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Toddlers' Postural Adaptations to Different Support Surfaces

Thomas A. Stoffregen, Karen Adolph, Esther Thelen,
Kathleen M. Gorday, and Yang-Yi Sheng

This study was undertaken to determine whether young children, after only a few weeks standing experience, could respond adaptively to the dynamical constraints imposed by different support surfaces. The spontaneous postural motions of young children (13–14 months old) were observed as they stood on surfaces that differed in length, friction, and rigidity. There were no externally imposed perturbations to stance. Children's postural control was remarkably adaptive: There were few falls on any of the surfaces. Moreover, the children showed surface-specific utilization of manual postural control (holding onto wooden poles), suggesting that manual control is an adaptive strategy for postural control. Finally, kinematic analysis suggested that, in some instances, children were able to employ independent control of the hips, contrary to previous models which had suggested that hip motions could not be controlled before the age of 3 years. Small, slow hip movements useful in controlling spontaneous sway (unperturbed stance) may serve as a basis for the development of larger, faster hip movements that are associated with imposed perturbations.

Stance is deceptively simple. It may appear to a casual observer that people waiting in line at a checkout counter or guards standing stiffly at attention are doing very little to maintain balance. However, experimental manipulations and careful measurements of postural movements reveal that stance depends on continuous active control, requiring coordination and effort. In ordinary upright stance, the body makes small swaying motions forward and backward. Under experimental conditions, anterior–posterior perturbations either of the ground surface or of the visible surroundings cause adults and children to generate compensatory postural sway (e.g., Forssberg & Nashner, 1982; Horak & Nashner, 1986; Lee & Aronson, 1974; Lee & Lishman, 1975; Nashner & McCollum, 1985; Stoffregen, 1985, 1986; Stoffregen, Schmuckler, & Gibson, 1987; Warren, Kay, & Yilmaz, 1996). These body motions are compensatory because their effect is to maintain

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Thomas A. Stoffregen, Kathleen M. Gorday, and Yang-Yi Sheng are with the Department of Psychology, University of Cincinnati, PO Box 210376, Cincinnati, OH 45221-0376. Karen Adolph is with the Department of Psychology, Carnegie Mellon University, Pittsburgh, PA 15213. Esther Thelen is with the Department of Psychology, Indiana University, Bloomington, IN 47405.

the body's center of mass over the feet. If the center of mass moves too far forward or backward, the person will fall.

Compensatory postural sway results from body movements that apply force to the surface of support (Stoffregen & Riccio, 1988). The analysis of postural control has concentrated on movements around the hip and ankle joints (Nashner & McCollum, 1985). Muscle action around the ankle joints applies torque to the supporting surface as the toes or heels press against it. Movements around the hip joint primarily generate shearing forces at the ground surface as the feet push forward or backward against it.

In the presence of imposed perturbations, adults successfully use both ankle and hip strategies, depending on the amplitude and acceleration of the perturbations (Horak & Nashner, 1986). In contrast, when infants and toddlers were tested on moving platforms, they showed primarily ankle movements (e.g., Forssberg & Nashner, 1982; Woollacott & Sviestrup, 1992). These findings led some researchers to conclude that young children cannot control bending action at the hips: "Adaptive mechanisms are underdeveloped in young children" (Forssberg & Nashner, 1982, p. 551). Forssberg and Nashner (1982) suggested that infants are born with a single, automatic motor program for postural control that produces sway around the ankle joints. They argued that during development, children use this single ankle-sway program as a basis for assembling additional programs (e.g., hip sway). Similarly, McCollum and Leen (1989, p. 237) argued that "infants would be expected to try the hip movement, but not to be successful in applying it to control balance . . . until they are 3–4 years old." Woollacott and Sviestrup (1992) also concluded that young infants must rely on ankle control.

Most research on postural control relies on a perturbation paradigm, in which participants are exposed to unpredictable, externally imposed threats to balance (Wade, Lindquist, Taylor, & Treat-Jacobson, 1995). These can be linear or angular motions of the support surface, of the visible surround, or both (e.g., Haas, Diener, Bacher, & Dichgans, 1986; Lee & Aronson, 1974; Nashner, 1976; Stoffregen et al., 1987). In adults, normal postural sway has a magnitude of 2 to 4 cm and a maximum velocity of 1 cm/s (Bensel & Dzendolet, 1968). The magnitude, velocity, and acceleration of experimentally imposed perturbations tend to be much greater than those found in normal, unperturbed stance. Imposed perturbations commonly have velocities of 10–40 cm/s (e.g., Lee & Aronson, 1974; Woollacott & Sviestrup, 1992) and excursions of up to 94 cm (Lee & Aronson, 1974). Sudden, unpredictable, imposed perturbations give rise to easily observable postural responses, such as lurching, staggering, and falling down (Lee & Aronson, 1974; Stoffregen et al., 1987). It is, in part, for this reason that researchers use the perturbation paradigm.

Research using the perturbation paradigm has led investigators to construct theories of postural control based on compensatory responses to unpredictable perturbations ("external threats to balance," Woollacott & Sviestrup, 1992, p. 24). However, outside the laboratory most falls, especially during infancy, do not result from external perturbations. Very few studies have addressed the validity of generalizing from the perturbation paradigm to maintaining stance in the absence of external perturbations (Assaiante & Amblard, 1995). The work that does exist suggests that there may be important differences in the control of posture with and without externally imposed perturbations (e.g., Aruin & Latash, 1995; Hayes & Riach, 1989; Williams, McCleneghan, & Ward, 1985).

One important difference is that imposed perturbations are followed by compensatory responses, whereas voluntary movements are preceded by anticipatory adjustments (Aruin & Latash, 1995; Assaiante & Amblard, 1995; Belen'kii, Gurfinkel', & Pal'tsev, 1967; Cordo & Nashner, 1982; Rochat & Bullinger, 1995). Differences between anticipatory actions and compensatory responses have not been addressed in most theories of postural control (e.g., Forssberg & Nashner, 1981; McCollum & Leen, 1989; Nashner & McCollum, 1985). Thus, the conclusion that before age 4 the nervous system cannot produce and control postural compensation at the hips may be premature.

One factor that may be critical for development is the speed with which postural motions must be executed if children are to succeed at maintaining balance. Fast movements needed to compensate for sudden, imposed perturbations are, in effect, emergency responses to an acute threat of falling. Although fast hip movements may be unavailable to novice standers (McCollum & Leen, 1989; Woollacott & Sviestrup, 1992), children may be able to use slower hip movements to compensate for slower, lower magnitude perturbations originating in their own activity (cf. Hayes & Riach, 1989). This would allow adaptive use of the hips much earlier in postural development than researchers have supposed. It might also provide a natural basis for a gradual extension of hip control to faster, emergency responses.

The present research was developed from a functional approach to perception and action (e.g., Adolph, 1995; Bardy, Marin, Baumberger, & Flückiger, 1996; Gibson et al., 1987; McGinnis & Newell, 1982; Riccio & Stoffregen, 1988; Slobounov & Newell, 1994; cf. Reed, 1989). We concentrate on constraints imposed by the physical dynamics of the animal–environment system. With this view, the development of stance is seen as a process in which children learn to cope with the constraints imposed by different environments and situations. Increasing control over the body permits children to explore safely the dynamics of the perceptual–motor workspace (Kugler & Turvey, 1987). Exploratory movements arise from the interaction of the dynamics of children's bodies and the dynamics of the supporting ground surface in the midst of a particular set of task or goal constraints (Riccio & Stoffregen, 1988).

Recent research shows that infants flexibly adapt locomotor responses to cope with balance constraints in a variety of tasks with different support surfaces. For example, young crawling infants avoided the deep side of an apparent drop-off on a visual cliff (e. g., Campos, Hiatt, Ramsay, Henderson, & Svejda; 1978; Rader, Bausano, & Richards, 1980). Walking infants crawled rather than walked over a compliant waterbed (Gibson et al., 1987), and walkers used a variety of sliding positions to go down risky slopes (Adolph, 1995).

From this functional perspective, stance on novel surfaces may reduce postural stability, which would induce children to search for situation-appropriate compensatory coordination modes. Children should be able to employ any coordination mode that they are able to control and that is supported by the environmental dynamics. Controlling some modes of coordination (e.g., sudden, large-amplitude hip movements) might depend on prior mastery of related modes that make smaller demands on precise coordination (e.g., smaller, slow hip movements). As noted above, the dynamics of the support surface strongly constrain the utility of different control actions. Thus, if children can maintain stance on a variety of surfaces at an early age, they should use a wide variety of coordination modes in doing so.

Few experiments have examined the effects of surface properties on postural control in stance, and there has been no systematic comparison of variations in postural control across a variety of different surfaces (Andres & O'Connor, 1990; Lee & Lishman, 1975; Lekhel, Marchand, Assaiante, Cremieux, & Amblard, 1994; McMahon & Greene, 1984; Stoffregen & Flynn, 1994). The present study provides the first developmental assessment of postural responses to a wide variety of support surfaces.

Most theories of postural control concentrate on swaying movements at the ankles and hips (e.g., Nashner & McCollum, 1985). However, in everyday situations, postural control is not limited to the lower limbs. For example, subway riders hold onto overhead straps or handles to stabilize posture against motions of the train, and house painters often hold onto a ladder with one hand while painting with the other. Cordo and Nashner (1982, p. 297) described manual control of posture in adults and concluded that "postural adjustments . . . can be elicited in any muscle that the subject . . . has perceived to be functionally useful in maintaining equilibrium" (cf. Riccio & Stoffregen, 1988).

Some researchers have examined stance in children who stood with manual support (Delorme, Frigon, & Lagace, 1989; Woollacott & Sveistrup, 1992). However, the children were not capable of maintaining stance without using their hands. These studies document the utility of the hands for early postural stabilization, but they leave open a more interesting question: Is early postural use of the hands reflexive or is it adaptive to the demands of specific situations? This question can be answered only by examining children who have a choice about whether to use their hands. In the present experiment, we observed manual control strategies in children who could stand on their feet without manual support, but might choose not to.

The present study had three aims: (a) to determine whether children who have recently learned to stand exhibit adaptive variation in postural control across variations in the dynamics of the support surface, including compensatory hip movements; (b) to determine whether children use manual support adaptively depending on surface properties; and (c) to address these questions in the absence of imposed perturbations to posture. We predicted that toddlers would show adaptive control of posture on a variety of surfaces, including adaptive use of the hands and hips.

Method

Participants

Eleven children participated in the study (due to fussiness one child did not complete all trials). Children were recruited from birth announcements in a local newspaper and were contacted via introductory letters and follow-up telephone calls. All children were within 3 weeks of their 14-month birthday (mean age = 14 months, 5 days) and could walk at least 10 feet independently in the laboratory. Walking experience (derived from parents' reports) ranged from 10 days to 5.5 months, with a mean of approximately 3 months.

Experimental Surfaces. We tested children's responses on four support surfaces: (a) a rigid high-friction surface, 41 × 53 cm (a sheet of plywood covered with a thin sheet of high-friction plastic, with a coefficient of friction of 2.06); (b) a soft mattress (a sheet of cloth-covered foam rubber), 44 × 64 × 5 cm; (c) a rigid low-friction surface (Formica coated with baby oil, with a coefficient of friction of 0.65), 31 × 41 cm; and (d) and a narrow beam, crosswise to the children's feet (a wooden bar, 3 × 60 × 4 cm). Two of these surfaces had reduced resistance to ankle torque (mattress and beam), leading to reduced effectiveness of ankle control. The low-friction surface had reduced resistance to shear force, leading to reduced effectiveness of hip control.

The experimental surfaces were placed on a raised wooden platform (71 × 91 × 76 cm), so that standing children were at parents' eye height. Two vertical support poles (1.5 cm diameter) were attached to the platform 17 cm apart. These were within easy reaching distance so that children could grasp them at any time.

Video Recording. An assistant videotaped each trial. Two cameras, at a 90° angle to one another, were used to generate a split screen recording of the left side and back of the body. To facilitate digital kinematic analysis, balls covered with retro-reflective material were attached to the left hip and shoulder.

Procedure

We used a within-subjects design. Each experimental surface was presented twice to each child, for a total of eight trials (two blocks of four trials, with each surface appearing once in each block). The high-friction surface was presented first in each block of trials, and the other three surfaces were presented in a counterbalanced order. An experimenter lowered the children onto each surface and encouraged them to stand on it facing their parents (Figure 1). The experimenter stood alongside children to ensure their safety. Parents attempted to maintain the children's attention forward, proffering toys and encouragement. Each trial lasted until chil-

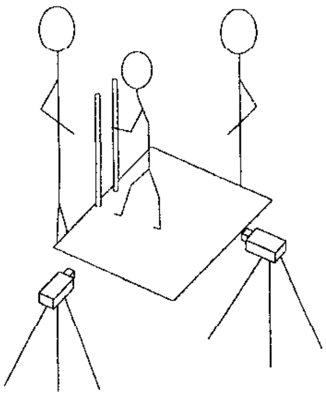

Figure 1 — Experimental setting. The parent stood directly in front of the child. An experimenter stood alongside to ensure the child's safety.

dren stood without help for 60 s or accumulated 120 s standing time with the experimenter's help.

Behavioral Coding. Coders scored children's sensitivity to different constraints on posture from videotapes: amount of accumulated time standing freely, without touching the poles, and without help from adults *(free standing)*; accumulated time standing while holding onto, or leaning against, one or both of the poles *(pole standing)*; and standing while being held or touched by an adult *(standing while held)*. In addition, coders scored the number of *staggers*, *squats*, and *falls*. The final category was *refusals*, instances when children refused to stand on the experimental surface. This included walking or *stepping off* the experimental surface, and refusal to use the legs for support when being lowered onto an experimental surface *(lifting legs)*.

There were two rounds of coding. In the first pass, two coders independently scored all tapes for accumulated time per trial in free standing, pole standing, and standing while held. Overall, there were 5,784 s of trial time (96 min, 18 s). Coders' categories were in exact agreement for 5,302 s, for an overall agreement rate of 90.9%.[1]

In the second pass, a different coder scored each trial for the occurrence of refusals, staggers, squats, and falls. For refusals, the entire video record was examined (many refusals occurred when the child was being held, either on or above the surface). For staggers, squats, and falls, coders examined only intervals that previously had been categorized as free standing or pole standing.

Digitizing of Postural Kinematics. Digital analysis of postural kinematics was performed on selected segments of the videotapes. An experimenter scanned intervals of free standing and pole standing and identified 10-s periods of "quiet stance," periods during which the child was not engaged in overt suprapostural movements, such as reaching, lifting, throwing, bending, or turning. Episodes were included if children were holding an object, as long as it was not manipulated (turned, raised, or lowered) during the episode. All episodes meeting these criteria were included. Sixty episodes were identified (Table 1). Several additional episodes were rejected because of noise in the data, primarily caused by reflectors that had come loose during the trial. Each of the selected episodes was digitized at 30 Hz, using the Peak Performance system. The digitized data were smoothed using a low-pass Butterworth filter with a 4.0 Hz cutoff frequency.

Table 1 Episodes of Quiet Stance Used for Digital Analysis of Postural Kinematics

	High friction	Mattress	Low friction	Beam
Free	18 (8)	9 (5)	11 (5)	0
Poles	2 (2)	4 (3)	2 (2)	14 (6)

Note. The number of children represented in each entry is given in parentheses.

Results

Successful Stance

Overall, children's postural control was remarkably successful. There was a total of only six falls, or one fall every 16 min. Six children never fell. Only one child fell twice, once on the beam during pole standing and once on high friction during free standing. Four other children each fell once on the mattress (all during free standing). The number of staggers and squats is presented in Table 2. The table shows that the majority of staggers occurred on the mattress while children were holding the poles. Squats occurred on all surfaces but were most common during free stance. Due to the sparseness of staggers, squats, and falls, no statistical analysis was performed.

Refusals

All children stepped off a surface at least once. Seven of the children also lifted their legs. Refusals were heavily concentrated on the beam (Table 3).

Hip Movements

In a pure ankle strategy, the hips do not bend. The hips and shoulders should move backward and forward together, resulting in a strong positive correlation between hip and shoulder motion for the x-axis. In a pure hip strategy, the hips and shoulders move in opposite directions (e.g., the shoulders move forward as the hips move back). This should result in a strong negative correlation between hip and shoulder.[2] Independent (uncoordinated) motion of the shoulders and hips should

Table 2 Staggers and Squats on Each Surface

	High friction		Mattress		Low friction		Beam	
	Free	Poles	Free	Poles	Free	Poles	Free	Poles
Staggers	1	0	1	5	1	0	0	2
Squats	3	0	5	0	5	1	0	5

Note. Free = free standing; poles = pole standing.

Table 3 Refusals (Total Instances Across All Subjects)

	High friction	Mattress	Low friction	Beam
Lifting legs	1	7	4	48
Stepping off	7	11	11	75

lead to correlations near zero; this would be classified by Nashner and McCollum (1985) as a mixed ankle–hip strategy.

We examined x-axis (fore–aft) data for evidence of pure hip and mixed ankle–hip control. We calculated time-series correlations between hip and shoulder over the duration of each of the quiet stance episodes. Correlation coefficients ranged from –.27 to +.94. Mean overall correlations are presented in Figure 2. The data in Figure 2 suggest that an ankle strategy was used on all surfaces. However, consideration of individual episodes indicates there was some motion of the hips independent of the shoulders. Figures 3, 4, and 5 present graphs of episodes with high and low correlations. Because quiet stance episodes were not evenly distributed across surfaces and children (Table 1), it was not possible to assess quantitatively the extent to which coordination patterns were surface-specific.

The correlations for 10-s episodes indicate instances of mixed ankle–hip control. Although we did not identify instances in which a pure hip strategy was maintained for the full 10 s, inspection of the time-series graphs suggested that pure hip control existed over shorter intervals. To further evaluate this possibility, we searched the quiet stance episodes for brief periods of pure hip control. Our intent was to identify exemplars that would serve as "existence proofs" for the use of hip control in these children. Short segments were picked by eye from the time-series graphs for hip and shoulder motion. Among these shorter segments were several for which the correlation between hip and shoulder was strongly negative: up to –0.9 over 1–4 s, with hip excursions of up to 5 cm, suggesting a pure hip strategy.

Instances of pure hip control were identified on all four experimental surfaces. Some examples are presented in Figure 6. The figure shows that independent motions of the hips were bidirectional (forward and backward), moving both away from and toward erect stance (see also Figure 5a). Motions of the hips away from erect stance might be uncontrolled; that is, they might be interpreted as uncontrolled buckling of the body in the early stages of a fall. However, motion at the hips that moves the body toward erect stance cannot be interpreted in this way. These examples make it clear that at least some of the children were capable of controlling several different patterns of coordination between the hips and shoulders.

Use of the Poles

Children's use of the poles was surface-specific, with negligible use on the high-friction surface and continuous use on the beam. Figure 7 shows the amount of time children spent using the poles as a function of surface properties. Children's aversion to free standing on the beam was not learned through falling or staggering, since there was a total of only one fall and two staggers on the beam. Repeated 2 (free stance vs. pole stance) × 2 (trials) × 4 (surfaces) measures analysis of variance on proportion of time for the 10 children who completed all trials showed a significant main effect for surface, $F(3, 9) = 6.52, p = .02$. Post hoc comparisons revealed a significant difference between high friction and beam, $t(1, 9) = 2.78, p = .02$, and between low friction and beam, $t(1, 9) = 2.28, p = .05$, but not between high friction and mattress, $t(1, 9) = 1.60, p = .14$, indicating that the main effect was produced by the mean for beam being lower than the other three. This is consistent with the children's general reluctance to stand on the beam.

Of greater interest was the interaction between surface and stance. This interaction was significant, $F(3, 7) = 34.13, p = .001$, confirming that pole standing and free standing were used differentially across surfaces. Post hoc one-sample t tests were performed to evaluate the simple main effect of stance on each of the surfaces, with a Bonferroni adjustment applied (with four tests conducted, the nominal α level became .0125). These revealed a significant preference for free standing on the high-friction surface, $t(9) = 5.56$, and a significant preference for pole standing on the beam, $t(9) = 6.988$, but no differences for the low-friction surface or the mattress. There were no other significant main effects or interactions.

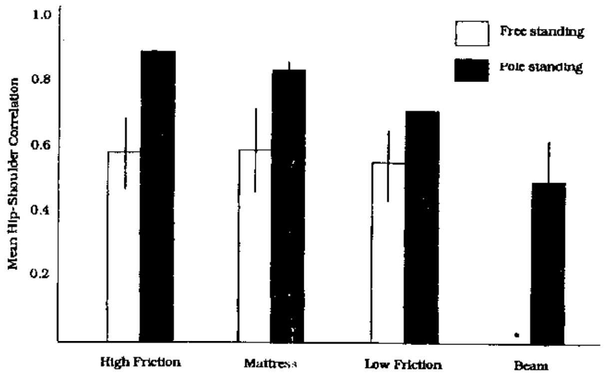

Figure 2 — Mean correlations between hip and shoulder across the duration of episodes of quiet stance. Vertical lines indicate the standard deviation, where $n > 2$ episodes. *There were no quiet stance episodes for free standing on the beam.

Discussion

Children in this study showed remarkably adaptive postural control actions to variations in surface properties. Results showed few outright failures of postural control. There were no falls on the low-friction surface and only one fall on the beam. The paucity of staggers, squats, and falls indicates that adaptive control was not prompted by losing balance on previous trials. Similarly, the singularly high rate of refusals on the beam could not have resulted from aversion based on failures. Moreover, although children may have experienced standing on compliant mattresses in their cribs, the beam and low-friction surfaces were novel. Similarly, toddlers exhibit few falls in standing tasks with imposed perturbations (Forssberg & Nashner, 1982) and choose adaptive alternatives to stance when challenged by novel compliant surfaces (Gibson et al., 1987) or steep slopes (Adolph, 1995).

Moreover, results showed that 14-month-old walking children are not limited to stance on surfaces that favor a simple ankle strategy. This finding questions claims that posture develops from a single, reflexive control strategy (Forssberg & Nashner, 1982; cf. Warren, Young, & Lee, 1986). Children spent the majority of their free standing time engaged in suprapostural activities (interacting with parents and/or playing with toys), further underscoring the ease with which they were able to maintain stance on the experimental surfaces.

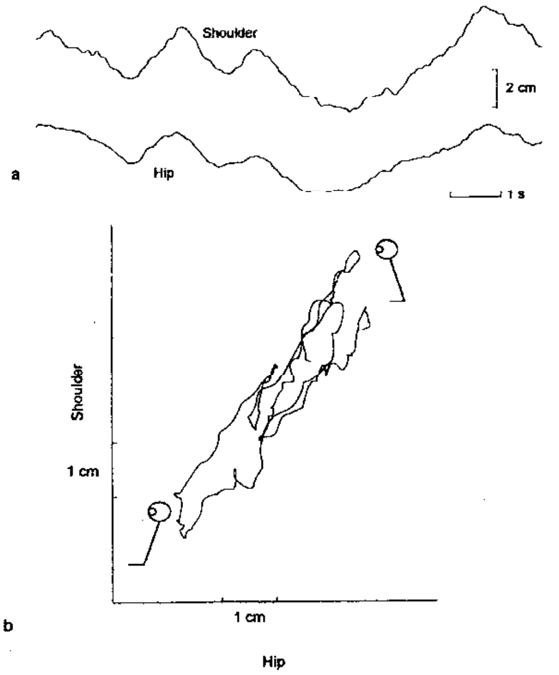

Figure 3 — Shoulder and hip motion for one 10-s period of quiet stance on the high-friction surface. Episodes in Figures 3–5 were selected to show differences in correlation between hip and shoulder motion. (A) Time-series graph of shoulder and hip motion. Upward displacement on the graph corresponds to anterior (forward) motion of the body. Time-series correlation between hip and shoulder, $r^2 = .92$. (B) The same episode, replotted to highlight spatial relations between shoulder and hip motion. In effect, B is a visual depiction of the correlation between hip and shoulder (cf. Nashner & McCollum, 1985, Figure 5). Stick figures indicate positions on the graph that correspond to forward and backward lean about the ankles.

Control of the Hips

The kinematic data suggest strongly that the children were able to control hip movements independently of the shoulders, and that in some instances they could produce negatively correlated motion of the hips and shoulders (Figure 6), in effect, a form of hip strategy. In particular, use of independent hip motions toward

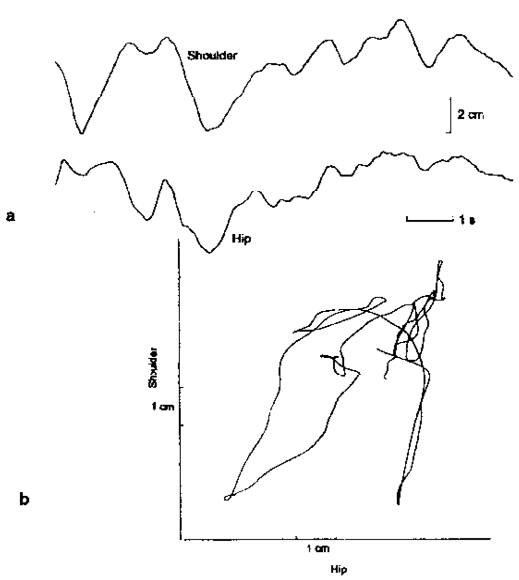

Figure 4 — Shoulder and hip motion, for one 10 s period of quiet stance on the low-friction surface. (A) Time-series graph of shoulder and hip motion. Upward displacement on the graph corresponds to anterior (forward) motion of the body. Time-series correlation between hip and shoulder, $r^2 = .56$. (B) The same episode, replotted to highlight spatial relations between shoulder and hip motion.

erect stance provides evidence that children's hip sways were adaptive compensatory responses. The lack of falls, together with the tendency to maintain an erect stance (Nashner & McCollum, 1985), indicates that the effects of any uncontrolled hip motions were compensated by controlled motions at the same joint. Similarly, Woollacott and Sviestrup (1992) reported patterns of muscle activation that may have arisen from hip movements in standing 14-month-olds. Assaiante, Thomachot, and Aurenty (1993) reported adaptive hip stabilization in the roll axis from the beginning of autonomous walking in children in the same age range. The hips were stabilized independent of the feet, and after 4 weeks, the shoulders were stabilized independent of the hips. This suggests that the hips were, to some degree, under independent control early in the development of walking.

The present results support the hypothesis that hip control begins with small-scale, anticipatory movements, and that larger, emergency responses to imposed

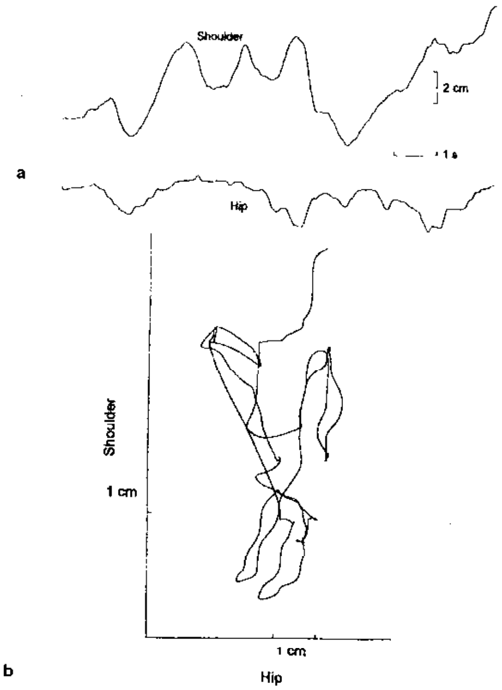

Figure 5 — Shoulder and hip motion, for one 10-s period of quiet stance on the mattress. (A) Time-series graph of shoulder and hip motion. Upward displacement on the graph corresponds to anterior (forward) motion of the body. Time-series correlation between hip and shoulder, $r^2 = -.74$. (B) The same episode, replotted to highlight spatial relations between shoulder and hip motion.

perturbations evolve from these. Our analysis of hip movements was limited to periods of quiet stance. Out of more than 90 min of behavior on the surfaces, we identified only about 10 min of quiet stance. Most of the time the children were engaged in obvious and sometimes vigorous suprapostural activities (cf. Stoffregen & Smart, 1996). There would have been a strong motivation for controlled use of the hips for many of these activities (Assaiante et al., 1993). Recent research by Rochat (1992) has made it clear that postural control is integrated with suprapostural action before the achievement of upright stance.[3]

Our data also support the hypothesis that children are capable of controlling a wide variety of coordination modes in the maintenance of stance. Novice standers may consistently employ different coordination modes as a means of learning their differential value in different situations. The knowledge thus gleaned might then be used to select preferred modes for specific situations. This may be related to a finding by Stoffregen et al. (1987), who exposed children to central and global optical flow in a moving room. The responses of older children (2–5 years old) resembled those of adults: Responses to room movements were observed only in the global flow condition. By contrast, children younger than 2 years did not differentiate between global and central flow but responded to both.

Surface-Specific Manual Control of Posture

All of the children in this experiment could stand and walk unsupported on the high-friction surface, and on this surface they preferred to avoid manual control, as have children of the same age in other studies (e.g., Forssberg & Nashner, 1982; Haas et al., 1986; Woollacott & Sviestrup, 1992). But manual control was still available to them and emerged spontaneously on other surfaces (Figure 7). Use of the poles was common on the mattress and the low-friction surface and was universal on beam. This finding suggests that manual control is a distinct, legitimate form of postural control (cf. Cordo & Nashner, 1982). Stance that is maintained through manual control is still stance. Regarding manually controlled stance as not being "independent" (Woollacott & Sviestrup, 1992) depends on the implicit assumption that bipedal control is primary. The adaptive, voluntary use of manual control in the present experiment undermines the assumption of bipedal primacy in postural development.

On the low-friction surface and the mattress there were approximately equal amounts of free standing and pole standing (Figure 7), but there was very little quiet stance when the poles were in use (only 6 episodes, as compared to 20 during free standing; Table 1). This suggests that on these surfaces, manual control was used to counter forces introduced by suprapostural movements. Such a strategy would be highly adaptive and would suggest that the children were sensitive to complex relations between suprapostural activity, postural stability, and different available strategies for postural control (Gibson et al., 1987; Riccio & Stoffregen, 1988; cf. McGinnis & Newell, 1982). In general, the surface-specific use of the poles indicates that manual control cannot be regarded as an "automatic," reflexive response (Delorme et al., 1989; Woollacott & Sviestrup; 1992). Findings from our analysis are consistent with some findings of Woollacott and Sviestrup (1992), who studied children who first learned to stand with manual control then switched to exclusive leg control. The switch from manual to nonmanual control was accompanied by a temporary increase in instability, which indicates that the use of the hands was adaptive in stabilizing posture.

The adaptive, surface-specific use of the poles would seem to contradict "bottom up" hypotheses of postural development. Assaiante and Amblard (1995) proposed that in the acquisition of bipedal posture, "unperturbed balance control . . . is organized from foot to head" (p. 21). Similarly, Woollacott and Sviestrup (1992) described as "correct" a "distal to proximal" organization of muscle activation. The authors of both of these studies asserted that stance develops through a sequential activation of specific anatomical effectors (particular muscles). Our children used both feet and hands on some surfaces (mattress and low friction) and

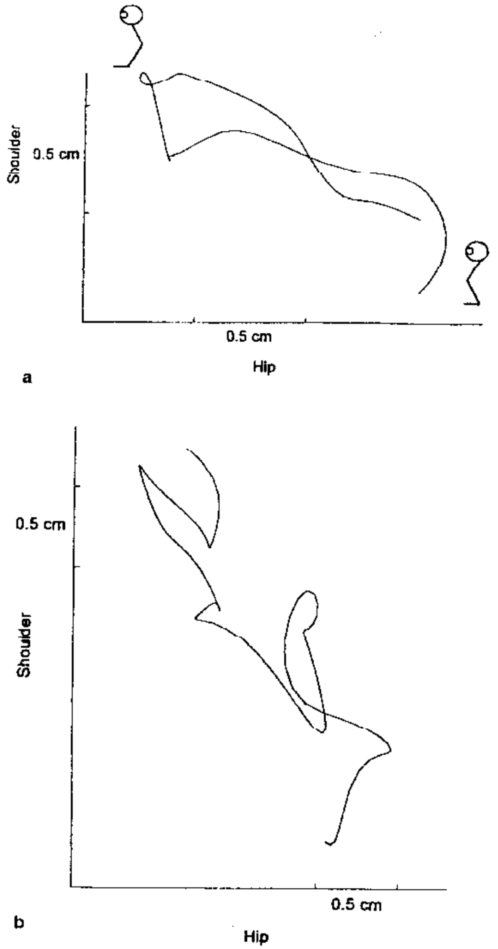

Figure 6 — Individual instances of negatively correlated hip and shoulder motion. (A) Beam, 1.0 s, $r^2 = -.84$. (B) High friction, 1.5 s, $r^2 = -.87$. (C) Mattress, 1.5 s, $r^2 = -.72$. (D) Mattress, 4.0 s, $r^2 = -.83$. In A, B, and D, the negatively correlated motion is oscillatory (bidirectional). Stick figures in A indicate positions on the graphs that correspond to forward and backward extrema of the hips in pure hip control.

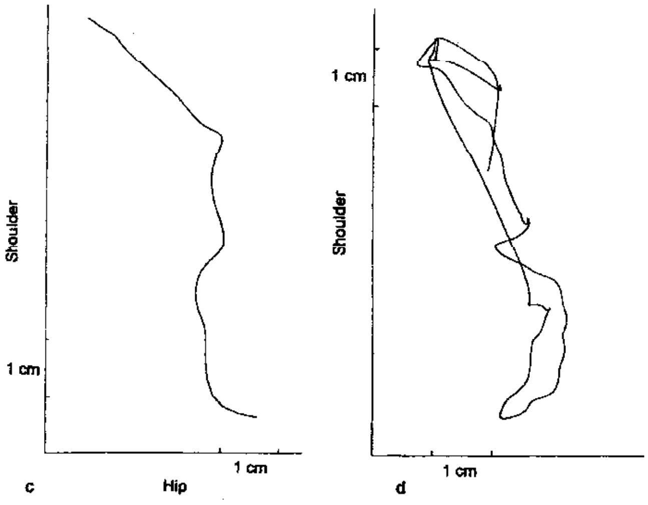

Figure 6 (continued)

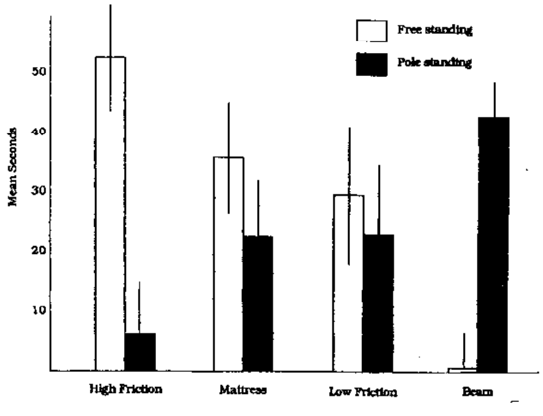

Figure 7 — Mean time spent in free standing and pole standing on the four experimental surfaces. Vertical bars show minus (where appropriate) and plus one standard error of the difference between seconds free standing and seconds pole standing.

used exclusively feet or exclusively hands on others (high friction and beam, respectively). This is not consistent with the model of Assaiante and Amblard (1995) or the analysis of Woollacott and Sviestrup (1992). Our data also do not fit comfortably into the analysis of McCollum and Leen (1989), who considered only motions of the ankles, knees, and hips.

We propose that postural development is not anatomy-specific but is function-specific (Riccio & Stoffregen, 1988; Thelen & Smith, 1994). The data suggest to us that the children used poles adaptively after perceiving the opportunities that they offered for support (Cordo & Nashner, 1982). The variety of control strategies (manual, hip, ankle) that appeared to be available to these children, and their adaptive surface-specific use of these strategies (rare falls), suggest that the children were skilled at detecting and exploiting affordances for erect posture, even as novices (Gibson et al., 1987; Mark, Balliet, Craver, Douglas, & Fox, 1990). A similar interpretation could be made of the original Cordo and Nashner (1982) data, which showed that leglike patterns of muscle activation occurred in the arms when manual control was available: Postural control was organized around situation-specific opportunities for stabilization, not around internal anatomical or neurophysiological structures.

Conclusion

The results of the present experiment suggest that 14-month-old children are not confined to a single, reflexive strategy for postural control. Instead, they use complex movements to control posture, and they use these movements successfully. These include movements of the hips and ankles and of the arms and hands.

The presence of successful, nonemergency hip movements indicates that models based on responses to sudden, imposed perturbations (which predict the absence of hip control) may not extend to the more general case of unperturbed stance (Assaiante & Amblard, 1995). This finding and related findings in other studies (Aruin & Latash, 1995; Assaiante & Amblard, 1995; Williams et al., 1985), should motivate researchers to reconsider the use of the perturbation paradigm as a theoretical or empirical model for the control of normal (unperturbed) posture.

The children in this study employed a wide variety of coordination modes in the maintenance of stance. Manual control was used in a surface-specific manner, suggesting perception of and adaptive response to at least some of the constraints on postural control imposed by different surfaces. Other coordination modes (involving the hips and ankles) did not appear to be surface-specific, yet these modes did not lead to losses of control (falling). This suggests that children may have been exploring a wide range of hip and ankle coordination patterns in a controlled manner. This would be functional if the children were attempting to determine which modes were most effective on each surface. Finally, our data indicate that even very young standers are able to spend most of their standing time engaged in suprapostural activities. Accordingly, future research should develop techniques that will make it possible to examine the integration of posture with suprapostural activities (e.g., Bardy et al., 1996; Stoffregen & Smart, 1996).

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Notes

[1] The *standing while held* category was included to permit the videotapes to be parsed into mutually exclusive behavioral categories. We felt that it was important to explicitly separate out time during which the child was being touched by an adult. No further analysis was performed on data in this category.

[2] Bending at the hip might also produce a positive correlation, for example, if both the hips and shoulders were moving forward but the shoulders moved much faster (this would be a strongly destabilizing motion, probably leading to a fall). Thus, a positive correlation between hip and shoulder does not guarantee that posture is being controlled at the ankles. However, a negative correlation strongly suggests that hip motion is in use.

[3] It seems likely that children in most studies of postural development are engaged in suprapostural tasks. Within the perturbation paradigm, these behaviors, and any anticipatory postural actions that may be associated with them, are not analyzed or reported. The present data call this practice into question (cf. Assaiante & Amblard, 1995) and motivate the development of new techniques for the analysis of postural control with suprapostural activity.

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