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Developmental Changes in Postural Stability During the Performance of a Precision Manual Task

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Posture becomes integrated with other goal-directed behaviors early in infancy and continues to develop into the second decade of life. However, the developmental time course over which posture is stabilized relative to the base of support during a dynamic manual precision task has not been examined. Postural-manual integration was assessed in 7-year-olds, 10-year-olds, and adults using a postural-manual task in which task precision (target fitting size) and postural difficulty (reaching distance to a target) were manipulated. The main dependent variable was postural time-to-contact (TtC). Results indicated systematic age effects in which TtC was shortest in the 7-year-olds, increased in the 10-year-olds, and was longest in the adults. Across all age levels, TtC was longer when performing a precision fit compared with a nonprecision fit and when fitting at a near target compared with fitting at a far target. Finally, TtC increased over the course of the manual fitting task, suggesting that posture became increasingly stable as the hand approached the opening. The ability to modulate postural TtC during the course of the fitting trial was most pronounced in adults as compared with both groups of children. These results suggest that even by 10-years of age, children are not yet able to fully integrate postural movements with goal directed manual tasks at adult-like levels.

***Keywords*:** development, postural time-to-contact, manual control, postural control

Upright posture and balance is typically controlled in a manner that allows stance to be maintained while completing a concurrent goal-directed behavior, often referred to as a supra-postural task (Balasubramaniam, Riley, & Turvey, 2000; Riccio, 1993). For example, when performing a visual fixation (Stoffregen, Smart, Bardy, & Pagulayan, 1999) or precision manual task (Haddad, Ryu, Seaman, & Ponto, 2010), body sway is minimized since any extraneous movements could reduce visual acuity or manual precision. However, when performing gross motor actions, tightly constraining postural sway is often not necessary to accomplish the task. Postural movements (assuming they will not destabilize stance) may therefore be allowed to help complete the task (Stapley, Pozzo, Cheron, & Grishin, 1999) and may also improve the flexibility and adaptability of the postural system (Riccio, 1993; Van Emmerik & van Wegen, 2002).

Developmental research has suggested proper postural control is necessary before other motor behaviors are developed and refined. For example, postural development is necessary before motor milestones such as reaching and locomotion emerge (Adolph, 2002; Bertenthal & Clifton, 1998). However, the developmental time course over which task-dependent postural control is refined and becomes adult-like is protracted, extending past the first decade of life (Haddad, Claxton, Keen, Berthier, Riccio, Hamill et al., 2012).

Typical spatial measures used to quantify center of pressure (CoP) time series data are calculated over multiple data points. Therefore, postural changes that occur within a trial (over smaller time-scales) are not captured. However, most daily tasks are dynamic in nature. The constraints of the task can therefore quickly change. For example, when leaning forward to reach for an object, the postural constraints at the end of the movement are more difficult since extraneous body movements when leaning forward can potentially be more destabilizing. For children, gaining the ability to quickly modulate the dynamics of posture is likely a key aspect of motor development.

Modulations of Postural Time-to-Contact When Performing a Supra-Postural Task

In a previous study, adults performed a standing fitting task in which precision requirements were manipulated (fitting a block into either a large or small opening). Spatial measures of postural sway and postural time-to-contact (TtC) were assessed during the course of

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the fitting movement (Haddad, Ryu, Seaman, & Ponto, 2010). Postural TtC is the time it takes the CoP to contact the base of support (defined by the boundaries of the feet) given its instantaneous position, velocity, and acceleration. Postural TtC has previously been shown to detect changes in postural control that are not detectable using more traditional measures (Haddad et al., 2010; Hertel & Olmsted-Kramer, 2007). Since postural TtC is assessed relative to the base of support, it is well suited to analyze postural control during dynamic supra-postural movements. In addition, postural TtC is assessed at each point of the CoP time series, allowing small time-scale postural modulations to be captured. Haddad et al. (2010) found that in the early phases of the movement, when the block first started moving toward the opening, postural stability was not tightly constrained (shorter TtC values were observed). However, as the movement progressed and the block approached the opening, TtC systematically increased. The longest TtC values were observed at the end of the movement, as the block was passing through the opening, suggesting participants were the most stable at this phase of the movement. Interestingly, these postural modulations were only observed in the precision trials (fitting through the small opening) using the postural TtC measure. The Haddad et al. (2010) study demonstrated that when performing precision dynamic tasks, young adults constantly modulate posture during a movement to satisfy the instantaneous constraints of a manual behavior.

In the current study, we used a standing precision fitting task, similar to the task described in Haddad et al. (2010), to examine the ability of 7- and 10-year-old children and adults to integrate posture with other goal-directed behaviors. Standing precision fitting tasks are appropriate to address the development of task-dependent postural control since task precision can easily be altered and the constraints change during the course of the movement. Therefore, the purpose of this study was to examine changes in postural TtC in children (ages 7 and 10 years) compared with adults while performing a manual fitting task requiring varying degrees of precision and body lean. These ages were chosen because the postural system of 7-year-olds has previously been identified as being a transition period during which more adult-like strategies are beginning to emerge (Haddad et al., 2012; Shumway-Cook & Woollacott, 1985).

Four hypotheses were formulated for this study. Firstly, we hypothesized that postural TtC would be shorter in the younger children compared with the older children and adults. This hypothesis predicts that young children will operate closer to their stability boundaries when performing a standing manual task (a situation that could potentially cause a postural instability or impede performance of the manual task). Secondly, we hypothesized that an increase in TtC (across all age groups) would be observed as the precision demands of the task increased. An increase in TtC would indicate that all age groups adopt a more stable posture when needed to successfully complete the supra-postural manual task. Thirdly, we hypothesized that a decrease in TtC would be observed as the postural demands of the task increased. A decrease in TtC would indicate that participants were less stable when leaning forward to complete the task. Finally, we hypothesized that there would be an interaction between age and the manipulated constraints. Specifically, we predicted that adults would be able to adopt a longer TtC (exhibit increased postural stability) compared with children when performing the more difficult manual fitting task.

Methods

Participants

A total of 51 participants, divided into three age groups, were recruited: Group one (n = 17) consisted of 7-year-olds (M_{age} = 7 years, 36 days; *SD* = 80 days); group two (n = 17) consisted of 10-year-olds (M_{age} = 10 years, 14 days; *SD* = 153 days); and group three (n = 17) consisted of adults (M_{age} = 20 years, 29 days; *SD* = 2.43 years). 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. Adult participants were recruited from the university undergraduate community. All participants were free of pathologies known to influence normal postural or movement control. Adult participants signed an informed consent form that was approved by the University Institutional Review Board. The parents of the 7- and 10-year-old children signed the informed consent. Children were given an age-appropriate explanation of the procedures. Adults (all undergraduate university students) received extra course credit for participating.

Procedures

Arm length, shoulder height, foot length, and foot width of the participants were measured and recorded. Arm dominance was assessed as the hand the participant uses to grasp an object. Participants were then asked to adopt a comfortable stance on the force plate behind a 3cm piece of wooden molding (mounted to the force plate). The width of the molding was slightly smaller than the width of the force plate. The molding was used to prevent the participant from stepping forward during the experimental trials. Participants were also instructed to maintain their initial foot position during all experimental trials. Highly visible tape was placed around the perimeter of the feet to mark the stance configuration. Foot position was monitored during each trial using a real time video feed. If the feet moved, the experimenter prompted the participant to return their feet to the marked perimeter, and the trial was repeated. This digital video recording (synchronized with the force plate data) was also used to determine the phase of each trial when the participant was fitting the block versus the phase of the trial where the block was acquired (for the next fit).

In all trials, participants were asked to fit a block (90 × 90 mm) into either a large (130 mm) or small (100 mm) opening in an object placement board (adjusted to shoulder height) with their dominant arm (Figure 1). The placement board was located directly in front of the participant during each trial. The board was designed so that the size of the opening, placement height, and distance from the participant could be adjusted (see Haddad et al., 2010). An accelerometer was attached to the back of the placement board to monitor accuracy during the fitting task. If the participant hit the perimeter while fitting the block through the opening, a "ding" sound was triggered by the accelerometer. CoP data were obtained at 100 Hz from one force platform (AMTI inc., Watertown, MA). The opening of the placement board was oriented to the participant's midline. The object placement board was placed at either a near distance (arm's length from the participant) or a far distance (1.5 arm's length from the participant).

The order of near and far conditions was counterbalanced across participants. The small and large opening conditions were randomly presented within each near and far block. This resulted in four experimental conditions: 1) near target, large opening; 2) near target, small opening; 3) far target, large opening; and 4) far target, small opening. Participants performed five successful trials per condition. A trial was considered successful if the block passed through without hitting the perimeter of the opening. After each fit, the experimenter took the block from the participant and placed it back on the table in front of the participant (the table was adjusted to waist height). The participant would then retrieve the block and place it again through the opening. If the participant hit the board during the fitting procedure an audible sound was activated by the accelerometer and the participant was asked to repeat the trial. The computer also recorded this contact.

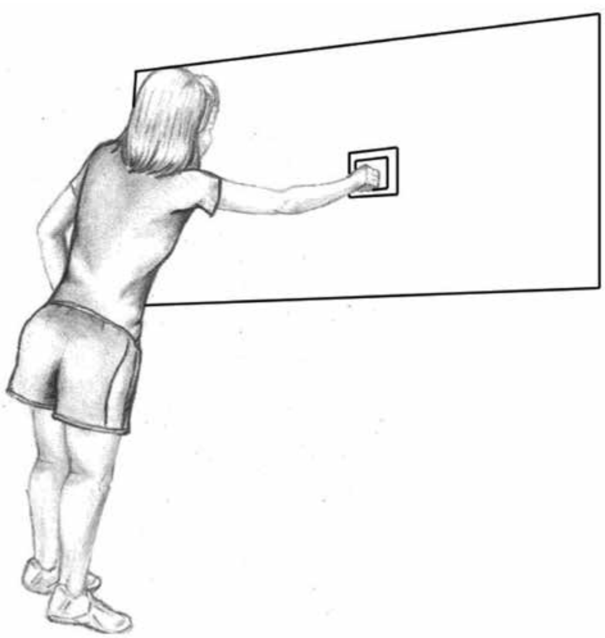

Figure 1 — Illustration of adult participant fitting the block through the small opening in the object placement board at the far distance.

Data Analysis

In each trial, only the phase when the participant was fitting the block was analyzed. This phase was defined from the time the participant picked up the block to when the block moved through the opening. CoP in the anterior-posterior (AP) and medial-lateral (ML) directions were then assessed for each trial for all four experimental conditions. Postural TtC was calculated using the equations in Slobounov, Slobounova, and Newell (1997) and Haddad, Gagnon, Hasson, van Emmerik, and Hamill (2006). In this method, a virtual trajectory is calculated using the instantaneous position, velocity, and acceleration of the CoP in both the AP and ML directions. TtC is then determined to be the time it would take the virtual trajectory to contact the base of support (foot boundaries) absent of any corrective postural response. The base of support was defined using a four-segment boundary. The posterior border of the boundary was the line connecting the Calcaneal Tuberosities of the two feet. The anterior boundary was the line connecting the Distal Phalanges of the great toe. The medial and lateral boundaries intersected the head of the Fifth Metatarsal and connected the anterior and posterior boundary (see Figure 2). All boundaries were determined by tracing the perimeter of the participants' feet while they were on the force plate. The TtC algorithms produce a new time series that contain all of the TtC values over the trial. The final TtC measure was calculated by averaging the TtC time series of all virtual trajectories.

To assess if participants modulated postural dynamics, TtC was also assessed over the course of the fitting movement. Because each trial was a different length, the TtC time series for each participant were normalized to 100 data points. TtC data were then averaged over epochs of 10 data points (10%).

Differences in TtC were assessed utilizing a three-way repeated-measures ANOVA with distance of the placement board (distance factor) and size of the opening (size factor) as the within participant independent variables and age group as the between participants independent variable. The dependent variables assessed in the ANOVA were TtC over the course of the whole trial and the TtC over the 10 epochs. Tukey post hoc tests were assessed when differences were observed. An alpha level of 0.05 was set as the threshold for significance. Changes in TtC epochs were assessed utilizing a four-way repeated-measures ANOVA with distance, size, and epoch as the within participant terms and age group as the between participants variable. Since measures of CoP magnitude are time independent, they cannot capture postural modulations that occur during the dynamic fitting task. Thus, no measures examining the magnitude of CoP movement were calculated.

Results

Average TtC as a Function of Task Constraint

Postural TtC was influenced by both the distance and size manipulations. TtC was longer in the small compared with the large opening ($F(1,48) = 305.12$; $p < .0001$, Figure 3). TtC was also longer in the near target compared with the far target ($F(1,48) = 105.15$; $p < .0001$, Figure 3). No age × distance or age × size interactions were observed, suggesting that all three age groups responded in a similar manner to both distance and size manipulations ($p > .05$). There was a main effect of age ($F(2,48) = 37.10$; $p < .0001$), where TtC was shortest in the 7-year-olds and longest in the adults (Figure 3). Tukey post hoc analyses revealed that all three age groups were significantly different from each other ($p < .05$).

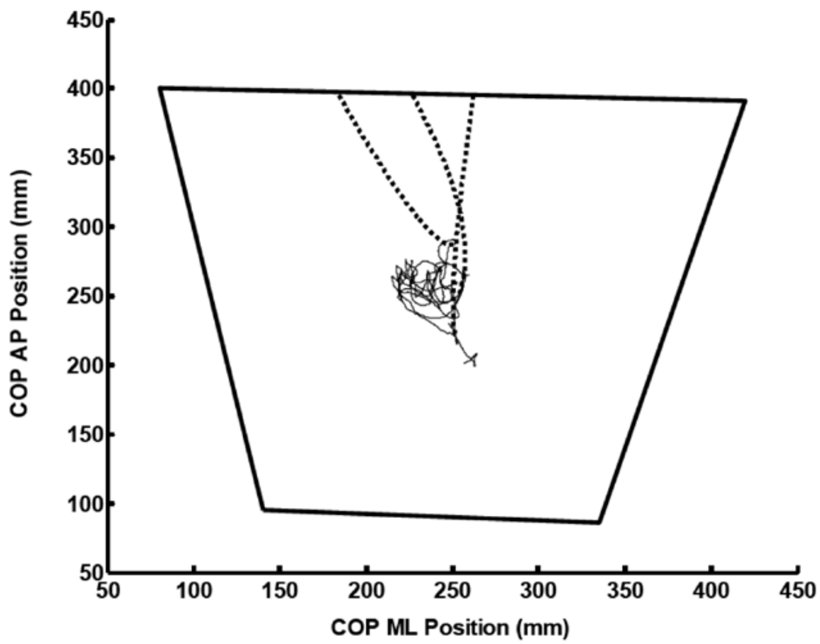

Figure 2 — Representative CoP data with three virtual TtC trajectories for a 7-year-old participant fitting the block through the large opening at the near distance. The CoP data used are shown by the solid black line. The three virtual trajectories (dotted black lines) from the CoP trace are extrapolated to the boundaries of support. In some instances the trajectories are parabolic. This arises when there is a differential direction between the acceleration and velocity vectors. Although only three trajectories are shown here, a boundary contact time from the virtual trajectory was calculated for each point in the CoP time series. All data are represented with respect to the force plate coordinate system.

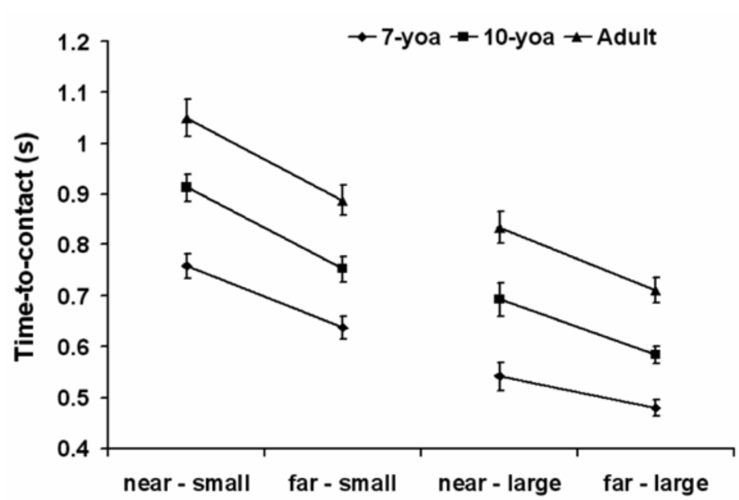

Figure 3 — Mean time-to-contact data for all three age groups in the near-small, far-small, near-large, and far-large conditions.

Evolution of the TtC During the Fitting Trial

In all age groups, the TtC time series tended to increase between the time the block was acquired and the moment the block passed through the target opening (Figure 4). To assess the change in TtC over the course of the trial, a four-way ANOVA was performed between age group and repeated within distance, size, and epoch (the 10 periods of time used to represent the fitting movement). Significant main effects were found for age ($F(2,48) = 36.94$; $p < .0001$), distance ($F(1,48) = 102.46$; $p < .0001$), size ($F(1,48) = 302.48$; $p < .0001$), and epoch ($F(9,432) = 276.72$; $p < .001$). Post hoc comparisons on epoch revealed that TtC remained constant over the first three epochs, steadily increased over epochs four through seven, and then remained constant over the last three epochs (Figure 5). Distance × epoch ($F(9,432) = 71.07$; $p < .001$) and size × epoch ($F(9,432) = 66.01$; $p < .001$) interactions were also found. In the distance × epoch interaction, the increase in TtC over epochs was greater in the near conditions compared with the far conditions. The same pattern was observed in the size × epoch interaction, where the increase in TtC over epochs was greater in the small opening condition compared with the large opening condition (Figure 5).

Although no two-way interactions between group and size, group and distance, or group and epoch were present, a three-way interaction between group × distance × epoch ($F(18,432) = 2.86$; $p < .0001$) was observed. Post hoc comparisons revealed this interaction emerged because adults increased their TtC to a greater extent between the far and near conditions over the last three epochs compared with either group of children (Figure 5).

Discussion

The purpose of this study was to examine developmental changes in the ability of children to modulate posture while performing a supra-postural manual task with varied precision and postural constraints. A clear developmental trend in TtC across all experimental conditions was observed. The 7-year-olds had the shortest TtC while the adults had the longest. These age effects suggest that adults are able to maintain a wider spatio-temporal stability margin to their base of support compared with 7- and 10-year-old children. In addition, 10-year-old children were generally able to maintain a wider stability margin compared with 7-year-old children when performing the fitting task. These wider margins could be beneficial in cases of unexpected perturbations in which additional CoP movements might be necessary to keep the projection of the COM within the base of support.

In older children (ranging from five to adolescence), most of the studies examining posture have been conducted using a quiet stance and sensory manipulation paradigm. These studies have basically found that somewhere 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 & Woollacott, 1985). Younger children are typically found to exhibit greater amounts of sway during quiet stance and much higher amounts of sway during various conditions

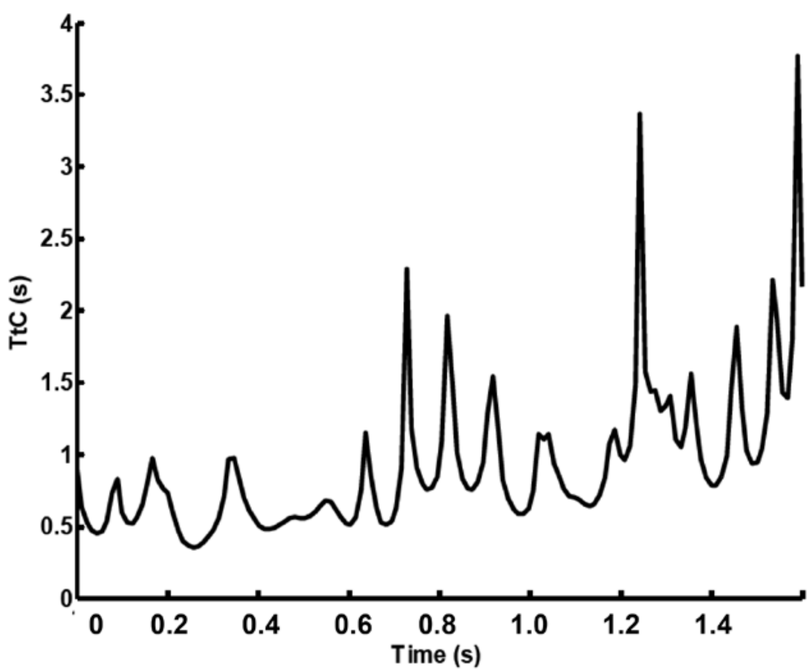

Figure 4 — Representative TtC time series in one fitting trial in the near/small condition (adult participant). There was a tendency for the TtC time series to migrate upwards toward the end of the trial when the participant was about to fit the block through the opening.

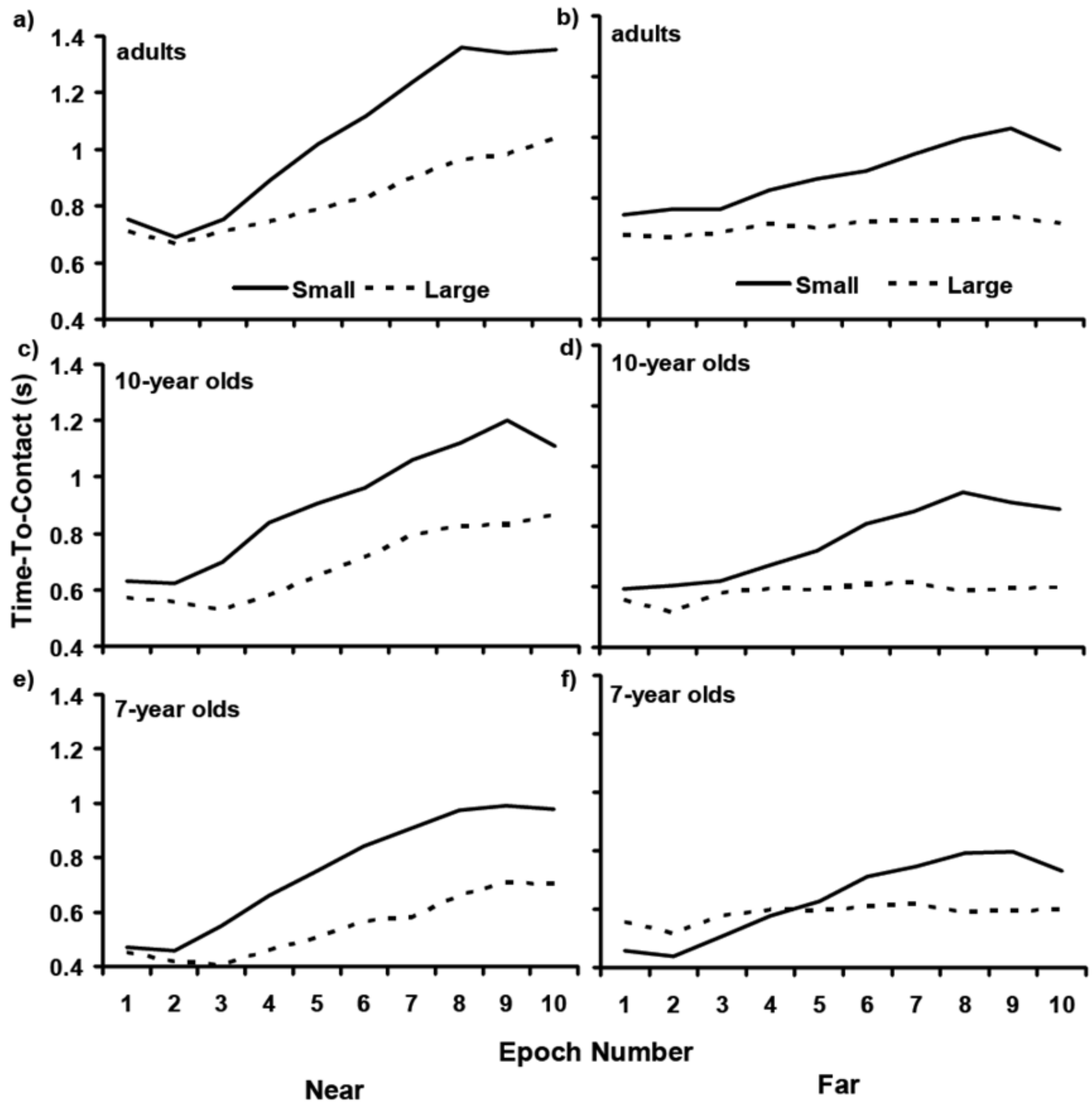

Figure 5 — TtC over the 10 epochs in the adults at the a) near and b) far conditions, in the 10-year-olds at the c) near and d) far conditions, and in the 7-year-olds at the e) near and f) far conditions. Although in all three age groups the TtC migrated upwards toward the fitting phase of the trial, this effect was strongest in the adult age group in the near-small condition.

imposing sensory manipulations as compared with 7- to 10-year-olds and adults.

More recent research has suggested that the time course of postural development is delayed under more challenging task constraints. For example, the postural transition period is delayed to approximately ten years of age when assessing more dynamic postural responses, such as responding to sensory conflicts or dynamical visual information (Baumberger, Isableu & Fluckiger, 2004; Sparto, Redfern, Jasko, Casselbrant, Mandel, & Furman, 2006). Results from the current experiment indicate that even at ten years of age, children may not have reached adult-like levels in tasks that require the integration between posture and manual behavior.

Development of Task-Dependent Postural Control

Similar to adults (e.g., Haddad et al., 2010), postural fluctuations relative to the base of support were not tightly controlled in the beginning of the fitting movement in both age groups of children. However, as the block approached the opening, TtC systematically increased and stayed elevated as the block was passing through the opening. The changes in TtC during the fitting movement suggest postural fluctuations are allowed when they do not threaten stability or interfere with the successful completion of a goal-directed task (Haddad et al., 2010). However, toward the end of the fitting movement, when any extraneous postural movements could threaten stability or impede performance of the precision task, posture became more constrained. Interestingly, the adult group exhibited the greatest increase in TtC suggesting the integration between posture and manual control continues to develop through late childhood (see Figure 4).

The reason why postural fluctuations were allowed in the beginning of the movement may be because they potentially add flexibility to the postural system and generate sensory information regarding the interaction between the individual, task, and environment (Latash et al., 2003; Riccio & McDonald, 1998; Van Emmerik & van Wegen, 2002). In the developmental literature, similar exploratory functions have been ascribed to the motor variability typically seen in children (Bertenthal & Clifton, 1998). Extraneous movements that do not immediately contribute to the completion of the task, provide information to the child that is used to learn how to more efficiently perform the task. For example, when learning to reach, movement variability causes the child to perform each reach a little differently (Bertenthal, 1999). This variability helps the child learn how to control their body within a dynamically changing environment and optimally perform the task. Essentially, variability allows the child to learn new affordances for action (Bertenthal, 1999). These affordances are often dynamic and therefore may change over small time scales. In the case of development, the child must learn that possible actions at one point of time may not be possible at other points of time due to factors such as change in body position, inertial forces, or support surface. In addition, changes in body dimensions, muscular strength, and modes of locomotion (Adolph, 2002) can all change affordances.

It is interesting to note that when performing the fitting task at the far distance, TtC decreased (participants were less stable) compared with when performing the task at the near distance. This finding demonstrates that posture is only stabilized when the precision constraints of the fitting task were made more difficult. We believe these results emerged because the postural difficulty of the task was increased to a level where it was not possible for participants to further stabilize (increase TtC) posture. Thus, participants appear to only stabilize posture to complete a precision manual task when they are able to do so (i.e., when the postural constraints are not difficult). However, when the postural requirements of the task are more difficult, stabilizing posture to complete a manual task may not be possible (even in adults).

In the current study, we examined 7- and 10-year-old children because the postural system of 7-year-olds has previously been identified as being a transition period during which more adult-like strategies are beginning to emerge (Haddad et al., 2012; Shumway-Cook & Woollacott, 1985). Interestingly, Claxton, Melzer, Ryu, and Haddad, (2012) found that the postural dynamics of newly standing infants change when they attend to and interact with a toy. Taken together, these results suggest that task-dependent postural control develops over a relative long time course that begins in infancy and concludes sometime after the first decade of life. In future studies, it would be interesting to examine in multiple age groups how task-dependent postural control changes throughout childhood.

In conclusion, when performing a manual task of varying constraint difficulty, adults maintain a longer temporal margin to the stability boundary compared with children. Although 10-year-old children reveal different postural dynamics compared with 7-year-old children, their postural responses to the manual task are not yet to adult levels. An examination of TtC across each fit trial revealed that all age groups modulated posture relative to a stability boundary, where the longest TtC times were observed just before the block passed through opening during the high precision fit (fitting through the smaller opening). Adults were better able to modulate postural TtC compared with children. Therefore, an important part of postural development is learning how to properly modulate between the expression and suppression of postural movements based on the constraints of a concurrently performed task.

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