitude and variability.

Differential maturation of parameters

The early maturation of the AI for all targets and the DI for two targets in the pitch plane is interesting in light of our previous study, where we examined the range and coordination of trunk and arm joint movement during reaches in the sagittal plane. In that study we observed that for the targets within arm's length (T1 and T2), trunk sagittal displacement and variability were significantly greater for 4–9 year olds as compared to 10–11 year olds and adults (Schneiberg et al. 2002). Thus while head–trunk coordination with respect to the direction of the arm motion and AI may mature early in the pitch plane, scaling of trunk motion is a component that matures much later in childhood. These results for seated reaches in a sagittal plane are similar to those of van der Heide et al. (2003) who also observed that the preference for an "en bloc" strategy characterized by an in-concert activation of direction specific trunk and neck muscles disappeared by the age of 2 years. After the age of 4 years, the preference for a descending recruitment order returns. Thus, it would seem from electromyographic studies, that the head becomes the dominant frame of reference from the age of 4 years, as a descending recruitment order for posterior postural muscles (cervical, thoracic, lumbar) begins to predominate at this age (van der Fits 1999b; van der Heide et al. 2003). Accordingly, improvements in task-related reaching control, at least for a similar type of movement, may be paralleled by some aspects of postural control development.

Our data indicate that the AIs for roll and yaw rotational directions do not mature as early in development as that for pitch. Similar differential development of stabilization has been observed for head and trunk control during uni- and bi-pedal hopping. Assaiante et al. (1997) reported earlier acquisition of the adult-like stabilization-in-space pattern of head and trunk segments for the pitch plane than for the roll plane. They suggested that the earlier pitch plane control occurred because of easier control of balance in the plane of movement. For reaching to sagittally placed targets and in particular, targets beyond reach, trunk pitch (anterior displacement) as well as trunk rotation in a direction opposite to the reaching arm are necessary. The organization of posture and movement of the head is related to the control of gaze (Berthoz and Pozzo 1988). Thus, stabilizing the head in space in the pitch plane may be necessary to achieve the functional goal of maintaining visual contact with the object. Once gaze position has been achieved, the head then maintains stability through the use of the HSS strategy.

Using the HSS pattern in the yaw rotational direction may not be as critical for reaches within arm's length, but more vital for reaches to targets beyond arm's length. For this target, the predominant pattern of DI was pattern 4, where both head and trunk moved in a direction opposite to the arm movement. In order to fixate gaze on the target, the head should move considerably less than the trunk. The need to maintain eye fixation on the target combined with increased amounts of trunk rotation likely drive an earlier maturation of head and trunk coordination in this plane for reaches beyond arm's length. It is possible that mapping reaching behavior in the subject's complete work space (not solely at body midline) and specifically requiring subjects to reach for targets at the limits of the work space may impose additional demands on control strategies. Reaching to midline targets may be successfully achieved through redundant coordination strategies while placing targets at the extremes may force selective stabilization of the head in a specific direction that in turn may change as a function of development.

A robust finding was that the adult pattern of AI for the roll direction was one of HST rather than HSS. Similarly, head–arm–trunk coordination in roll was also characterized predominantly by the DI pattern 4 where the head and trunk move away from the arm. For the reaching task, the adult pattern was one where head–trunk–arm coordination patterns were selected and organized to stabilize gaze on the object. This was done by adopting an HSS pattern for yaw and pitch. Since movements however in the roll plane do not affect visualization of the target, they used an HST pattern to minimize head wobble. The children tended to use the same coordination patterns for all three planes and used less selective control. This is consistent with head–trunk coordination patterns for a full body task (sit-to-stand) in children and adults (Christine Assaiante, personal communication).

Maturation as a function of task difficulty

In general, developmental studies of head–trunk coordination suggest an initial use of an HST strategy where head movement is fixed to the movement of the lower trunk segment (Assaiante et al. 2005). During the course of development, the head segment dissociates from the trunk and the strategy becomes space-referenced, with the head maintaining a spatial orientation relative to a vertical or external frame of reference. However, an ontogenetic model for sensorimotor organization developed by Assaiante and Amblard (1995) suggests four phases of development where stable coordination strategies emerge over time. The emergence of these strategies does not always follow a fixed chronological sequence and may change as a function of environmental constraints or task difficulty, including visual constraints, changes in the base of support, object size and location, and gravitational demands. The ongoing development of postural control strategies throughout childhood has also been reported for anticipatory control during bimanual load-lifting tasks (Schmitz et al. 1999).

In our study, the emergence of the mature DI at 4–5 years of age (in most conditions) may reflect an earlier ability to uncouple movements of the arm and trunk, than observed for more complex tasks, such as holding an object in one hand while reaching with the other (Roncesvalles et al. 2005). In general, the development of reaching skills (Hay 1978; Roncesvalles et al. 2005), postural adjustments during reaching (van der Heide et al. 2003; Schneiberg et al. 2002), bimanual load-lifting tasks (Schmitz et al. 1999), posturokinetic tasks (Assaiante 2000; Haas et al. 1989; Hay and Redon 1999, 2001), and the production of isometric forces for precision grip (Forssberg et al. 1992) have also been shown to have a non-chronological and protracted course which may not be completed by the age of 11 years. This study presents a detailed snap-shot of head–trunk–arm kinematics for midline reaches and adds to the growing description of intersegment and interjoint coordination for different tasks that will eventually lead to a more general description of the maturation of movement production in TD children. Taken together with previous studies, our data support the hypothesis that development of head–trunk coordination during reaching does not follow a fixed sequence and depends on task constraints. These data may be used as a normative database for comparison of movements made by children with motor disabilities.

In summary, reaching for a target is a complex motor skill requiring trunk and head coordination with respect to the reaching arm in order to accurately achieve the goal. The ability to control the head, trunk and arm, both separately and with respect to each other is a skill that improves with age, even though the youngest subjects were able to perform the task in an elementary way. Maturation of different aspects of this coordination occurs at different ages, and may be related to physiological maturation as well as task constraints.

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