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RESEARCH ARTICLE

The development of infant upright posture: sway less or sway differently?

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Abstract Postural control is an important factor for early motor development; however, compared with adults, little is known about how infants control their unperturbed upright posture. This lack of knowledge, particularly with respect to spatial and temporal characteristics of infants' unperturbed independent standing, represents a significant gap in the understanding of human postural control and its development. Therefore, our first analysis offers a thorough longitudinal characterization of infants' quiet stance through the 9 months following the onset of independent walking. Second, we examined the influence of sensory-mechanical context, light touch contact, on infants' postural control. Nine typically developing infants were tested monthly as they stood on a small pedestal either independently or with the right hand lightly touching a stationary contact surface. In addition to the longitudinal study design, an age-constant sample was analyzed to verify the influence of walking experience in infant postural development without the confounding effect of chronological age. Center of pressure excursions were recorded and characterized by distance-related, velocity, and frequency domain measures. The results indicated that, with increasing experience in the upright, as indexed by walk age, infants' postural sway exhibited shifts in rate-related characteristics toward lower frequency and slower, less variable velocity oscillations without changing the spatial characteristics of sway. Additional touch contact stabilized infants' postural sway as revealed by decrease in sway position variance, amplitude, and area as well as lower frequency and velocity. These results were confirmed by the age-constant analysis. Taken together, our findings suggest that instead of progressively reducing the sway magnitude, infants sway differently with increasing upright experience or with additional somatosensory information. These differences suggest that early development of upright stance, particularly as it relates to increasing postural and locomotor experience, involves a refinement of sensorimotor dynamics that enhances estimation of self-motion for controlling upright stance.

Keywords Posture · Development · Infant · Somatosensory · Standing

Introduction

Postural control is an essential ability in developing motor skills needed for daily living activities (Bertenthal and Clifton 1998). To control the multi-segmented body over its support base requires an accurate and reliable relationship between sensation and action that is adaptive to an ever changing environment and task demands. This relationship is not yet fully developed at birth. Indeed, it takes infants almost a year to stand independently and many years thereafter to develop adult-like postural control. While the sensorimotor control of posture has been extensively studied in adults (cf. Horak and Macpherson 1996), surprisingly little is known about infant upright postural control in the

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first 2 years of life. Early researchers provided chronologies of postural milestones such as when infants sit, stand, and walk (Gesell 1946; McGraw 1932; Shirley 1933). Later, studies explored how infants use sensory information in the development of their postural control by recording their responses to discrete sensory and mechanical perturbations (Forssberg and Nashner 1982; Lee and Aronson 1974; Sveistrup and Woollacott 1996) or how their posture is coupled to sensory (mostly visual) information (Barela et al. 2000; Bertenthal et al. 1997, 2000; Metcalfe et al. 2005b). Unlike the research on adult postural control, no studies have fully characterized unperturbed, independent stance in infants in the first months after they stand independently. If we are to understand how infants develop and refine their sensorimotor control over postural behaviors, it is necessary to first understand the development of infants' unperturbed, independent upright posture. Therefore, the purpose of the present study was to address this significant gap in our knowledge by analyzing infants' quiet, unperturbed stance from the onset of independent walking and thereafter for a period of time that will allow us to precisely characterize the aspects of postural sway, which undergo change as typically developing infants gain upright postural experience.

Human upright posture is never motionless. Contemporary conceptualizations view postural sway as the result of dynamic and complex processes in which the postural control system is continuously adapting to a range of internal and external perturbations (Horak and Macpherson 1996; Kiemel et al. 2002). Adults' quiet stance has been characterized in many studies and models have been proposed to explain the sensorimotor control of the human postural system. From this research, adults' upright posture is consistently described as a low-frequency motor behavior with two major components: a slow drift component and a fast damped-oscillatory component, with the former accounting for the majority of postural sway variance (Collins and De Luca 1993; Dijkstra 2000; Kiemel et al. 2002; Zatsiorsky and Duarte 1999). Using different approaches, studies have attempted to link these two components to the underlying physiological control mechanisms. For example, the fast component is usually explained by the control dynamics of an inverted pendulum (e.g., Johansson et al. 1988) while the slow dynamics are attributed to errors in postural state estimation (Kiemel et al. 2002, 2006). In addition to the rate-related features (i.e., in the frequency domain), research has also found that the amount of adults' postural sway increased with aging (Newell et al. 1997; Prieto et al. 1996), diseases (Bronstein et al. 1990), or challenging tasks (Woollacott and Shumway-Cook 2002). On the other hand, postural sway could be attenuated by providing additional sensory information (somatosensory or vision) (Jeka et al. 2000; Jeka and Lackner 1994; Prieto et al. 1996).

Little is known about how the dynamics of human postural control develop in the early stages of the life span. While toddlers have been shown to gradually increase their upper body stability during upright locomotion (Ledebt and Bril 2000), our previous study using stabilogram-diffusion analysis suggested no developmental change in the center of pressure (COP) sway variance of infants' upright stance across the first year of independent walking (Metcalfe et al. 2005a). Instead, the rate constant at which infants' postural sway decayed to maximum variance decreased as they gained more walking experience, suggesting that infants' posture relied more on the slow dynamics process resulting from the errors of state estimation. Rate-related information (i.e., velocity and frequency) from the sensory environment has been suggested as critical for human postural behavior (Dijkstra et al. 1994; Jeka et al. 2004; Kiemel et al. 2006). Changing the rate-related characteristic of infants' postural sway may enhance the integration of sensory information in the postural control system. Therefore, the rate-related features of quiet postural sway may provide important information about the sensorimotor control of human posture during infancy.

In a study of 12 to 14-month-old infants, investigators found that infants' postural sway, like adults', was concentrated mostly in the low end (below 1.5 Hz) of the frequency spectrum (Ashmead and McCarty 1991). Due to the low spectral resolution (0.25 Hz) of this study and its cross-sectional research design, it is unknown whether the frequency distribution of infants' postural sway was different from adults' or changed developmentally. In 2 to 14-year-old children, enhanced postural control has been described as exhibiting decreased variance (Newell et al. 1997; Riach and Hayes 1987), velocity (Riach and Starkes 1994) and frequency of postural sway (Riach and Hayes 1987). These results are consistent with the notion that postural development involves changes in rate-related features of the postural behavior that enhance the integration of sensory information in the postural control system. What remains unknown is whether the developmental processes of changing rate properties of postural control start as early as infancy when dramatic changes in infants' standing behavior are observed.

It is often seen that newly standing/walking infants hold onto furniture to help balance their body in the upright position. For example, research observations indicate that 13 to 14-month-old infants tended to hold onto an external supporting object when standing on a narrow surface (Stoffregen et al. 1997). Additional somatosensory cues from the hand lightly touching a stationary surface has been shown to significantly attenuate body sway during upright stance in young adults (Jeka and Lackner 1994) as well as in infants during the first year of independent walking (Metcalfe and Clark 2000). Given these observations, touch also provides a window to study how infants use sensory information to help control their unsteady upright posture at earlier developmental epochs. In a previous study, in which infants stood with the hand touching a contact surface, Barela and colleagues examined the temporal relationship between touch force and infants' postural sway (Barela et al. 1999). At the developmental milestone of pull-to-stand, the force that infants applied to the contact surface through the hand lagged temporally behind their postural sway, indicating the use of touch forces mechanically. However, after a few months of independently walking, the temporal relationship changed such that applied forces through the hand led body sway. These results, as suggested by the authors, indicate infants' use of touch for prospective postural control. Yet, without a full characterization of the unperturbed, independent postural behavior, it remains unclear how the dynamics of infants' upright postural sway are influenced by the use of additional touch contact.

Our purpose in this study was, first, to fully characterize the development of infant posture in "hands-free", quiet upright stance by examining changes in both spatial and temporal (i.e., rate-related) features of the infants' postural sway over the first year of independent walking. Second, we investigated how lightly touching a contact surface may influence the dynamics of infants' postural sway during upright stance. Our overall goal was to provide a foundation for the development of infant postural control so that future research can be extended to better understand the sensorimotor control of infants' upright posture.

Method

Participants

Nine infants (6 males and 3 females; 5 Caucasian, 1 African–American, and 3 Asian) were recruited from the surrounding areas of the University of Maryland, College Park. All infants were born full-term without birth complications or any history of developmental delay. At 6, 9, and 12 months of age, infants were assessed with the Bayley Scales of Infant Development (Bayley 1993) to verify that their development was within normal limits. Infants entered the study when they were able to sit independently (mean age = 6.3 ± 0.7 months) and were tested monthly until they have been walking independent for 9 months (mean age at walk onset = 11.8 ± 1.7 months). Walk onset was defined as the day when the infant took three continuous independent steps. For the purpose of this investigation, infants were only assessed at the ages when they could maintain independent upright stance (i.e., "hands free"); specifically from walk onset onward. All infants were paid a modest compensation per testing session and each infant's parent or guardian provided written informed consent prior to inclusion in the longitudinal study. To provide a reference group for comparison, five healthy adults (2 females and 3 males) were also included in this study. These adults (mean age = 29.8 ± 8.2 years) were unpaid volunteers who provided written informed consent. All experimental procedures were approved by the Institutional Review Board at the University of Maryland, College Park.

Apparatus and procedure

Figure 1 illustrates the experimental set-up for infants, wherein each participant stood on a pedestal mounted on a force platform in parallel stance with eyes open, either independently (no-touch) or with his/her right hand lightly touching a stationary surface (touch). Similarly, adults stood on a pedestal in a position analogous to the infants. Data were acquired remotely with a customized LabView™ program. All signals were sampled at 50.33 Hz in real time and synchronized to a manual trigger at trial onset.

Touch apparatus

For the infants, the contact surface was a customized touch bar, which was a 4.4-cm diameter convex surface formed by the top half of a 45.7 cm long PVC tube. The touch bar was

Fig. 1 An infant stands independently on a pedestal in the no-touch condition. An experimenter sits in front of the infant to keep his/her attention in the task. In the touch condition, the infant's hand lightly touches the bar, which is pictured here to the infant's right

positioned to the right of the infant at approximately the iliac crest level in the touch condition. The purpose of this convex surface was to be "touchable" without being "graspable" by the infants. The contact surface was attached atop two support columns, each instrumented with force transducers (Interface MB-10; Scottsdale, AZ) for resolving applied hand vertical forces. For the adults, the contact surface was a 5-cm diameter circular metal plate mounted on a tripod and positioned to the right and forward of each participant at the iliac crest level. The touch apparatus for the adults was identical to those used in previous experiments (Jeka et al. 1998b). Previous studies have consistently reported that infants (Barela et al. 1999; Metcalfe et al. 2005a, b) and adults (Jeka et al. 1998a, b) applied small vertical forces, around 3.8 and <1 N, respectively, during quiet stance with the right hand touching the touch apparatus.

Postural sway recording

Center of pressure excursions in medial–lateral (CP_{ML}) and anterior–posterior (CP_{AP}) directions were calculated from ground reaction forces measured by a force platform (Kistler 9261A). Three-dimensional upper trunk and approximate center of mass displacements were sampled using a Logitech 6-dimensional position tracking system (VR Depot; Boony Doon, CA). The present analysis focused on the results of CP sway trajectories.

Procedures

After entering the laboratory, the infant was given a brief period of acclimation to the laboratory (e.g., playing with toys, interacting with the experimenters). The testing area was constructed as an approximately $2.1 \times 5.1\ \mathrm{m}^2$ room formed by black curtains that reduced distractions from the surrounding laboratory environment. Following the acclimation period, the infant was introduced to a small pedestal (10 cm deep × 20 cm long × 11 cm tall) affixed to the force platform. The purpose of the pedestal was to discourage the infant from moving their feet during testing. The infant's shoes were removed and, once placed on the pedestal, the position of the touch apparatus was adjusted to the appropriate height and the Logitech trackers were affixed.

During the testing session, the infant completed five conditions including: independent stance (no-touch), touching a static surface (touch), and three conditions of touching an oscillating surface (frequencies = 0.1, 0.3, 0.5 Hz; amplitudes = 1.6, 0.59, and 0.36 cm, respectively). Three trials were collected in each condition and all trials lasted 60 s except for the 0.1 Hz trials, which were 90 s. The 15 trials were presented in a randomized order except that an independent stance trial never occurred within the first five trials. This decision was based on our previous experience with this paradigm, which has shown that infants tend not to participate in touch conditions when independent stance trials are presented first.

For this study, our purpose was to examine the development of unperturbed, quiet upright stance and the effect of static touch on sway. Therefore, our analyses focused only on the conditions in which the infants: (1) stood independently; or, (2) touched the static surface. The data from the three dynamic touch conditions are presented elsewhere (Metcalfe et al. 2005b).

To facilitate participation, an experimenter sat in front of the infant and attempted to maintain his/her attention with toys or books. The parent or guardian was always present and helped position the infant for each trial as well as prevent any possible falls. One to three short breaks were taken between trials when needed and the total testing session lasted for 25–50 min depending on the infant's cooperation. All infant testing sessions were displayed on a remote monitor and video taped with a standard sVHS recorder (Panasonic AG-7350) for online observation of trials during acquisition as well as later behavioral coding. The videotape records were synchronized with the analog data using an event synchronization unit (PEAK Performance Technologies; Englewood, CO) and time-stamped with a SMPTE code generator (Horita RM-50 II; Mission Veijo, CA). Following completion of all experimental conditions, the infant's height and weight were measured.

Experimental equipment and procedures for adults were the same as for the infants with some exceptions. Adult participants stood on a block (19 cm deep × 40.5 cm long × 29.5 cm tall) that was analogous to that used for the infants, but scaled to the adult's larger body size. During the testing session, the participant completed four conditions including: independent stance, touching a stationary surface, touching an oscillating surface similar to the infants (frequency = 0.3 Hz; amplitude = 0.59 cm), and touching an oscillating surface in which the amplitude of oscillation halved at 30 s (0.3 cm) and then stopped at 60 s during the trial. Two trials were collected in each condition and all trials lasted for 30 s except for the decreasing-amplitude trials, which were 90 s. The eight trials were presented in randomized order. For this analysis we focused only on the two conditions in which the adult participant stood either independently or with the hand touching a static surface. Details of adult testing procedures are presented elsewhere (Metcalfe et al. 2005b).

Data reduction and analysis

Behavioral coding

Following infant data acquisition, videotapes were reviewed independently by two trained coders for valid segments of quiet posture. Criteria for valid segments included: (1) standing independently from the experimenter or parent; (2) no vigorous head, arm, or trunk movement; (3) no falling, bouncing movement, or foot displacement; (4) appropriate touch for the experimental condition, that is continuously touching but not grabbing the touch bar in the static touch condition and hands completely free in the no-touch condition; and, (5) at least a 10-s segment that met the previous criteria. Only those segments identified as acceptable by two coders were used for subsequent data analyses. Adult data were not video coded, as these participants were able to complete the task in the specified duration without actions that invalidated trial segments.

After behavioral coding for infants, the length of each standing segment varied, ranging from 10 (shortest accepted duration) to 60 (whole trial) s. Two measures of stance duration were computed: mean segment time (MST) and total stance time (TST). MST was calculated as the averaged duration across all segments while TST was the sum of all segment durations of each infant within one testing session.

Postural sway measures

All data and signal processing were performed using customized programs written in MATLAB (Version 6.12, Mathworks Inc., Natick, MA). Raw signals of CP_{ML} and CP_{AP} time series with the mean removed were low-pass filtered using a recursive second-order Butterworth filter ($f_{cut\text{-}off} = 5$ Hz). Resultant CP (CP_R) data were calculated from CP_{ML} and CP_{AP} to characterize infants' postural sway. To fully describe infants' standing posture, we included three groups of measures derived from CP_R displacements: distance-related, velocity, and frequency measures.

Distance-related measures included sway amplitude, area, and position variability. Sway amplitude was computed as a mean of the absolute values of CP_R displacement. It is a directionless measurement of how far the body moves away from the mean position. Sway area is a statistically based estimate of a confidence ellipse that encloses approximately 90% of the points on the CP trajectories (Prieto et al. 1996). Position variability was calculated as the standard deviation of CP_R displacements and represents the average deviation from the center-upright position. For each infant postural data segment, sway velocity is derived from CP_R displacements. Two measures, mean velocity and velocity variability, were computed as the average and standard deviation of sway velocity. For frequency measure, power spectrum density of CP_R time series was computed using multi-taper method with eight tapers to characterize the frequency distribution of infants' standing posture. Total power was calculated as the integrated area of the power spectrum from 0 to 5 Hz. To describe the distribution of postural sway across frequencies, spectral bandwidth was determined as the frequency range that starts from 0 Hz and accumulated 50% power of the frequency spectrum. This measure represents the breadth of the frequency distribution accounting for fluctuations in infants' postural sway. Presented in Fig. 2 are examples of CP excursion during one trial segment and its corresponding frequency spectrum from an infant at 1 and 8 months post-walking and a young adult.

Statistical analysis

To longitudinally characterize infants' upright posture, infants' postural data across the 9 months post-walking were analyzed to examine how it changes with increasing upright postural experience and touch. Walk Age (days elapsed after walk onset) was used to normalize all data to each individual infant's developmental level. For each dependent measure, hypothesis testing was conducted on averages, weighted by the segment length, within each infant and Walk Age. Mixed-model regression analysis was used to determine the influence of Touch and Walk Age on each dependent measure. This method was selected because it differentially accounts for fixed (e.g. experimental manipulations) and random (e.g. within-subject) sources of variation as well as provides tools to assess variance heterogeneity and to control for correlated measures. It also allows for random patterns of missing cells and thus, is well suited for analysis of longitudinal data where missing data typically occur. In the statistical model, random-effects were specified as Infant as well as Infant × Walk Age and Infant × Touch interactions, to control for within-subject effects. During the regression procedures, a method similar to backwards selection was used to determine which fixed-effects parameters (Walk Age, Touch and their interaction) were most strongly related to the dependent variables. For the comparison between infants and young adults, mixed model two-way ANOVA (2 Group × 2 Touch conditions) with Touch as the within-subject effect was used to determine whether infants after 9 months of walking were different from the adult group.

The purpose of this study was to examine the development of infants' upright posture and its relation to increasing walking experience. However, as infants' experience increases, so too does age. Infants' chronological age might be a confounding factor for the observed developmental changes. To verify the effect of walking experience in infant postural development, an age-constant sample was drawn from the longitudinal data to eliminate the confounding effect of age. This age-constant sample included data from all nine infants at similar chronological age (mean ± SD 15.5 ± 0.3 months) but with their Walk Age varying from 0 to 16.3 months (mean ± SD

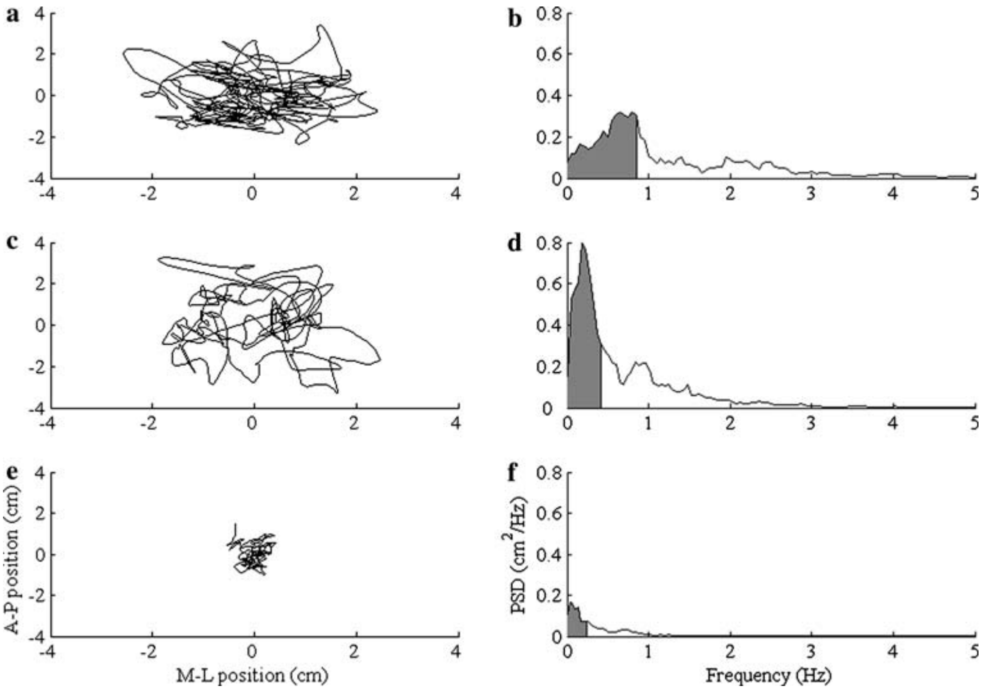

Fig. 2 Exemplar of CP trajectories and power spectrum for **a**, **d** an infant at 1 month post-walking; **b**, **e** the same infant at 8 months post-walking; and **c**, **f** an adult. The *grey area* represents the spectral bandwidth in which 50% power of the frequency spectrum was accumulated

3.5 ± 1.8 months) (Table 1). Mixed-model regression analysis was used to determine the influence of Walk Age and Touch on each postural measure. All statistical analyses were performed with the statistical analysis software (SAS) program (Release 8.01, SAS Institute Inc., Cary NC, USA). A P value equal to or less than 0.05 was defined as statistically significant.

Results

After behavioral coding, the mean segment time (MST) across walk ages and touch conditions was 28.2 ± 17.5 s. No significant effect was found in Walk Age, Touch, or their interaction (all $P > 0.1$). The total stance time (TST) was significantly influenced by Walk Age ($P < 0.01$) as well as the interaction effect of Walk Age × Touch ($P < 0.05$). Further examination revealed that TST significantly lengthened with increasing Walk Age, from 50.6 to 112.5 s with a rate of 0.18 s/day, only in the no-touch condition (Bonferroni adjusted $P < 0.01$) but not in the touch condition (adjusted $P > 0.1$).

The mean and standard deviations of all postural measures within each Walk Age level (months elapsed after walk onset) are presented in Table 2.

Table 1 Sub-sample of the age-constant analysis

Infant	1	2	3	4	5	6	7[a]	8	9[a]
Chronological age (months)	15.4	16.0	15.9	15.5	15.0	15.5	15.6	14.9	15.5
Walk age (months)	4.0	5.2	5.0	6.3	2.0	4.1	1.2	2.8	0

[a] Data were obtained only in the touch but not no-touch condition for infants 7 and 9

Distance-related postural sway measures

In the first 9 months of independent walking, infants showed no developmental changes with increasing Walk Age in the distance-related measures of their standing postural sway (all $P > 0.1$, Fig. 3). However, when the infant touched a stationary surface, the amount of sway decreased 8.30% in position variability, 15.46% in amplitude, and 31.67% in area compared to the no-touch condition. The observed attenuation was realized as a significant effect of Touch on the dependent measures of sway variability ($F(1, 69.4) = 6.04$, $P < 0.05$), amplitude ($F(1, 69.6) = 23.66$, $P < 0.0001$), and area ($F(1, 69.7) = 25.39$, $P < 0.0001$). No significant Walk Age × Touch interaction was found.

Compared to young adults, infants at 9-month post-walking showed significantly higher sway variability, amplitude, and larger area (all $P < 0.001$). Touch significantly attenuated the distance-related measures of postural sway in both 9-month post-walking infants and young adults (all $P < 0.005$).

Table 2 CP_R based postural sway measures of unperturbed upright stance in infants across the first 9 months of independent walking and young adults

Walk age (months)	Sway variability (cm)		Sway amplitude (cm)		Sway area (cm^2)		Mean velocity (cm/s)		Velocity variability (cm/s)		Spectral bandwidth (Hz)	
	NT	T	NT	T	NT	T	NT	T	NT	T	NT	T
0	0.62 ± 0.18	0.63 ± 0.22	1.08 ± 0.30	1.07 ± 0.45	11.59 ± 5.99	10.22 ± 8.64	7.01 ± 2.70	6.16 ± 2.93	4.59 ± 1.39	4.15 ± 1.73	0.71 ± 0.11	0.61 ± 0.17
1	0.69 ± 0.19	0.53 ± 0.13	1.22 ± 0.34	0.85 ± 0.17	14.79 ± 8.07	6.80 ± 2.98	7.87 ± 3.21	5.79 ± 1.55	4.98 ± 1.80	4.10 ± 0.82	0.70 ± 0.23	0.67 ± 0.19
2	0.68 ± 0.19	0.69 ± 0.27	1.25 ± 0.34	1.12 ± 0.43	14.96 ± 6.23	12.01 ± 10.14	7.29 ± 1.78	6.52 ± 1.40	4.58 ± 1.12	4.34 ± 1.03	0.64 ± 0.97	0.52 ± 0.15
3	0.67 ± 0.08	0.68 ± 0.22	1.18 ± 0.16	1.06 ± 0.27	12.66 ± 4.00	9.56 ± 4.11	6.96 ± 1.01	6.32 ± 0.54	4.38 ± 0.70	4.08 ± 0.22	0.58 ± 0.03	0.52 ± 0.22
4	0.82 ± 0.40	0.77 ± 0.33	1.43 ± 0.70	1.29 ± 0.60	22.98 ± 21.52	17.09 ± 13.17	7.45 ± 2.99	6.47 ± 2.48	5.00 ± 1.90	4.34 ± 1.38	0.53 ± 0.12	0.51 ± 0.17
5	0.63 ± 0.16	0.58 ± 0.19	1.11 ± 0.28	0.94 ± 0.32	11.99 ± 5.43	8.54 ± 5.52	5.66 ± 2.17	4.74 ± 2.50	3.84 ± 0.88	3.20 ± 1.13	0.50 ± 0.11	0.40 ± 0.10
6	0.68 ± 0.12	0.60 ± 0.15	1.27 ± 0.25	1.03 ± 0.27	15.25 ± 5.37	9.65 ± 4.34	5.68 ± 1.77	4.37 ± 1.84	3.92 ± 0.77	3.06 ± 0.84	0.55 ± 0.09	0.38 ± 0.09
7	0.66 ± 0.22	0.64 ± 0.26	1.17 ± 0.41	1.05 ± 0.43	13.89 ± 8.15	9.98 ± 7.33	5.39 ± 1.39	4.84 ± 1.63	3.83 ± 0.86	3.58 ± 1.10	0.47 ± 0.13	0.42 ± 0.13
8	0.66 ± 0.18	0.58 ± 0.30	1.19 ± 0.34	0.99 ± 0.47	14.02 ± 6.62	9.13 ± 8.79	4.97 ± 1.43	3.95 ± 1.65	3.63 ± 0.98	2.98 ± 1.34	0.46 ± 0.05	0.43 ± 0.13
9	0.81 ± 0.18	0.68 ± 0.15	1.49 ± 0.29	1.16 ± 0.28	20.32 ± 7.62	12.35 ± 5.27	5.50 ± 1.37	4.63 ± 1.70	3.86 ± 0.67	3.92 ± 1.32	0.45 ± 0.10	0.44 ± 0.12
Adults	0.42 ± 0.11	0.23 ± 0.11	0.71 ± 0.21	0.41 ± 0.17	4.08 ± 2.69	1.33 ± 1.16	1.48 ± 0.43	1.06 ± 0.40	1.07 ± 0.31	0.76 ± 0.30	0.31 ± 0.07	0.34 ± 0.12

Walk age was presented as months elapsed after walk onset. The values shown are the mean ± standard deviation among infants for each walk age level

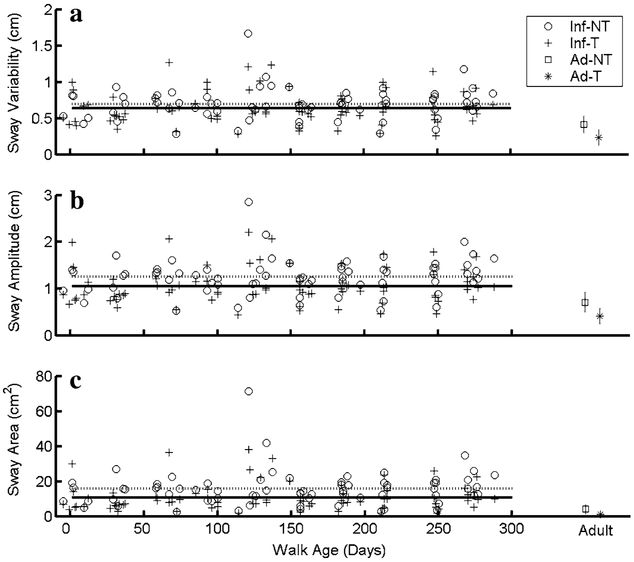

Fig. 3 Variability (**a**), amplitude (**b**), and area of 90% ellipse (**c**) of CP_R sway in infants across Walk Age and adults in touch (*T*) and no-touch (*NT*) conditions. Regression estimates of infant postural data were indicated by *solid line* for T and *dotted line* for NT condition

Postural sway velocity

The velocity of infants' postural sway was significantly influenced by Walk Age and Touch (Fig. 4). With increasing Walk Age, infants showed a linear decrease of their postural sway speed (0.009 cm/s per day, $F(1, 69.6) = 14.46$, $P < 0.001$) and its variability (0.004 cm/s per day, $F(1, 73.8) = 7.16$, $P < 0.01$). When touching a stationary surface, infants' postural sway was slower ($F(1, 30.6) = 49.27$, $P < 0.0001$) and less variable ($F(1, 16.1) = 14.30$, $P < 0.005$) compared to the no-touch condition. No Walk Age × Touch effect was revealed in the velocity measures.

Compared to young adults, infants at 9-month post-walking were faster ($F(1, 11) = 35.01$, $P < 0.001$) and more variable ($F(1, 11) = 63.66$, $P < 0.0001$) in their postural sway velocity. However, neither Touch nor Group × Touch interaction showed significant influences on the postural sway velocity of young adults and infants at 9-month post-walking (both $P > 0.05$).

Postural sway frequency

The frequency distribution of infant postural sway significantly changed with increasing Walk Age and Touch (Fig. 5). Spectral bandwidth, which is mathematically equivalent to the median frequency, showed a significant decrease with increasing Walk Age ($F(1, 66.1) = 45.42$, $P < 0.0001$) and Touch ($F(1, 67.7) = 12.33$, $P < 0.001$). No significant Walk Age × Touch interaction was found. During the period of investigation, infants' mean body

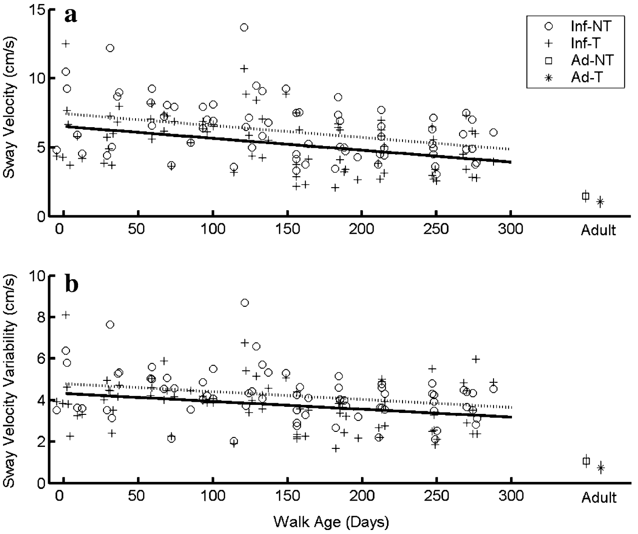

Fig. 4 Mean (**a**) and variability (**b**) of CP_R sway velocity in infants across Walk Age and adults in touch (*T*) and no-touch (*NT*) conditions. Regression estimates of infant postural data were indicated by *solid line* for T and *dotted line* for NT condition

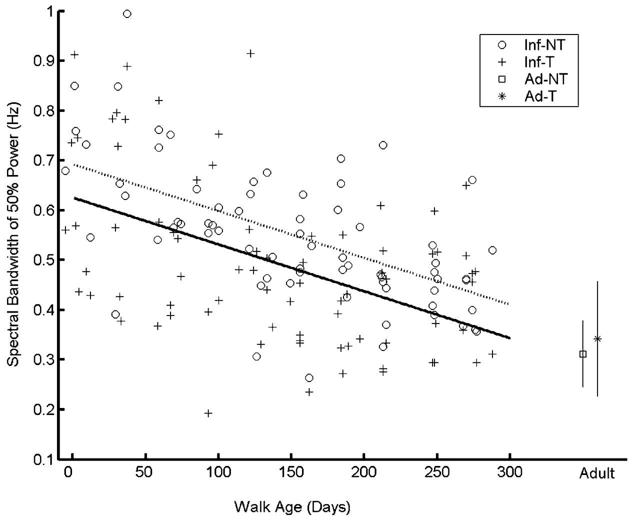

Fig. 5 Spectral bandwidth within which 50% power of CP_R frequency spectrum accumulates in infants across Walk Age and adults in touch (*T*) and no-touch (*NT*) conditions. Regression estimates of infant postural data were indicated by *solid line* for T and *dotted line* for NT condition

height increased from 75.59 cm at walk onset to 85.18 cm at 9 months post-walking. To consider that the decrease in spectral bandwidth in developing infants may be due to an increase in body height, linear mixed-model regression model was reapplied including body height as a covariate. The results revealed that, after considering body height, Walk Age remained a significant factor in the decrease of spectral bandwidth in the first 9 months of independent walking ($F(1, 25.3) = 32.27$, $P < 0.0001$). From walk onset to 9-month post-walking, the spectral bandwidth of infants' postural sway decreased from 0.6–0.7 to 0.4–0.5 Hz. After walking for 9 months, infants continued to show higher spectral bandwidth for postural sway than young adults ($F(1, 11) = 6.04$, $P < 0.05$). However, no significant Touch or Group × Touch interaction effect on the spectral bandwidth was found for infants at 9-month post-walking and young adults.

While the spectral bandwidth decreased with increasing Walk Age, the position variance of infants' postural sway remained the same. To directly test whether the decreased spectral bandwidth was due to increasing postural sway in the relatively low frequency range, spectral power accumulated within 0–0.5 Hz was calculated. Mixed model regression analysis revealed that, with increasing Walk Age, infants increased postural sway in the low frequency range ($F(1, 119) = 5.34$, $P < 0.05$). The power accumulated within 0–0.5 Hz was not significantly influenced by Touch or Walk Age × Touch interaction (both $P > 0.05$).

Age-constant sample

Using an age-constant design, the results from the sample of 15- to 16-month-old infants confirmed our findings in the longitudinal study. With more walking experience, infants showed lower spectral bandwidth of their standing postural sway ($F(1, 4.98) = 22.8$, $P < 0.05$). This Walk Age effect remained significant ($F(1, 2.95) = 18.47$, $P < 0.05$) even after considering infants' body height as a covariate for the observed frequency changes. Consistent with the longitudinal results, distance-related postural measures did not change with increasing walking experience (all $P > 0.1$) but infants' sway amplitude was reduced by hand touch ($F(1, 5.985) = 7.22$, $P < 0.05$). Touch also seemed to lower the spectral bandwidth ($F(1, 5.12) = 6.22$, $P = 0.054$) and the velocity of infants' standing postural sway ($F(1, 6.1) = 5.39$, $P = 0.059$).

Discussion

In the present study, we sought to provide fundamental information regarding postural development of infants' upright stance. Using both longitudinal and age-constant study designs, our results suggest that early development of upright postural control involves changes in the rate-related characteristics rather than a progressive attenuation of postural sway. More specifically, along with increasing walking experience, infants' upright postural sway develops toward a lower frequency, a slower and less variable velocity. What changes in the development of standing posture is more a question of "how" rather than "how much" the infant sways. Additional light touch contact from the hand helped stabilize infants' upright posture by attenuating the sway magnitude and also changed the dynamics (i.e., velocity and frequency) of the sway.

Development of unperturbed upright stance

Surprisingly, infants did not consistently sway less in upright stance as they mastered bipedal walking. Our findings of no significant sway magnitude attenuation as infants gain more experience in upright standing and walking is contrary to previous studies that showed age- or experience-related decrease in sway variability in older children (i.e., 2–14 years old) (Riach and Hayes 1987) and infants during the transition to independent walking (Barela et al. 1999). The discrepancy between the present research and previous studies may be due to the longer stance duration required in the present study. Barela et al. used 10-s segments, while we used segments that were up to 60 s long (mean = 28.2 s). Longer stance duration allows better characterization of infants' postural behavior. Indeed, we suggest that the lack of consistent attenuation of postural sway in early development may be unique in infancy. Two mechanisms have been hypothesized to explain the existence of postural sway: one is exploratory and the other is performatory (Reed 1982; Riley et al. 1997). Exploratory postural sway creates sensory information for the system to explore sensorimotor relationships for postural control system; whereas performatory postural sway uses sensory information to control posture. For infants who have presumably not yet formed a reliable and stable sensorimotor relationship for postural control, it is important to explore the postural state space so as to experience varied sensorimotor interactions. Postural sway of a newly walking infant may be functional in gathering sensory information that would enhance the calibration of the sensorimotor relationship for postural control and help postural estimation for producing appropriate responses. The interaction of enhanced stability and increased exploration may result in no observable change in the overall magnitude of sway. Therefore, the lack of a decrease in sway magnitude could be an important feature for the developmental process ongoing within newly walking infants. As infants showed more postural sway than young adults in the present study and age-related changes were reported in children in previous studies (Riach and Hayes 1987), we suggest that the developmental change of postural sway attenuation may be observed in a larger time scale (i.e. year).

Similar to previous studies in adults (Zatsiorsky and Duarte 1999), children (Riach and Hayes 1987), and toddlers (Ashmead and McCarty 1991), infants' standing postural sway in their first 9 months of independent walking exhibited low-frequency oscillations. During the first 9 months following the onset of independent walking, infants progressively increased the dominance of their postural sway in the lower end of the frequency spectrum. The decrease in sway frequency in developing infants might result from two sources: mechanical and control mechanisms. Rapid anthropometrical changes in infants' second year may serve as a mechanical basis for the observed frequency changes. Using a theoretical inverted pendulum model, McCollum and Leen (1989) predicted that postural development could be characterized as a decrease in sway frequency based on the constraints of infants' body anthropometrics. In their equations, lower sway frequency was expected from the increasing body height of the growing infant. Our results revealed, however, after increased body height was accounted for statistically, Walk Age remained significant for frequency changes in infants' standing posture. Therefore, while the observed changes in sway frequency in early postural development may partially be explained by the growth-induced mechanical factors, our evidence indicates that there is more to the story, namely, changes in the control system underlying more mature upright stance. We argue that the development of infants' upright posture may involve changes in sensorimotor control mechanisms as well as anthropomorphic changes associated with growth processes that lead to different postural behaviors.

The increase in infants' postural sway at the lower end of the frequency spectrum suggests that infants' postural system may develop so as to rely more on the estimation process and less on the fast corrective corrections. Walking provides dynamic sensorimotor experiences and enables the infant to refine the sensorimotor relationship that allows utilizing the sensory information to estimate the body position and motion in the environment. Thus, infants are better able to predict the outcomes of their own actions and to prevent excessive corrective actions. This developmental change from reactive to prospective postural control has also been suggested in a previous study in which infants changed the use of touch forces through the hand touching a contact surface to assist control of standing posture during the transition to independent walking (Barela et al. 1999). Prospective control with postural estimations allows infants to plan for appropriate compensatory corrections and, therefore, avoid losing balance while performing various motor tasks, such as walking. The increased dominance of incorporating sensory information in forming postural estimates during early postural development is also supported by the decrease in the sway velocity with increasing walking age. During the first year of independent standing and walking, infants' postural sway develops from ballistic toward more sensory-guided actions. Slower sway allows the infant to better use sensory feedback in estimating and adjusting their postural actions and thus to prevent excessive movements. Through upright posture experience in standing and walking, infants may learn to refine the sensorimotor relationship and thus to better incorporate sensory information in the postural control system. This developmental process of sensorimotor integration may last into childhood as the decrease in postural sway velocity has also been shown in children between 4 and 13 years of age (Kirshenbaum et al. 2001; Riach and Starkes 1994). Taken together, our results in the rate-related characteristics (i.e., frequency and velocity) of infants' postural sway in quiet stance support the idea that early postural development involves a refinement of sensorimotor dynamics that enhances utilizing sensory information in estimating self-motion in the environment.

In this current study, developmental changes in infants' upright posture were not found in mean amplitude or position variance but, rather, found in the mean sway velocity and its variability. Velocity compared to position as a postural sway measure, has been shown to reflect more robust results for adults' postural behaviors in various sensory conditions (Kiemel et al. 2006). Our results, therefore, would suggest that sway velocity may also be a more sensitive measure for detecting developmental changes in infants' postural behavior in quiet stance. In addition, velocity information from sensory inputs has been shown to be more critical than position or acceleration information for the control of quiet stance in adults (Jeka et al. 2004; Kiemel et al. 2002, 2006). Postural sway creates sensory feedback, and thus, changes in postural sway velocity alter the critical information from the sensory feedback. Therefore, the changes we see in sway velocity during development may tune the motor system so as to enhance the integration between perception and action. We suggest our results point to this possibility as an important mechanism underlying the development of sensorimotor integration.

Influence of static touch contact

Although the amount of infants' postural sway did not consistently change with increasing upright postural experience, it was attenuated when infants lightly touched a stationary contact surface. This finding is consistent with previous research in adults (Jeka and Lackner 1994), children (Riach and Hayes 1987), and infants (Metcalfe et al. 2005a; Metcalfe and Clark 2000). Sway variability has been related to the effectiveness of the postural control system (Prieto et al. 1996) and it has been consistently suggested that additional sensory information (vision or touch) helps stabilize posture (Jeka and Lackner 1994; Kiemel et al. 2002; Metcalfe et al. 2005a; Metcalfe and Clark 2000; Riach and Hayes 1987). In infants, the touch effect in stabilizing upright posture remains robust even though touch may also allow infants to explore a variety of upright postures (Metcalfe and Clark 2000).

In addition to attenuating the amount of sway, touch contact also led to decrease in the sway velocity and its variability. It has been shown that degrading somatosensory inputs resulted in increase in the magnitude as well as velocity of adults' postural sway (Jeka et al. 2004). Touching a contact surface provides information about body position and velocity from configurations of the hand to the body. This somatosensory information can further be used in estimating the current postural state and in guiding future postural responses (Jeka and Lackner 1994; Kiemel et al. 2002). Our frequency measures further showed that, as the infant touched a stationary contact surface, the sway frequency decreased without significant changes in the amount of sway in the lower end of spectrum (0–0.5 Hz). These results suggest that light touch contact helps the formation of the postural state and therefore attenuates the amount of corrective actions. Additional touch contact from the hand stabilizes infants' standing posture not only by attenuating the magnitude of their sway but also by changing the dynamics of the sway; that is, the frequency and velocity characteristics of the postural behaviors.

Conclusion

Our present study showed that early development of upright postural control after learning to walk is not featured as a progressive reduction of postural sway. Instead, early postural development may involve fine tuning the dynamics of the sensorimotor system for postural control through enhancing the use of sensory information to form postural estimates and to generate appropriate responses. Walking provides dynamic and rich sensorimotor experience in the upright position and therefore may enhance the development of infants' postural control. Lightly touching a stationary contact surface stabilizes infants' standing posture by attenuating the magnitude of their sway as well as changing the dynamics of the sway.

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