2012

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Published in final edited form as:
J Exp Child Psychol. 2012 February ; 111(2): 286–298. doi:10.1016/j.jecp.2011.08.002.

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Abstract

Studies have suggested that proper postural control is essential for the development of reaching. However, little research has examined the development of the coordination between posture and manual control throughout childhood. We investigated the coordination between posture and manual control in 7- and 10- year-old children, and adults during a precision fitting task as task constraints became more difficult. Participants fit a block through an opening as arm kinematics, trunk kinematics and center of pressure data were collected. During the fitting task the precision, postural and visual constraints of the task were manipulated. Young children adopted a strategy where they first move their trunk towards the opening and then stabilize their trunk (freeze degrees of freedom) as the precision manual task is being performed. In contrast, adults and older children make compensatory trunk movements as the task is being performed. 10-year-old children were similar to adults under the less constrained task conditions, but resembled the 7-year-old children under the more challenging tasks. The ability to either suppress or allow postural fluctuations based on the constraints of a supra-postural task begins to develop at about ten-years-of-age. This ability, once developed, allows children to learn specific segmental movements required to complete a task within an environmental context.

Keywords

Development; Manual Control; Postural Control; Coordination

Introduction

Individuals do not typically stand for the sake of standing. Rather, bipedal stance affords other goal-directed behaviors such as reaching and manipulating objects. Proper motor function, therefore, requires that the postural system is integrated and coordinated with other goal-directed behaviors in a way that allows specific tasks to be performed while balance is maintained (Gardner et al., 2001; Riccio & Stoffregen, 1988).

In adults, movements of the trunk are integrated with hand and arm movements. Ma and Feldman (1995) identified two functional synergies used to complete a reaching task involving the trunk. The first, termed a reaching synergy, is responsible for transporting the

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hand to the target. The second, a compensatory synergy, moves the trunk and the arms without influencing the trajectory of the hand. The compensatory synergy allows for trunk fluctuations without negatively affecting the trajectory of the hand and arm. These trunk fluctuations are important because they help maintain a flexible system which is capable of attenuating perturbations that could occur during the movement.

The postural system is also highly integrated with goal-directed behaviors and will regulate postural sway in accordance with the constraints of a concurrently performed task. When performing manual behaviors (such as reaching and pointing), the center of mass (CoM) is often translated within the base of support (in an anticipatory or temporally coordinated manner) to aid in the completion of the manual task (Pozzo, Stapley, & Papaxanthis, 2002; Patron, Stapley & Pozzo, 2005; Stapley, Pozzo, Cheron, & Grishin, 1999; Kaminski & Simpkins, 2001). However, when performing actions that require more precision (e.g. standing and reading), postural fluctuations are minimized in order to complete the task (Stoffregen et al., 1999; Bardy et al., 1999).

The Developmental Coordination of Posture and Manual Control in Infancy

The development of many motor milestones such as reaching (Bertenthal & Clifton, 1998) and locomotion (Adolph, 2000) depends to a large degree on the coordination between posture and goal-directed behaviors (Bertenthal & Clifton, 1998; von Hofsten, 1993). Two independent lines of research, the development of anticipatory postural control and the developmental effects of postural stabilization on reaching, have suggested that posture begins to integrate with goal-directed behaviors early in infancy.

Anticipatory postural responses, where the postural muscles activate prior to the prime mover muscles, are scaled to the movement and allow stability to be maintained while the task is performed (Aruin, Forrest, & Latash, 1998). At 8-months-of-age, infants begin to activate postural muscles in a task specific manner (van der Fits et al., 1999; von Hofsten, 1993). Soon after, postural trunk muscles with latencies similar to that of adults are activated when reaching (von Hofsten & Woollacott, 1989). Several months later, as the child approaches one-year-of-age and gains the capabilities of independent stance, anticipatory postural strategies are used to control the CoM within a much narrower base of support (Forssberg & Nashner, 1982) and are adaptable based on the goal or context of the movement (van der Fits et al., 1999).

An immature postural system slows the development of many motor milestones. Specifically, tasks such as reaching and grasping are impossible to perform without the proper level of postural control (Bertenthal & Clifton, 1998; Gibson & Pick, 2000; von Hofsten, 1993). For example, spontaneous arm movements observed in neonates become much more accurate when postural support is provided (von Hofsten, 1993). Even after the development of reaching, 6-month-olds produce more mature reaches when external postural support is given (Hopkins & Rönnqvist, 2001). Interestingly, infants seem to be sensitive to their own postural shortcomings and reach less when objects are outside of arm's length (McKenzie et al., 1993). This general finding has also been observed in a visually challenging environment (when the room is dark), where 6-month-old infants do not reach for sounding objects outside of their reaching capabilities (Clifton et al., 1991). Around the time independent sitting emerges, infants will begin to use their trunk to lean and grasp objects outside of arms' length. (Yonas et al., 1993; Rochat & Goubert, 1995).

Development of the coordination between Posture and Manual Control

Children exhibit adult-like kinematic reaching profiles by 2-years-of-age (Berthier & Keen, 2006). However, the postural system continues to develop through childhood. Between 4-6-

years-of-age the postural system is in a transition period where more adult-like postural responses are beginning to emerge (Shumway-Cook & Woolacott, 1985). This transition period is delayed to approximately 10-years-of-age when children are examined under more difficult (compared to the traditional quiet stance) paradigms, such as when responding to sensory conflicts, dynamic visual information or during manual precision fitting tasks (Baumberger et al. 2004; Sparto et al. 2006; Haddad et al. 2008).

Infant reaching research is typically conducted with the child securely fastened to a modified high chair or secured in the parent's lap. The importance of posture in these paradigms is therefore minimized because balance is never challenged. To date, only a few studies have examined reaching behavior in young children when the trunk (a segment involved in both reaching and posture) either was not secured or was a required degree of freedom to complete the task (Haddad, Claxton & Keen, 2005; Rochat & Goubet, 1995; Yonas & Hartman, 1993). In these studies, it was observed that coordinated reaching movements involving the trunk segment emerge around 12-months-of-age. However, this coordination is immature compared to adults, suggesting that under more difficult task constraints the developmental time course of reaching may be delayed. Not until 8-10 years-of-age do children exhibit adult-like coordination between trunk and hand movements (Schneiberg, Sveistrup, McFadyen, McKinley & Levin, 2002).

While there are many studies examining reaching in infants and children in the absence of any postural perturbations and many studies examining the postural system in the absence of any suprapostural task, little information exists regarding the exact time course and mechanisms underlying the developmental coordination between posture and manual control in children. The purpose of this paper was, therefore, to examine the coordination between posture and manual control in 7- and 10-year-old children and adults as the constraints (distance, precision and vision) of a precision fitting task were systematically manipulated. The fitting task required participants to stand and fit a block through either a large or small opening that was placed at either arms' length or 1.33 arms; length from the body. The fitting movement was divided into three phases; the accelerative, decelerative and adjustment. The accelerative and decelerative phase of the movement represents the time when the block is being transported towards the opening. The adjustment phase of the movement represents the time when the block is passing through the opening.

Three specific hypotheses were examined. First, it was hypothesized that children would stiffen their trunk segment (exhibit a decrease in trunk speed as the block is being transported towards the opening and an increased trunk straightness ratio) when performing a precision fitting movement. The task constraints were not predicted to influence the fitting movement during the transport of the object. A trunk stiffening strategy increases the trunk straightness ratio because little forward displacement of the trunk is present during the movement. Freezing the trunk segment would simplify the inter-segmental coordination necessary to complete the task. However, this strategy would limit the child's ability to adapt their movements to changing task constraints. Thus, a trunk freezing strategy would suggest that children do not yet have the ability to utilize more adaptive control strategies when performing standing precision manual task. More adaptive trunk control was predicted to emerge as a function of development.

The second hypothesis was that the ability to stabilize the body as the block is passing through the opening (during the adjustment phase of the movement) would improve with development. Unlike the transport phase of the fitting movement, the body must stabilize as the block is passing through the opening. Any uncontrolled body fluctuations could perturb the hand and impair manual precision. Given the precision nature of the task, the specific task constraints were also predicted to influence body stabilization in each age group during

the adjustment phase of the movement. The velocity of the trunk and center of pressure (CoP) during the adjustment phase was used to address the second hypothesis.

The third hypothesis is that coordination between the wrist and trunk and the wrist and center of pressure during the entire fitting movement would improve as a function of development. The coordination between these variables reflect how the bodies multiple degrees of freedom are coordinated and controlled during a manual task. Since more complex movements typically develop later than simpler movements, it was predicted that 10-year olds would exhibit adult-like coordination only under the less difficult task constraints (e.g. fitting the block through the large opening or at a near distance)

The three age groups were chosen because previous work has suggested that children begin to transition to more adult levels of postural control around 7-years-of-age under static tasks and around 10-years-of-age under more complex tasks. Thus, these ages were thought to capture the major postural transition periods. Although previous studies have mostly examined the coordination between posture and manual control using either a pointing or grasping task, we chose a fitting task while standing. It was believed the constraints and stability requirements of a standing precision task would be accentuated over a seated grasping or pointing paradigm.

Method

Participants

Fifty-seven participants, divided across three age group, were recruited. Group 1 consisted of 7-year-old-children (n=19, mean = 7 years, 36 days; SD = 80 days). Group 2 consisted of 10-year-old children (n=19, mean = 10 years, 18 days; SD = 153 days). Group 3 consisted of college-aged adults (n=19, mean = 20 years, 29 days; SD = 2 years, 157 days). The methodologies and consent form were approved by the University of Massachusetts Institutional Review Board. The 7- and 10-year-old participants were identified from state birth records. A recruitment letter was then sent to parents followed by a phone call. The parents of the 7- and 10-year-old children signed the informed consent. Children were explained the procedures using a language they would understand and gave verbal assent. Adult participants were recruited from the university undergraduate community and were free of pathologies known to influence normal postural or movement control.

Procedure

Three-dimensional kinematic data (using two VZ4000 motion trackers from Phoenix Technologies; Burnaby, British Columbia) and kinetic data (using one AMTI force platform; Watertown, MA) were collected at 100 Hz. Active infrared markers were placed on the shoulder, elbow, and wrist of the participant's dominant arm. Four markers were also attached to a rigid body and secured to the participant's trunk (between the scapulae). Arm dominance was identified as the hand the participant uses to reach for an object. Each experimental session was recorded with a digital video camera that was synchronized with the kinematic and kinetic data. Prior to the start of data collection, arm length, shoulder height, foot length, and foot width were measured and recorded. The participant was then asked to step onto the force plate with their feet shoulder width apart. All infrared markers were then secured. A small bar was placed on the force plate in front of the participant's feet so that they would not step forward during the trials.

Participants were required to fit a block (90 × 90 mm) into an object placement board while standing. The object placement board contained an opening in its center aligned with the midline of the participant. The placement board was designed so that its height, opening size, and distance relative to the participant could be easily adjusted.

In each trial, participants fit the block into either a large (130 mm) or small (100 mm) opening that was placed at either a near distance (arm's length) or a far distance (1.33 arm's length). The near and far trials were blocked and the order counterbalanced across participants. Within each near and far block, opening size (large, small) and visual manipulations (lights on, dark) were randomized. In the dark condition, the room was completely dark. The testing room contained no windows, all lights were turned off and all electronics were covered. Only the block and perimeter of the opening (which were painted with glow in the dark paint) were visible. During each condition, participants were asked to fit the block through the opening without contacting the sides of the opening. An experimenter (who stood behind the object placement board) would take the block after it was completely through the opening and then put it on a table (adjusted to waist height) in front of the participant. The participant would then retrieve the block and place it again through the opening. This sequence was repeated until five successful fits were performed. The fitting board was instrumented with an accelerometer so that a computer would make a ringing sound if the block hit the board as it was passing through the opening. The participant was asked to repeat trials where the block contacted the board as it was passed through the opening.

Data Analysis

The five accurate fitting trials performed within each of the conditions were analyzed (inaccurate fitting trials were not further analyzed). Out of the entire time series to emerge from each trial, only the phase where the subject was fitting the block through the opening was used for subsequent analysis. This phase was defined as the time between when the block was first lifted off the table to when the block first broke the plane of the opening. Therefore, data collected before the participant grasped the block and after the block was fit through the opening were not further analyzed.

Three main phases were observed in the speed profile of the wrist during the manual fitting task (Figure 1). During the first two phases of the fit (the accelerative and decelerative phases) the block was transported to the opening of the fitting board. The third phase, an adjustment phase, occurred when the hand was making small endpoint corrections (or adjustments) in preparation to performing the fit.. When fitting through the large opening (non-precision condition) the adjustment phase was typically very small. Because the demands of the task varied based on the phase of the fitting movement, several of the kinematic and postural variables were calculated over the periods of time when the wrist was in its accelerative, decelerative and adjustment phase of the fit.

Kinematic data were collected from markers placed on the fitting arm and the trunk segment. From the markers placed on the trunk, average trunk speed over the three phases of the reach and the straightness of the trunk trajectory were all calculated. Speed was calculated using a first central difference method. The straightness of the trunk trajectory was calculated as the total path distance traveled by the trunk divided by the straight-line distance (Berthier & Keen, 2006). An increase in straightness ratio was used to indicate a trunk movement that is less straight during the reach.

Center of pressure (CoP) position – the point location of the vertical ground reaction force vector - was calculated in both the anterior-posterior (AP) and medial-lateral (ML) directions from the raw force plate data using equations 1 & 2.

$$CoP(AP) = \left[\frac{My + (Zoff * Fx)}{Fz} \right] * -1 \quad (1)$$

$$CoP(ML) = \left[\frac{Mx + (Zoff * Fy)}{Fz} \right] \quad (2)$$

Where: Fx, Fy, and Fz are the linear forces along the anterior-posterior (AP), medial-lateral (ML) and vertical axes, respectively. Mx and My are the moments about the AP and ML axes, respectively, and Z*off* is the vertical offset from the top of the plate to the origin of the force plate coordinate system. CoP data was used to assess whole body postural movements during each fitting trial. From the AP and ML CoP data, the average speed of the net CoP and the speed of the net CoP over the three reach phases were assessed. All data was calculated using custom written Matlab software (Mathworks Inc., Natick MA).

Temporal coordination between the wrist and trunk and wrist and center of pressure (CoP) was assessed as the time between when the wrist reached maximum speed relative to the trunk (wrist – trunk coordination) and when the wrist reached maximum speed relative to the CoP (wrist – CoP coordination).

In all variables, a mixed 4-way analysis of variance (ANOVA) between age (7-year-olds, 10-year-olds and adults) and within distance (far, near), size (large, small) and light (lights on, dark) was used to assess possible differences among the dependent variables. A Tukey post-hoc test was used to assess differences between age groups when significance was found. Due to the amount of comparisons made, a conservative alpha level of .01 was established as the threshold for significance.

Results

In all variables, only the main effects of group and group by task constraint interactions are reported. Main effects of task constraints and interactions between the task constraints (distance, size, and light) are not reported since they are not needed to address the stated developmental hypotheses. The average speed of the trunk during the accelerative and decelerative phase of the fit and the trunk straightness ratio was examined to address Hypothesis 1. The average speed of the trunk and center of pressure during the adjustment phase of the fit was examined to address Hypothesis 2. The temporal coordination between the wrist and CoP and the wrist and trunk were examined to address Hypothesis 3.

Trunk Kinematics

Average trunk speed (as the wrist was in its accelerative, decelerative and adjustment phase) and the trunk straightness ratio during the fitting movement were calculated. Main effects of age and any age × task constraint interactions indicated age related differences in trunk control during the precision fitting task.

7-year-olds exhibited a significantly higher average trunk velocity during the accelerative phase of the fitting movement (M = 173.5 mm/s) compared to the 10-year-olds (M = 113.6 mm/s) and adults (M = 116.7 mm/s), F (2, 54) = 9.76, p<.001, ηp^2=.217. No significant differences were observed between the 10-year-olds and adults. No interactions between age and any of the other task constraint variables were observed during the accelerative phase of the fitting movement (Figure 2a & 2b). During the decelerative phase of the fitting movement, there was a significant interaction between age and opening size. Average trunk speed was significantly greater in the 7-year-olds (M = 89.0 mm/s) compared to the 10-year-olds (M = 71.1 mm/s) and adults (M = 68.1 mm/s) when fitting through the small opening. There were no differences between the 7–year-olds (M = 98.1), 10-year-olds (M = 86.14) and adults (M = 93.3 mm/s) when fitting through the large opening; F (2,54) = 4.91, p=.001,

ηp^2=.170. No interactions between age or any of the other task constraint variables were observed during either the decelerative phase of the fitting movement (Figure 2c & 2d).

During the adjustment phase of the fitting movement a 3-way age × distance × size interaction was observed. The adults tended to exhibit the lowest degree of trunk speed in the adjustment phase when fitting at the near distance (Figure 2e). 7-year-olds however exhibited the lowest degree of trunk speed when fitting at the far distance (Figure 2f) but this was the case for the large opening only, $F(2,54) = 7.703$, p=.001, $\eta p^2 = .243$.

A significant age × fitting distance interaction was observed in the straightness ratio of the trunk, $F(2,54)=4.36$, p=.004, $\eta p^2 = .192$. When the postural constraints of the fitting task were made more difficult (far condition), adults exhibited a larger straightness ratio (Figure 2). An increase straightness ratio is indicative of a less smooth reach.

Postural Control: Center of Pressure

During the adjustment phase of the fit, positional changes of the trunk and wrist were very small. Average CoP speed during this phase of the fit therefore represents postural movements not associated with the transport of the arm. Rather, CoP speed during the adjustment phase of the fit represents postural movements that are produced as the hand is completing the precision task. Compared to both groups of children, adults were better able to stabilize their posture as the hand was making the precision movement. Specifically, average CoP velocity during the adjustment phase was lower in the adults (M = 39.7 mm/s) compared to both the 10- (M = 57.0 mm/s) and 7-year-old children (M = 61.7 mm/s), $F(2,54) = 12.274$, p<.000; ηp^2 = ..353. No interactions between age and any of the task constraints were observed.

Coordination between the Wrist and Center of Pressure

There was a significant age × distance interaction in the coordination between the time when the wrist and CoP reached max velocity, $F(2,54)=10.81$; p=.001, $\eta p^2 = .247$ (Figure 3). At the near distance, peak wrist and CoP speed occurred within 50 ms in all age groups. At the far distance, peak CoP speed occurred 235 ms, 153 ms and 87 ms before peak wrist speed in the adults, 10- and 7-year-old children respectively. Post-hoc analysis revealed that 7-year-olds were significantly different from the adults (p=.009).

Coordination between the Wrist and Trunk

In all age groups and conditions the peak speed of the trunk and wrist occurred within 250 ms of each other. An age × distance × size interaction ($F(2,54)=11.67$; p<.0001, $\eta p^2 = .275$) were found. When fitting through the small opening in the near target condition, the 10-year-olds and adults appeared to show a temporal synchronization (time lag on average of 32 ms) between the trunk and arm at the near distance (Figure 4a). The temporal coordination in the 7-year-olds was not as strong and was on average greater than 100 ms. In the far target condition, however, all age groups converged and appeared to show temporal synchronization, where the trunk and wrist reached peak speed within 50 ms of each other (Figure 4).

When fitting through the large opening, strong synchronization was observed at the near distance in all age groups (Figure 4b). At the far distance, however, the age groups diverged. In the 7-year-olds, peak trunk speed was reached approximately 125 ms after the wrist. Peak trunk speed, however, was reached before peak wrist speed in both the 10-year-olds (75 ms) and adults (200 ms).

Discussion

The current study examined how trunk, wrist and postural (CoP) movements were coordinated during a fitting task in children of varying ages and adults as distance, precision and visual constraints were manipulated. Three main findings were observed. First, compared to adults, children appear to use very different strategies to coordinate and control their trunk and arm while performing a precision manual task. Second, strategies to stabilize the block during the adjustment phase of the fitting task differ between children and adults. Third, even by 10-years-of-age children have still not developed adult-like levels of coordination and control when performing more difficult standing manual tasks.

Developmental Changes in Trunk Control during the Fitting Movement

To address Hypothesis 1, the average speed of the trunk during the accelerative and decelerative phases (the time when the block is being transported towards the opening) and the trunk straightness ratio were examined. It was hypothesized that 7-year-old children would freeze their trunk segment (lower trunk speed and higher straightness ratio) as the block was being transported towards the opening. The kinematic data did not support this hypothesis. Specifically, 7-year-old children exhibited increased trunk speed during the accelerative phase of the fit and during the decelerative phase of the fit when fitting through the small opening, The increased trunk speed in the younger children is somewhat counterintuitive since it would move their center of mass closer to the limits of the base of support, which could potentially threaten balance.

Developmental differences were also revealed when examining the path the trunk traveled (as assessed by the trunk-straightness ratio). Specifically, 7-year-olds had a lower straightness ratio compared to the 10-year-olds and adults in the far target condition. The increased straightness suggests that, when reaching for far targets, young children exhibit less motion out of the direct path of the trunk. Adults and older children may have reduced straightness of the trunk because they are generating more compensatory trunk movements to stabilize the hand as they prepare to fit the block through the opening.

These results suggest that when the constraints of the fitting task were more difficult, 7-year-old children adopted a strategy of ***move and stabilize***. With this strategy, the trunk is quickly displaced so that the manual task can be performed (higher accelerative and decelerative trunk speeds). However, any movements not related to the goal-directed manual task are attenuated so they will not affect the endpoint trajectory. With development, the move and stabilize strategy is replaced with a more robust and adaptable ***move and modulate*** strategy. Under this strategy the dual postural and movement functions of the trunk are carried out in parallel rather than serially. That is, as the trunk is displaced to accomplish the manual behavior, simultaneous compensatory movements adjust for potential endpoint errors in a manner similar to that described by Ma and Feldman (1995).

Although potentially less adaptable, the move and stabilize strategy observed in young children may be a form of motor learning where degrees of freedom are originally frozen but then, with practice and age, are released. With the release of these degrees of freedom, movements become more expert (Bernstein, 1967; Vereijken, van Emmerik, Whiting, & Newell, 1992) and possibilities for action can be further explored (Bertenthal, 1999; Berthier, Rosenstein & Barto, 2005). A second reason why children appear to exhibit a move and stabilize strategy may be related a hypothesis originally proposed by Schneiberg et al. (2002), suggesting that children exhibit a lack of feed-forward control when involving the trunk in goal-directed movements. Adults, on the other hand, preplan movements based on a coordinate system dictated by the endpoint (Flash & Hogan, 1985).

Endpoint Stabilization during the Precision Fitting Movement

As the block passes through the opening (the adjustment phase), stabilization of the endpoint (the block) becomes important. If whole body postural orientations and adjustments are not properly minimized and controlled, the arm could be perturbed and accuracy of the movement or balance could be diminished (Riccio & Stoffregen, 1988). Thus, to address Hypothesis 2, the average speeds of the trunk and CoP during the adjustment phase of the fit were examined. The adjustment phase is the time during the fitting movement where the hand must make highly accurate movements to successfully fit the block through the opening. It was hypothesized that children would be less able to stabilize both trunk and center of pressure compared to adults. Additionally, it was hypothesized that trunk and CoP stabilization would improve as a function of development. Interestingly, this hypothesis was only partially supported. Rather, it appears that younger children and adults use different strategies to stabilize the endpoint.

During the adjustment phase of the fit, trunk speed was lower in 7-year-olds when the postural constraints of the task were made more difficult (fitting at the far distance) compared to adults. However, CoP speed was greater in both 7- and 10-year-old children. Adults, therefore, appear to control the endpoint by minimizing CoP movements while children control the endpoint by reducing trunk movements. The CoP stabilization strategy may be better in terms of accuracy in that a stable dynamical interaction with the support surface is adopted and maintained (Riccio, 1993). Therefore, perturbations (either externally or self induced) can be easily sensed and compensated for by shifts in the CoP. The trunk strategy exhibited by children may be slightly easier to control (e.g. it is easier to just freeze the trunk to control hand precision). However, any perturbations, especially those originating externally or in the lower extremity, would easily be transmitted through the ‘stiffer’ trunk and may impact the precision of the task. Newly reaching infants primarily generate arm movements using the trunk and shoulder joint. However, with experience, infants begin to incorporate movements of the distal arm joints into the reach (Berthier, Clifton, McCall & Robin, 1999). Interestingly, it appears that the same proximal to distal maturation observed in infants continues in older children as they learn to perform more complex tasks that require the coordination of many of the body's degrees of freedom (Berthier et al. 1999).

Learning how to control postural orientations and adjustments based on the constraints of a supra-postural tasks could be a prime factor determining the development of motor abilities throughout childhood. Young children may begin to realize regions of permissible postural sway (thresholds of movement that still afford specific supra-postural tasks) for various movements, allowing for the development of various motor milestones (Adolph, 2002). Then, as children age, they refine their ability to modulate postural dynamics based on the goals of the supra-postural task.

The differing strategies used to stabilize the block as it passed through the opening did appear to influence fitting accuracy. In general, fitting accuracy improved with age. Specifically, fitting accuracy through the small opening was 47%, 62% and 90% for the 7- and 10-year-old children, and adult participants respectively. When fitting through the large opening all participants were accurate 100% of the time.

Developmental Changes in the Coordination of Posture and Manual Control

To address Hypothesis 3, the coordination between the hand and trunk and the hand and CoP was assessed during the entire fitting movement. It was hypothesized that children would exhibit poorer coordination compared to adults. Additionally, it was hypothesized that coordination would improve as a function of development.

Previous research has shown that in sitting postures, the temporal coordination between the trunk and arm attains adult-like levels by 4-5 years-of-age (Bard, Hay & Fleury, 1990; Scheinberg et al., 2002). Our data, however, points to a much later time course. The coordination measures examined showed that even 7-year-old children have not attained adult like control. In contrast, it was found that 10-year-old children are in a region in which they are transitioning to more adult-like levels of control. For example, the temporal coordination between postural (CoP) and manual (wrist) control and between wrist and trunk kinematics showed that all age groups exhibited similar coordination when the constraints of the task were not that difficult. However, when the task constraints were made more difficult the 7-year-olds exhibited more immature coordination patterns..

Interestingly, although the temporal wrist-trunk and CoP-wrist coordination patterns of 10-year-olds resembles adults; as discussed above, 10-year-old children still were not able to minimize CoP movements to the same level of adults during the adjustment phase of the reach. Based on the results from the CoP and trunk kinematic analysis, a proximal to distal developmental progression appears to occur, where trunk movement of the 10-year-olds appears to reach adult like levels before whole body postural adjustments of the CoP. Taken together, these results suggest that during tasks requiring altering degrees of precision and postural configurations, 10-year-olds appear to be in a transition period where their postural and manual control systems are starting to integrate to adult like levels (but are not yet quite at that point). The exact developmental trajectory of posture – manual coordination therefore depends on a large degree to the concurrently performed supra-postural task. Claims regarding when postural or manual control in children reach adult like levels need to take into consideration the nature and difficulty of the task.

Summary and conclusions

In this study, it was found that children do not exhibit the same trunk assisted manual synergies as adults. Specifically, older children and adults tend to adopt a ‘move and modulate’ strategy whereas young children appear to use a ‘move and stabilize strategy. Also, it was found that young children stabilize and control manual precision by freezing the trunk. However, adults tend to stabilize and control precision by controlling whole body postural fluctuations (minimizing the CoP). In general, changes in the aforementioned strategies suggest that young children have less adaptable strategies to control the body's degrees of freedom when performing precision manual movements. Finally, 10-year-old children appear to be in a transition period and more adult coordinative modes are beginning to emerge.

Acknowledgments

This research was supported by National Institutes of Health grant R37 HD027714 to Rachel Keen and National Institutes of Health Fellowship 5F31NS050930-02 to Jeffrey M. Haddad.

References

Adolph KE. Specificity of learning: Why infants fall over a veritable cliff. Psychological Science. 2000; 11:233–238.

Adolph, KE. Learning to Keep Balance. In: Kail, R., editor. Advances in Child Development & Behavior. Vol. 30. Amsterdam: Elsevier Science; 2002. p. 1-40.

Aruin AS, Forrest WR, Latash ML. Anticipatory postural adjustments in conditions of postural instability. Electroencephalography and Clinical Neurophysiology/Electromyography and Motor Control. 1998; 109:350–359.

Bard C, Hay L, Fleury M. Timing and accuracy of visually directed movements in children: control of direction and amplitude components. Journal of Experimental Child Psychology. 1990; 50:102–118. [PubMed: 2398328]

Bardy BG, Marin L, Stoffregen RJ, Bootsma RJ. Postural coordination modes considered as emergent phenomena. Journal of Experimental Psychology: Human Perception and Performance. 1999; 25:1284–1301. [PubMed: 10531664]

Baumberger B, Isableu B, Fluckiger M. The visual control of stability in children and adults: Postural readjustments in a ground optical flow. Experimental Brain Research. 2004; 159:33–46.

Bertenthal, BI. Variation and selection in the development of perception and action. In: Savelsbergh, G., editor. Nonlinear analyses of developmental processes. Amsterdam: Elsevier Science Publishers; 1999.

Bertenthal, BI.; Clifton, RK. Perception and action. In: Damon, W., editor. Cognition, perception and language. John Wiley and Sons; 1998. p. 51-102.

Bernstein, N. The Coordination and Regulation of Movements. Oxford: Pergamon; 1967.

Berthier NE, Clifton RK, McCall DD, Robin DJ. Proximodistal structure of early reaching in human infants. Experimental Brain Research. 1999; 127:259–269.

Berthier NE, Keen R. Development of reaching in infancy. Experimental Brain Research. 2006; 169:507–518.

Berthier NE, Rosenstein MT, Barto AG. Approximate optimal control as a model for motor learning. Psychological Review. 2005; 112:329–246. [PubMed: 15783289]

Balasubramaniam R, Riley MA, Turvey MT. Specificity of postural sway to the demands of a precision task. Gait & Posture. 2000; 11:12–24. [PubMed: 10664481]

Clifton RK, Perris EE, Bullinger A. Infants' perception of auditory space. Developmental Psychology. 1991; 27:187–197.

Davids K, Shuttleworth R, Button C, Renshaw I, Glazier P. “Essential noise”: Enhancing variability of informational constraints benefits movement control: A comment on Waddington and Adams (2003). British Journal of Sports Medicine. 2004; 38:601–605. [PubMed: 15388548]

Flash T, Hogan N. The coordination of arm movements: An experimentally confirmed mathematical model. Journal of Neuroscience. 1985; 5:1688–1703. [PubMed: 4020415]

Forssberg H, Nashner LM. Ontogenetic development of postural control in man: adaptation to altered support and visual conditions during stance. Journal of Neuroscience. 1982; 2:545–552. [PubMed: 7077364]

Gardner DL, Mark LS, Ward JA, Edkins H. How do the task characteristics affect the transitions between seated and standing reaches? Ecological Psychology. 2001; 13:245–274.

Gibson, EJ.; Pick, AD. An ecological approach to perceptual learning and development. New York, NY: Oxford University Press; 2000.

Haddad, JM.; Claxton, LJ.; Keen, R. Reaching beyond arm's length: The development of coordination between the trunk and arm in one-year-old children; Presented at the Society for Research in Child Development (SRCD) meeting; Atlanta, GA. 2005 April.

Haddad JM, Van Emmerik REA, Wheat JS, Hamill J. Developmental changes in the dynamical structure of postural sway during a precision fitting task. Experimental Brain Research. 2008; 190:431–441.

Hamill, J.; Haddad, JM.; Li, L.; Heiderscheit, BC.; Van Emmerik, REA. Clinical relevance of coordination variability. In: Davids, K.; Bennett, SJ.; Newell, KM., editors. Variability in the Movement System: A Multi-Disciplinary Perspective. Champaign, IL: Human Kinetics; 2006.

Hopkins B, Ronnqvist L. Facilitating postural control: Effects on the reaching behavior of 6-month-old infants. Developmental Psychobiology. 2001; 40:168–182. [PubMed: 11857331]

Kaminski TR, Simpkins S. The effects of stance configuration and target distance on reaching. I. Movement preparation. Experimental Brain Research. 2001; 136:439–446.

Ma S, Feldman AG. Two functionally different synergies during arm reaching movements involving the trunk. Journal of Neurophysiology. 1995; 73:2120–2122. [PubMed: 7623104]

McKenzie BE, Skouteris H, Day RH, Hartman B, Yonas A. Effective action by infants to contact objects by reaching and leaning. Child Development. 1993; 64:415–429. [PubMed: 8477626]

Patron J, Stapley PJ, Pozzo T. Whole body reaching in normal gravity and microgravity reveals a strong temporal coordination between postural and focal task components. Experimental Brain Research. 2005; 165:84–96.

Pozzo T, Stapley PJ, Papaxanthis C. Coordination between equilibrium and hand trajectories during whole body pointing movements. Experimental Brain Research. 2002; 144:343–350.

Purves, D.; Augustine, GJ.; Fitzpatrick, D.; Katz, LC.; LaMantia, AS.; McNamara, JO.; Williams, SM. Neuroscience. Sunderland, MA: Sinauer Associates, Inc.; 2001.

Riccio GE, Stoffregen TA. Affordances as constraints on the control of stance. Human Movement Science. 1988; 7:265–300.

Riccio, GE. Information in movement variability about the qualitative dynamics of posture and orientation. In: Newell, KM.; Corcos, DM., editors. Variability and Motor Control. Champaign, IL: Human Kinetics; 1993. p. 317-358.

Rochat P, Goubert N. Development of sitting and reaching in 5- to 6- month-old infants. Infant Behavior and Development. 1995; 18:53–68.

Schneiberg S, Sveistrup H, McFayden B, McKinley P, Levin MF. The development of coordination for reach-to-grasp movements in children. Experimental Brain Research. 2002; 146:142–154.

Shumway-Cook A, Woollacott MH. The growth of stability: postural control from a development perspective. Journal of Motor Behavior. 1985; 17:131–147. [PubMed: 15140688]

Sparto PJ, Redfern MS, Jasko JG, Casselbrant ML, Mandel EM, Furman JM. The influence of dynamic visual cues for postural control in children aged 7-12 years. Experimental Brain Research. 2006; 168:505–516.

Stapley PJ, Pozzo T, Cheron G, Grishin A. Does the coordination between posture and movement during human whole-body reaching ensure center of mass stabilization? Experimental Brain Research. 1999; 129:134–146.

Stoffregen TA, Smart LJ, Bardy BG, Pagulayan RJ. Postural stabilization of looking. Journal of Experimental Psychology: Human Perception and Performance. 1999; 25:1641–1658.

van der Fits IBM, Klip AWJ, van Eykern LA, Hadders-Algra M. Postural Adjustments During Spontaneous and Goal - Directed Arm Movements in the First Half-Year of Life. Behavioural Brain Research. 1999; 106:75–90. [PubMed: 10595423]

Vereijken B, van Emmerik R, Whiting H, Newell K. Free(z)ing degrees of freedom in skill acquisition. Journal of Motor Behavior. 1992; 24:133–142.

von Hofsten C. Prospective control: A basic aspect of action development. Human Development. 1993; 36:253–270.

von Hofstren C, Woollacott MH. Anticipatory Postural Adjustments During Infant Reaching. Neuroscience Abstracts. 1989; 15:1199.

Yonas A, Hartman B. Perceiving the affordance of contact in four- and five-month-old infants. Child Development. 1993; 64:298–308. [PubMed: 8436036]

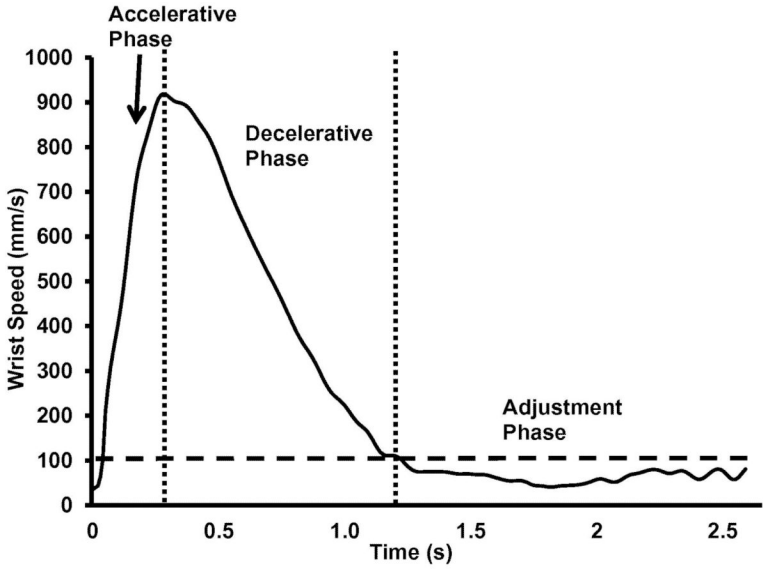

Figure 1.

Example triphasic speed profile of the wrist marker when fitting through the small opening. The first phase (accelerative), was defined as the time period between when the block first started to move (as identified by the synchronized DV recording) to the time the wrist reached maximum velocity (denoted by first vertical dotted line). The second phase (decelerative) was defined as the time period between max velocity to the time when the wrist velocity fell below 100 mm/s (denoted by second vertical dotted line). The accelerative and decelerative phases represented the transport of the hand to the opening. The last phase of the reach, the adjustment phase, was when small adjustments of the hand were made when preparing to fit the block through the opening. The onset of the adjustment phase was identified as the point in time when speed of the wrist first dropped below 100 mm/s. The offset of the adjustment phase was identified as the point of time when the block broke the plane of the opening (as identified by the synchronized DV recording). A similar profile was observed when fitting through the large opening except that the duration of the adjustment phase was much shorter.

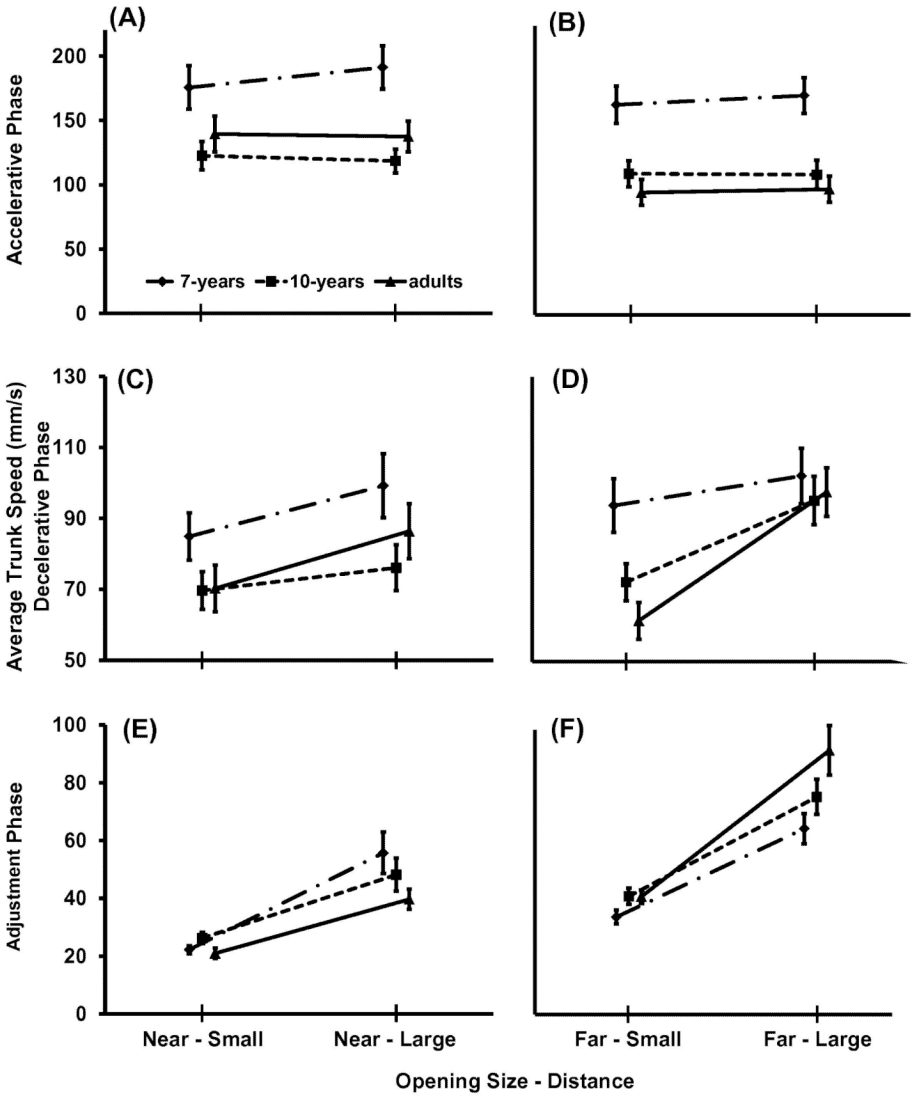

Figure 2.

Average trunk speed while the wrist was in the accelerative (2a, 2b), decelerative (2c, 2d) and adjustment phase (2e, 2f) of the fitting movement. The left column represents data from the near target condition and the right column data from the far target condition for the small and large openings. Data are collapsed across trials in the light and dark trials.

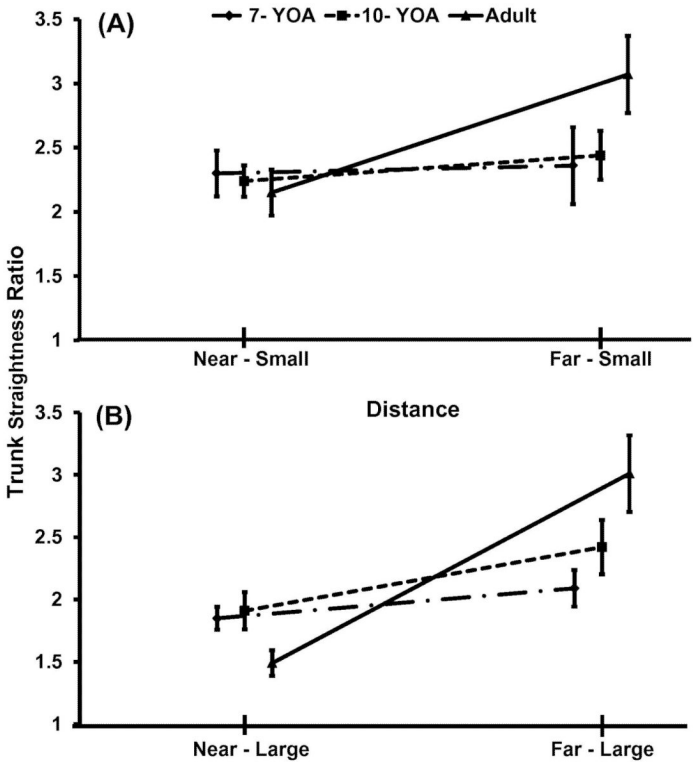

Figure 3.

Straightness ratio of the trunk for the a) small and b) large opening at the near and far distance. Data are collapsed across the light and dark conditions. Higher numbers represent a less straight path.

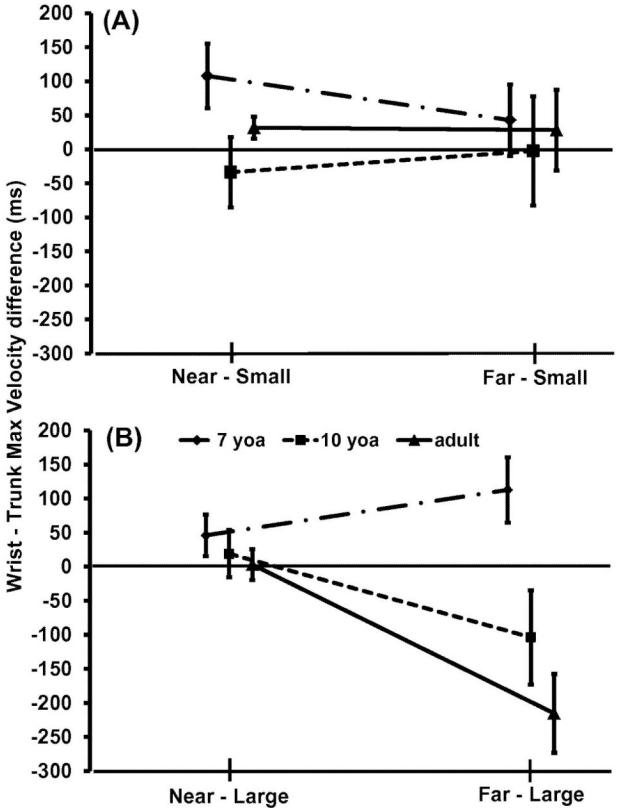

Figure 4.

Temporal coordination between the time when the trunk reached max speed relative to the wrist when fitting through a) the small opening and b) the large opening. Data are collapsed across the light and dark conditions.