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Abstract The aim of the experiment was to examine how children coordinate the degrees of freedom of the arm and trunk when performing interceptive actions that correspond to daily life activities. For that purpose, children were required to reach and grasp a stationary ball while standing (condition C1), a stationary ball while walking (C2), and a moving ball while standing (C3). The resulting movements were measured in world-centered and body-centered coordinates, and then subjected to three-dimensional kinematic analysis. The different coordinate frames of reference were used to determine the interaction between arm and trunk movements. Children adapted their coordination in the two moving conditions (C2 and C3) by decelerating longer towards the ball and exhibiting more interaction between the arm and trunk movements than in the stationary condition (C1). These results indicate that, like adult participants, children adapt to the constraints imposed by complex, interceptive actions by recruiting additional degrees of freedom of the trunk, which are coordinated with the hand to produce a movement that preserves an appropriate level of impact at hand/object collision.

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Introduction

Interceptive action, a task that occurs in everyday life activities, varies from catching balls in sports, to simply reaching for a glass of lemonade. All of these everyday tasks require a reaching movement, which can be influenced by the confluence of task, organismic and/or environmental constraints. For example, when adult participants reach for the more distant of two objects they exhibit an increased peak magnitude and longer deceleration time compared to reaching for the closer object (Paulignan et al. 1991a, 1991b). Therefore, although often seen as somewhat trivial and simple tasks, successful performance often requires subtle modifications to the movement kinematics. This ability to modify the movement to suit the current constraints is afforded by the availability of redundant degrees of freedom, coupled to a sensitive perceptual apparatus.

While adult reaching behavior has been extensively studied (Jeannerod 1981, 1984; Jakobson and Goodale 1991; Zaal et al. 1998), only recently have the kinematics of children's reaching movements been examined. Developmental research has shown that with increases in age, children (4–11 years) exhibit less variable and more coordinated hand and trunk movements (Schneiberg et al. 2002), and straighter hand trajectories with a smoother bell-shaped velocity profile (Kuhtz-Buschbeck et al. 1998). Age-based differences in how children respond to changes in task constraints have also been reported. Kuhtz-Buschbeck et al. (1998) found that children (aged 6–7 years) reached to more distant objects with a longer movement time, higher peak velocity and longer deceleration phase, but they did not exhibit appropriate modifications when object size was altered. However, Pryde et al. (1998) found that older children (age 9–10 years) did respond to changes in object size by exhibiting a longer movement time, lower peak velocity and longer deceleration time. Developmental differences in the ability to modify the movement kinematics in response to changing constraints are probably underpinned by developmental changes in the perceptual apparatus, with older children becoming more sensitive to egocentric information such as object size (Konczak et al. 1997). Children aged between 6 and 10 years, however, are able to deal with allocentric information (i.e., changing object distance).

While the studies of interceptive action in children have focussed on how task constraints such as object size and distance influence the kinematics of reaching and grasping movements, there has been little work that has considered how they perform more complex movements such as those found in everyday life activities, involving the control of the many degrees of freedom. Further, in the limited studies that have examined the coordination between hand and trunk, participants performed a relatively simple reach movement from a seated position to a stationary object (Schneiberg et al. 2002). This is less complex than reaching for a stationary object while walking, a task that is confronted by children at an early age. Such a task involves three separate components (walking, reaching and grasping), and therefore requires the coordination of multiple degrees of freedom.

With adults participants, Marteniuk and colleagues (Marteniuk et al. 2000; Marteniuk and Bertram 2001) demonstrated that the amount of trunk flexion and rotation varied according to whether they reached during standing or during locomotion. This finding required the use of a novel analysis procedure in which the movement of the hand was compared relative to a fixed, world-centered frame of reference (normally used in prehension research), and to a body-centered frame of reference (i.e., the trunk). The latter method of analysis effectively eliminates the movement of the trunk, including any contribution of gait, from the movement of the hand. Therefore, it allows the movement of the hand to be viewed independent of the movement of the rest of the body. When analyzed from a world-centered frame of reference, participants reached with a skewed, bell-shaped trajectory of the hand in both standing and walking conditions. However, when the trajectory was analyzed relative to the participant's trunk, the body-centered frame of reference, this pattern was not evident in the walking condition. The net displacement of the hand was actually backward and towards the trunk. The authors suggested that, when interception is combined with locomotion, arm and trunk movements act in cooperation to produce a skewed, bell-shape trajectory of the hand, enabling participants to maintain speed and accuracy.

Depending on the task constraints (e.g., standing or walking), adult participants achieve precise positioning of the hand towards the target during interceptive actions by altering the coordination between the arm and trunk (Kaminski et al. 1995; Steenbergen et al. 1995; Adamovich et al. 2001). However, although children aged 7 to 10 years old have developed adult-like standing postural adjustments (Shumway-Cook and Woollacott 1985; Woollacott et al. 1989; Nougier et al. 1998), and are able to modify their reaching movement according to task constraints such as object distance, it is not yet known how they coordinate the degrees of freedom of the arm (shoulder, elbow and wrist) and trunk during natural interceptive actions. The current experiment was designed to examine this issue. To this end, we compared children's movements from a world-centered to a body-centered frame of reference (Marteniuk et al. 2000), as they reached for a stationary ball while standing (condition C1) and walking (C2), and for a moving ball while standing (C3).

Materials and methods

Participants

Ten healthy children (six boys and four girls; age 8±1 years, mean ±SD) participated in this experiment after parents signed ethical approved informed consent forms. All children performed the experiment with their preferred hand; seven children were right-hand dominant, three were left-hand dominant. The study was approved by the Regional Committee for Medical Research Ethics, Manchester, UK.

Procedure and design

Participants were required to reach and grasp with their preferred hand a tennis ball (6.5 cm in diameter) located on a table. The table height was adjusted to the participant's body height so that it was level with the end of the thumb when the arm was held vertical beside the table, and consequently varied from 60 to 80 cm. Participants were asked to reach and grasp (i.e., intercept) a stationary ball while standing (C1), a stationary ball while walking (C2), and a moving ball while standing (C3). In C1 and C3, the horizontal distance between the participant's hand in the start position and the target location was 30 cm, and the corresponding lateral distance was 10 cm. In C2 the horizontal distance between the participant and the target was 2.5 m. In the stationary ball conditions (C1 and C2), the movement commenced when the experimenter gave an auditory starting signal. In the moving ball condition (C3), the ball was released by the experimenter and then rolled down an open tube of 1.5 m length. The ball approached the participant with an average speed of 0.7 m/s and arrived in the general vicinity of a marker located on the table (a red circle of 10 cm diameter). Participants were instructed that they should start their movement only after the ball had been released. Participants were asked to keep their hands beside their legs prior to commencing the reach and grasp. To become familiar with the task, participants performed three practice trials. When the task requirements were fully understood participants performed 15 trials in three counter-balanced blocks (N=45).

Apparatus

Four digital high-speed cameras (GR-DVL9800, JVC) were used to record the displacement of 13 markers positioned on the body and one marker on the ball. The markers were placed on both sides of the external face of the acromion processes of the shoulders, on the lateral epicondyle of the humerus of the elbows, on the styloid processes of the wrists and on the phalangeal joint of the middle fingers. These markers were used to determine the kinematics of the arm as it reached towards the ball. One marker was placed on the sternum and two markers on both SIAS (spina iliaca anterior superior) of the pelvis to determine the kinematics of the trunk. To follow the movement of the head during the trial, two markers were placed on the head beside the eye.

Two pairs of cameras operating at a sampling rate of 50 Hz were located on each side of the participant to record the movement. Each pair of cameras was arranged with an inter-camera angle of 75°, such that the field of view covered the right or left side of the body. The cameras were calibrated using a 17-point 3-D calibration frame, covering the volume (2 m^3) in which the movement occurred. Two known points of reference were digitized to determine the accuracy of the system (0.02 mm). A light-emitting diode (LED) placed in the field of view of each pair of cameras was illuminated by the experimenter just prior to the start of the trial (i.e., to coincide with the auditory signal or ball release). This enabled cameras to be synchronized during later analysis. After completing the data collection, the video footage was transferred to a 3-D motion analysis system (SIMI), where the markers were digitized for odd-numbered trials (n=8). Only the odd-numbered trials were digitized in order to reduce the amount of analysis while still providing a satisfactory representation of performance across the testing session. The three-dimensional coordinates for each marker were calculated using a Direct Linear Transform algorithm. The data was then filtered using a low-pass second-order filter, with a cutoff frequency of 8 Hz. Displacement and velocity data of the wrist were analyzed to determine the characteristics of the reaching movement.

Dependent measures of reaching performance

Although the interceptive action performed in the present study consisted of both a reach and grasp phase, only the former was analyzed. A program was developed to identify key events in the displacement and velocity profiles. First it was necessary to determine the moment of movement initiation and moment of contact (Corbetta and Thelen 1995), and hence the reach phase of the interceptive action. The moment of contact was defined as the moment at which the distance between wrist and tennis ball was equal to or less than 3 mm. Movement initiation was defined as the moment at which the velocity of the wrist increased beyond 0.05 m/s for a minimum of 20 ms[1]. Based on previous research on reaching in children (Kuhtz-Buschbeck et al. 1998; Pryde et al. 1998) the following kinematic variables were extracted: peak velocity, movement time and deceleration time (time after peak wrist-velocity until the moment of contact). The data was calculated relative to a fixed, world-centered frame of reference, by subtracting a known coordinate on the table from the wrist coordinates. To calculate the data relative to a dynamic, body-centered frame of reference, the trunk (sternum marker) coordinates were subtracted from the wrist coordinates. The latter allowed the determination of the extent to which the body movement contributed to the movement of the hand (Marteniuk et al. 2000). Trunk contribution was quantified by calculating the excursion of trunk flexion/extension and trunk rotation. Excursion is the sum of the angular change over time. These variables were calculated from the angle formed between the markers placed on the sternum, shoulder and pelvis in a sagittal, transverse and frontal plane. The elbow excursion, which consisted of both elbow flexion and elbow extension, was calculated from the resulting angle between the shoulder, elbow and wrist markers.

Data analyses and statistics

Data were first analyzed by visually inspecting the spatial path-plots of the wrist trajectory in a world-centered and body-centered frame of reference, for each subject's individual trials. This required the wrist coordinates in the x-dimension (forward displacement), to be plotted against the coordinates in the y-dimension (vertical displacement). Visual inspection of the video footage and the graphs of the wrist trajectories showed that the wrist movement was performed predominantly in a two-dimensional plane. The wrist coordinates of the z-dimension did not change very much regardless of condition, and were therefore not considered in further analysis.

In order to quantify the (dis)similarities in the world-centered and body-centered plots, the recognition coefficient (R), which is the peak value of the cross-correlation between the spatial path plots, was calculated (see Sparrow et al. 1987). The recognition coefficient is sensitive to the size, shape and orientation of a spatial path plot, and is therefore a good measure of (dis)similarity between two coordination patterns. R ranges from −1.0 to +1.0 according to the degree of similarity, such that as R approaches zero, the spatial path plots become increasingly dissimilar in shape. R was calculated from each participant's spatial path plots, the data of which were first normalized to 100 points, and then averaged across the eight trials. The resulting R-values were z-transformed before being submitted to an analysis of variance (ANOVA) with repeated measures on the condition factor. Post hoc (Tukey HSD) analysis was used to test significant main and interaction effects. For the discrete kinematic variables, the intra-individual means were calculated from the eight trials performed in each of the three conditions. The peak velocity and time after peak velocity data were then submitted to separate 3 (condition)×2 (frame of reference) repeated measures analysis of variance (ANOVA). Main and interaction effects were examined using the Tukey HSD post hoc procedure. Data on movement time and angular changes were submitted to one-way ANOVA with repeated measures on the condition factor, since these variables were independent of the frame of reference calculation.

Results

Spatial path plots

World-centered wrist-trajectories compared with body-centered wrist-trajectories

The movements within a condition were generally performed with consistency of shape (all lines showed similar trajectories). This was particularly evident in the moving ball condition (C3) and the standing, stationary ball condition (C1) (see Fig. 1). When considering the wrist displacement relative to the body-centered and world-centered frames of reference, visual differences between the conditions were evident. The wrist trajectory in the standing and moving ball conditions appeared similar when plotted in a world-centered and body-centered frame of reference (see Fig. 1A,B and E,F). This was not the case in the walking condition (C2). While the wrist trajectory in a world-centered frame of reference (Fig. 1C) followed a similar pattern to that in the standing and moving ball conditions (Fig. 1A,E), the wrist trajectory in body-centered coordinates (Fig. 1D) first moved away and up from the trunk before reversing back towards its original orientation. These visual differences between frames of reference were confirmed by the finding of a significant effect of condition in the z-transformed recognition coefficients ($F_{(2,18)}$=66.32, p<0.0001). The spatial path-plots relative to a world-centered and body-centered frame of reference were less similar in the walking condition (C2) than in the standing

[1] Our paradigm differs from that used by Marteniuk et al. (2000), in which movement initiation was defined as the moment an additional target was touched prior to the reach. We decided not to use an additional target because we felt this placed restrictions on the reaching movement that were not faced when normally performing this task in everyday life.

conditions (C1 and C3) (as shown in Table 1, R=0.15 for C2, 0.87 for C1 and 0.76 for C3).

Kinematic variables

Peak velocity of wrist in x- and y-dimensions

For peak velocity of wrist in *x*-dimension (PVX), there was a significant main effect of condition ($F_{(2,18)}$=60.25, p<0.001) and frame of reference ($F_{(1,9)}$=200.42, p<0.001) and a significant condition×frame of reference interaction ($F_{(2,18)}$=243.62, p<0.001). Post hoc (Tukey HSD) testing revealed that in the walking condition only (C2), participants exhibited a higher peak velocity (p<0.001) when analyzed in world-centered coordinates. Further, PVX in the walking condition (C2) was significantly higher compared with that in both the standing (C1) and moving ball condition (C3) for both world-centered and body-centered coordinates (p<0.001) (see also Table 2 for the means and significant effects).

For the variable peak velocity of wrist in *y*-dimension (PVY), there was a significant main effect of condition ($F_{(2,18)}$=11.66, p<0.05), and a significant condition×frame of reference interaction ($F_{(2,18)}$=10.33, p<0.05). There was no significant main effect of frame of reference ($F_{(1,9)}$=2.10, p>0.05). Post hoc (Tukey HSD) testing revealed that in the walking condition (C2) participants exhibited a higher PVY when analyzed in world-centered coordinates (p<0.001). Participants also exhibited a lower PVY in the moving ball condition (C3) than in the other two conditions (p<0.001).

Movement time and deceleration time in x-dimension

A significant main effect of condition was noted for both movement time ($F_{(2,18)}$=15.63, p<0.0001) and deceleration time ($F_{(2,18)}$=23.61, p<0.0001). Post hoc analysis revealed that participants consistently reached with a longer movement time and deceleration time in the walking

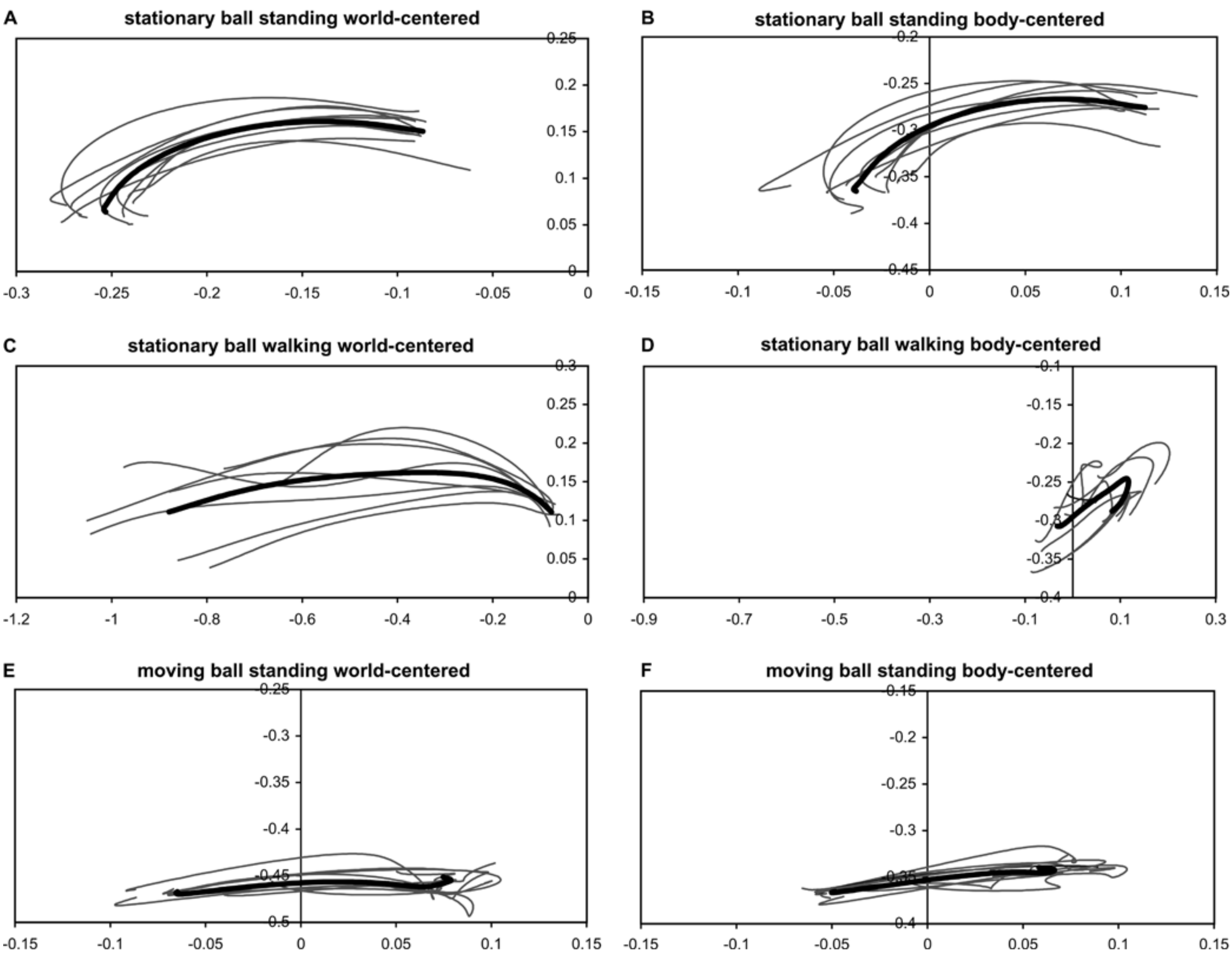

Fig. 1A–F Spatial path plots of the wrist displacement of a representative subject in all three conditions analyzed from a world-centered (**A,C,E**) and a body-centered (**B,D,F**) frame of reference. Plots **A,B** and **E,F** are on the same absolute scale. The plots **C** and **D** are also on an equivalent scale, but this has been increased to aid comparison. *Thick lines* represent the average of all trials

Table 1 Means of recognition coefficients (R) of the differences between the spatial path plots for the three conditions examined

Subject	Recognition coefficient: world-centered − body-centered		
	Stationary ball–Walking	Stationary ball–Standing	Moving ball–Standing
1	0.12	0.94	0.92
2	0.22	0.98	0.94
3	0.11	0.92	0.79
4	0.11	0.86	0.54
5	0.25	0.91	0.86
6	0.14	0.94	0.69
7	0.19	0.80	0.66
8	0.09	0.96	0.88
9	0.12	0.90	0.65
10	0.17	0.52	0.70
Average	0.15	0.87	0.76

(C2) and the moving ball conditions (C3) than in the standing condition (C1).

Excursion

Significant main effects of condition were found for trunk-rotation ($F_{(2,18)}$=16.89, p<0.01) and trunk flexion/extension ($F_{(2,18)}$=21.95, p<0.01). Post hoc analysis revealed that participants exhibited more trunk rotation and trunk flexion/extension in the walking condition (C2) than in standing and moving ball conditions (C1 and C3) (p<0.001). There was no difference between the latter two conditions. There was no significant difference in elbow flexion/extension across all three conditions ($F_{(2,18)}$=0.25, p>0.05).

Discussion

The present study aimed to investigate how children coordinate the degrees of freedom of the arm and trunk during natural interceptive actions. We extended previous research, which has typically examined reaching and grasping of static objects from a stationary position (Kuhtz-Buschbeck et al. 1998; Pryde et al. 1998; Pare and Dugas 1999; Schneiberg et al. 2002), by examining how children intercept stationary and moving balls while walking or standing. Additional restrictions, such as stabilizing the trunk, which is often carried out in reaching and grasping studies, or tapping a point before the actual reaching task (often used to define movement initiation), were not imposed in this study. This allowed the children to perform the interceptive actions in a more realistic setting, which corresponded more closely to that experienced in everyday-life activities. Because the study did not aim to examine developmental differences, different age groups were not compared. However, the children were of an age at which they would have developed a perceptual system enabling them to respond to allocentric information such as object distance (Konczak and Dichgans 1997).

Trunk contribution to the reaching movement was examined using a methodology first reported by Marteniuk and colleagues (Marteniuk et al. 2000; Marteniuk and Bertram 2001), which involved calculating the wrist coordinates from both world-centered and body-centered

Table 2 Means of dependent variables (with SD in parentheses) as a function of condition and frame of reference. For the dependent variables movement time and the joint angles, no results are reported for the factor frame of reference because this had no influence on the calculation. *PVX* Peak velocity in horizontal (x) direction, *PVY* peak velocity in vertical (y) direction

Variable	Condition					
	Standing		Walking		Moving ball	
	World-centered	Body-centered	World-centered	Body-centered	World-centered	Body-centered
PVX (m/s)	0.44[a] (0.07)	0.44[a] (0.06)	1.68[c] (0.41)	0.65[b] (0.24)	0.33[a] (0.10)	0.33[a] (0.09)
PVY (m/s)	0.32[a] (0.15)	0.32[a,c] (0.14)	0.40[d] (0.13)	0.35[c] (0.12)	0.20[b] (0.11)	0.21[b] (0.10)
Movement time (s)	449.48[a] (117.45)	–	756.51[b,c] (220.33)	–	773.88[c] (209.71)	–
Time after PVX (s)	180.97[a] (123.91)	184.68[a] (125.62)	553.01[b] (143.16)	572.46[b] (170.22)	465.65[b] (201.49)	456.38[b] (185.27)
Trunk rotation (deg)	5.05[a] (3.03)	–	16.22[b] (6.78)	–	7.41[a] (3.33)	–
Trunk flexion (deg)	5.20[a] (2.44)	–	15.26[b] (5.30)	–	7.42[a] (3.72)	–
Elbow excursion (deg)	45.38[a] (33.55)	–	38.97[a] (12.90)	–	40.17[a] (32.07)	–

[a,b,c,d]Significant differences between the two factors, condition and frame of reference, after post hoc analysis; where two conditions have the same superscript there was no significant difference for that variable

frames of reference. This analysis revealed that children exhibited a different coordination between the trunk and arm in the three reach and grasp conditions. When the movement of the hand was viewed relative to a world-centered frame of reference, participants reached with a bell-shaped wrist trajectory in both standing and the walking conditions. When wrist trajectories were viewed relative to a body-centered frame of reference, there was no longer a bell-shaped trajectory in the walking condition. The hand first progressed upward and away from the trunk, followed by a reversal in direction such that the hand moved backward and towards the trunk up to the moment of impact. This was accompanied by an increased amount of trunk flexion and rotation. Despite these differences, the reach trajectories were performed with consistent shape.

There were also differences in the temporal evolution of the reach. When there was movement between the participant and object, other than that caused by the reach itself, movement time and deceleration time were extended. This effect was not reported by Marteniuk and colleagues, and is probably explained by the fact that their use of a metronome constrained the timing of the response. The prolonged deceleration time was evident in both frames of reference, and for the walking condition was accompanied by an increased peak velocity of the reach in the horizontal direction. Given that the horizontal speed at which children approached the object in the walking condition (average speed of 0.85 m/s) was similar to the speed at which the object approached them in the moving ball condition (0.7 m/s), it may appear surprising that there was a difference in peak velocity. However, it must be remembered that the task constraints required the children to perform the reaching movement while maintaining walking speed, and therefore the cumulative speed of the hand relative to the object was increased. This could have been reduced if participants had kept the hand by their side and grasped the ball as they walked past. However, this was not the preferred coordination. Instead participants exhibited elbow flexion and extension comparable to the standing conditions, and coupled this to an increased trunk excursion in the walking condition.

It has been suggested that modifications to the hand trajectory serve to maintain an acceptable level of impact between the hand and ball under the constraints imposed by the different conditions (Marteniuk et al 1990; Savelsbergh et al. 1996). For example, adult participants exhibit a longer deceleration time when reaching and grasping a fragile object (light bulb) in order to avoid a harsh impact (Marteniuk et al. 1990). It has also been reasoned that the contribution of additional degrees of freedom, such as the trunk, to reaching is influenced by the desired contact between the hand and object to be grasped (Steenbergen et al. 1995). Reaching for a full cup results in a longer deceleration phase and an increased trunk contribution compared to reaching for an empty cup. In the present study, reaching to intercept the moving ball and walking to intercept a stationary ball both required different demands for controlling the impact between hand and object compared to interception of a stationary ball while standing. If participants simply exhibited the reach response used in the standing, stationary-ball condition, the velocity of hand relative to the object, and hence impact, would be increased by movement of the object (moving-ball condition) or participant (walking condition). Although we did not measure impact directly, a subsidiary analysis on the world-centered wrist velocity during the final 60 ms prior to contact revealed a significant main effect of condition ($F_{(2,18)}$=38.36, p<0.05). Children exhibited a lower wrist velocity prior to contact in the moving-ball condition than in the standing and walking conditions (means: standing 0.27 m/s, walking 0.35 m/s, moving ball −0.5 m/s). Interestingly, in the moving-ball condition the wrist was often moving in the same direction as the ball (i.e., back towards the child) just prior to contact (see also Fig. 1). The implication is that children were sensitive to the potential change in impact resulting from participant or object motion, and therefore modified their reach response accordingly. As expected, this involved a lengthening of the deceleration time and movement time. This is consistent with findings reported for adult participants intercepting an object moving with speeds ranging between 0.5 and 1.25 m/s (Mason and Carnahan 1999). In the walking condition, children also deemed it necessary to couple the change in deceleration time and movement time with an increased contribution from the trunk. According to Steenbergen et al. (1995), it is probable that the trunk became more involved because children perceived there was a greater potential impact in the walking condition. More work on this issue using a range of different object and participant approach velocities is required to further elucidate this issue.

In addition to extending our understanding of how natural (daily life) interceptive actions are coordinated in normal children, the present study also provides a baseline from which to compare reaching behavior in children with motor disorders such as cerebral palsy. The use of clinical assessment scales that characterize gross motor function according to the developmental motor milestones in normal children has been suggested to be a limiting factor in the rehabilitation of arm and hand function in children with motor disorders (Schneiberg et al. 2002). Such scales do not provide information about the quality of movement and are therefore less sensitive in the assessment of the motor consequences of therapeutic interventions (Ketelaar and Helders 1998). For example, an analysis of gross motor function may not necessarily reveal the difficulties that people with cerebral palsy have flexing and extending their elbow, and the consequent involvement of the trunk (Steenbergen et al. 2000). Such information is necessary in order to evaluate and improve the current clinical assessment scales.

References

Adamovich SV, Archaumbault PS, Ghafouri M, Levin M, Poizner H, Feldman AG (2001) Hand trajectory invariance in reaching movemnets movements involving the trunk. Exp Brain Res 138:288–303

Corbetta D, Thelen E (1995) A method for identifying the initiation of reaching movements in natural prehension. J Mot Behav 27:285–293

Jakobson LS, Goodale MA (1991) Factors affecting higher-order movement planning: a kinematic analysis of human prehension. Exp Brain Res 86:199–208

Jeannerod M (1981) Intersegmental coordination during reaching at natural visual objects. In: Long J, Baddeley A (eds) Attention and performance, vol 9. Erlbaum, Hillsdale NJ, pp 153–268

Jeannerod M (1984) The timing of natural prehension movements. J Mot Behav 16:235–264

Kaminski TR, Bock C, Gentile AM (1995) The coordination between trunk and arm motion during pointing movements. Exp Brain Res 106:457–466

Ketelaar MVA, Helders PJ (1998) Functional motor abilities in children with cerebral palsy: a systemtaic literature review of assessment measures. Clin Rehabil 12:369–380

Konczak J, Dichgans J (1997) The development toward stereotypic arm kinematic during reaching in the first 3 years of life. Exp Brian Res 117:346–354

Konczak J, Borutta M, Dichgans J (1997) The development of goal-directed reaching in infants. Exp Brain Res 113:465–474

Kuhtz-Buschbeck JP, Stolze H, Boczek-Funcke A, Johnk K, Heinrichs H, Illert M (1998) Kinematic analysis of prehension movements in children. Behav Brain Res 93:131–141

Marteniuk RG, Bertram CP (2001) Contributions of gait and trunk movements to prehension: perspectives from world- and body-centered coordinates. Motor Control 2:151–165

Marteniuk RG, Leavitt JL, MacKenzie CL, Athenes S (1990) Functional relationships between grasp and transport components in a prehension task. Hum Mov Sci 9:149–176

Marteniuk RG, Ivens CJ, Bertram CP (2000) Evidence of motor equivalence in a pointing task involving locomotion. Motor Control 4:165–184

Mason AH, Carnahan H (1999) Target viewing time and velocity effects on prehension. Exp Brain Res 127:83–94

Nougier V, Bard C, Fleury M, Teasdale N (1998) Contribution of central and peripheral vision to the regulation of stance: Developmental aspects. J Exp Child Psychol 68:202–215

Pare M, Dugas C (1999) Developmental changes in prehension during childhood. Exp Brain Res 125:239–247

Paulignan Y, Jeannerod M, MacKenzie CL, Marteniuk RG (1991a) Selective pertubation of visual input during prehension movements: the effects of changing object size. Exp Brain Res 87:407–420

Paulignan Y, MacKenzie CL, Marteniuk RG, Jeannerod M (1991b) Selective pertubation of visual input during prehension movements: the effects of changing object position. Exp Brain Res 83:502–512

Pryde KM, Roy EA, Campbell K (1998) Prehension in children and adults: the effects of object size. Hum Mov Sci 17:743–752

Savelsbergh GJP, Steenbergen B, Van der Kamp J (1996) The role of fragility information in the guidance of precision grip. Hum Mov Sci 15:115–127

Schneiberg S, Sveistrup H, McFadyen B, McKinley P, Levin MF (2002) The development of coordination for reach-to-grasp movements in children. Exp Brain Res 146:142–154

Shumway-Cook A, Woollacott MH (1985) The growth of stability: postural control from a developmental perspective. J Mot Behav 17:131–147

Sparrow WA, Donovan E, Van Emmerik R, Barry EB (1987) Using relative motion plots to measure changes in intra-limb and inter-limb coordination. J Mot Behav 19:115–129

Steenbergen B, Marteniuk RG, Kalbfleisch LE (1995) Achieving coordination in prehension: joint freezing and postural contributions. J Mot Behav 27:333–348

Steenbergen B, Hulstijn W, Lemmens IHL, Meulenbroek RGJ (2000) The coordination of reaching and grasping in spastic hemiparesis. Hum Mov Sci 19:75–105

Woollacott MH, Shumway-Cook A, Williams H (1989) The development of posture and balance control in children. In: Shumway-Cook MHWA (ed) Development of posture and gait across the life span. University of South Carolina Press, Columbia, pp 77–96

Zaal FTJM, Bootsma RJ, Van Wieringen PCW (1998) Coordination in prehension. Exp Brain Res 119:427–435