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What Changes in Infant Walking and Why

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This study compared the relative contributions of growing body dimensions, age, and walking experience in the development of walking skill in 9- to 17-month-old infants ($N = 210$), 5–6-year old kindergartners ($N = 15$), and college students ($N = 13$). Kinematic measures derived from participants' footprints showed characteristic improvements in walking skill. As children became bigger, older, and more experienced, their steps became longer, narrower, straighter, and more consistent. Improvements reflected a narrowing base of support and increasing control over the path of progression. Although both infants' age and the duration of their walking experience contributed to improvements in walking skill, experience was the stronger predictor. This finding suggests that practice is the more important developmental factor for helping infants to conquer their weak muscles and precarious balance.

Two of the central goals of developmental psychology are to describe what changes as children acquire new skills and to understand why changes occur. In this study we examined a fundamental skill in development—independent walking. Like most developmental achievements, research on walking has been more successful at meeting the goal of description and less successful at meeting the goal of explanation. A rich literature describes characteristic improvements in walking skill, but few studies have focused on the underlying causes of developmental change. One obstacle to progress may have been methodological. Previous studies of infant walking have been largely limited to small samples. Although a handful of infants followed longitudinally is sufficient to document naturally occurring changes in walking skill, a relatively large sample of participants is required to statistically compare the contributions of various developmental factors. To redress this problem, we devised a quick and inexpensive footfall method to obtain measures of walking skill in a large group of infants, and in smaller comparison groups of kindergartners and adults. Armed with this sample, we tested whether growing body dimensions, age-related changes in neuromuscular maturation, and practice executing movements over weeks of walking experience may have contributed to the observed improvements in walking patterns.

Infant Walking

Walking is one of the most studied skills of children's motor achievements. For more than half a century, researchers have concocted innovative ways to document improvements in infant walking—the scratches in the floor left by hobnailed boots (Dougan, 1926), chalk impressions of infants' feet on black photographic paper (Wolff, 1929), and series of footprints made from olive oil sprinkled with graphite (Shirley, 1931), ink-coated corn plasters (Ogg, 1963), or from walking through talcum powder (Scrutton, 1969; Scrutton & Robson, 1968). Perhaps most ingenious was the technique devised by McGraw and Breeze (1941) for capturing the placement of infants' steps. Babies walked over an array of tiny, black, rubber cones and white evaporated milk, sandwiched between two glass plates. As their feet contacted the glass surface, the cones deformed and displaced the milk revealing a real-time trace of babies' footsteps. Following in the

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tradition of the early pioneers, recent researchers have capitalized on new recording technologies to measure the placement and timing of infants' steps—force plates (Bril & Breniere, 1992), high-speed film (Clark, Whitall, & Phillips, 1988), video (Thelen, Bril, & Breniere, 1992), and marker-tracking motion analysis systems (Vereijken & Thelen, 1997).

Both the cruder, old-fashioned techniques and the technically more sophisticated modern recording methods yield similar measures of walking skill. Footfall measures, for example, show that most newly walking infants have a gait like Charlie Chaplin. They take small unsteady steps with their legs splayed wide apart and their toes pointing externally to the sides (e.g., Bril & Breniere, 1989; McGraw, 1935, 1945; Shirley, 1931). In fact, the lateral distance between their feet can exceed the front-to-back distance between consecutive steps. There is high variability from step to step, and the distance each leg travels is not symmetrical (e.g., Clark et al., 1988). Because of their instability on one foot, most new walkers lack the time to point their toes upward before foot contact (Thelen et al., 1992). As a result, they plant their entire foot down immediately, like wielding a club, or they walk on their toes (Forssberg, 1989; McGraw, 1945). As walking improves, infants take longer steps, maintain a smaller lateral distance between their feet, point their toes more to the front, and display a rhythmical heel-toe progression, and the coordination between the legs approaches perfect symmetry.

Although not tested formally, several researchers have noted that the improvements in infants' walking may be nonlinear (Bril & Breniere, 1992; McGraw, 1940; Shirley, 1931). Unlike some developmental functions such as vocabulary acquisition where improvements are initially slow then spurt upward in the second year of life (Fenson et al., 1994) or imitation where the function is U-shaped (Bower, 1976), developmental changes in infant walking resemble the negatively accelerated performance curves found typically in motor-learning tasks (Schmidt & Lee, 1999). Improvements appear to be most rapid and dramatic in the first 3 to 6 months after walking onset then begin to asymptote over the next several months (e.g., Bril & Ledebt, 1998). Some researchers believe that children's gait patterns resemble those of adults after a year or so of independent walking (Burnett & Johnson, 1971), but others argue that walking is not fully developed until around 7 or 8 years of age (Bernstein, 1967; Breniere & Bril, 1998; Bril & Ledebt, 1998; Sutherland, Olshen, Cooper, & Woo, 1980).

Developmental Factors

Researchers widely agree that increased strength and postural control are the proximal cause of improvement in the development of walking. Infants must acquire sufficient strength to control forward propulsion while supporting their body on one leg and sufficient postural control to keep their bodies in equilibrium, especially during periods of single limb support (Breniere & Bril, 1988; McGraw, 1935, 1945; Thelen, 1984a; Vereijken, Pedersen, & Storksen, 2002). In support of this argument, Breniere and Bril found that the vertical acceleration of infants' center of mass is negative at foot contact. New walkers literally fall downward into each step. The size of the negative value steadily decreases, reflecting increasing postural control during the single support phase when infants are standing on one leg. By 4 to 5 years of age, the sign of the vertical acceleration of children's center of mass becomes positive like that of adults, meaning that they are no longer in a state of free fall (Breniere & Bril, 1988, 1998; Bril & Breniere, 1993). In essence, babies propel themselves forward by falling downward while they stand on one foot and then catching themselves with their moving foot. Older children and adults, in contrast, have sufficient strength and balance to control forward propulsion by pushing upward with the leg supporting their body (Bril & Breniere, 1993).

What distal developmental factors might affect increases in strength and balance? The literature sustained several fierce battles over the roles of body growth, neural maturation, and experience regarding the onset of independent walking—the age at which infants take their first independent steps (e.g., Forssberg, 1985; McGraw, 1932, 1935, 1945; Shirley, 1931; Thelen, 1983, 1984a, 1984b, 1995; Thelen & Smith, 1994; Zelazo, 1983, 1984, 1998; Zelazo, Weiss, & Leonard, 1989). However, no research to date has explicitly tested the effects of body growth, age, and experience on facilitating improvements in walking skill—the change from a "Charlie Chaplin" toddler to mature adult-like gait. During the same time children's walking skill improves, there are dramatic structural changes in their bodies, important changes in neural maturation, and cumulative opportunities to gain experience.

Body dimensions. In their first 2 years of life, infants' overall chubbiness decreases while their muscle mass increases, and their body dimensions become less top-heavy and more cylindrical (Palmer, 1944). Changes in body growth could affect strength and balance by changing the biomechanical constraints on movement. For example, defying gravity simply to lift the legs in an upright position requires a sufficiently high muscle-to-fat ratio in the legs (Thelen, Fisher, & Ridley-Johnson, 1984). Bearing the body's weight on one leg while hoisting the other requires additional leg and hip strength plus sufficiently strong muscles in the back and abdomen to stabilize and support the leg movements (Bertenthal & Clifton, 1998). Overall chubbiness could affect strength and balance because more strength is required to move a heavier body and destabilizing torques build up faster as the body rotates around the ankles or hips. More cylindrical proportions mitigate the effects of destabilizing torques by lowering infants' center of mass. Indeed, chubbier, more top-heavy infants tend to begin walking at later ages than slimmer, more cylindrically shaped infants (Adolph, 1997; McGraw, 1945; Shirley, 1931). Experimentally induced changes in body build (loading infants with weights, etc.) to simulate more babyish proportions result in decrements in babies' level of walking skill (Adolph & Avolio, 2000; Schmuckler, 1993; Vereijken et al., 2002).

Of course, in principle, changing body dimensions could affect changes in gait parameters without affecting strength and balance, simply because of the geometry of the limbs. Typically, movement scientists model walking as an inverted pendulum (Townsend, 1981; Winter, 1995). During single limb support, the foot on the floor acts as the pivot around which the leg and upper body rotate until the other foot contacts the floor. The previously moving foot acts as the new pivot point for the inverted pendulum motion of the body when the other leg begins its step. According to the pendulum model, the length and angle of the lever arm predicts the amplitude of the rotating movement. Thus, on this account, leg length should be related to stride length, step length, and step width. Such a prediction holds considerable intuitive appeal: Parents' steps may be longer and narrower than their infants' steps simply because parents have longer legs. Trouble balancing on one leg, however, may preclude taller, longer legged infants from benefiting from the potentially longer arc of their swinging leg. Like their shorter legged peers, they may be forced to plant their swinging foot before it completes its full arc. Despite the prevalence of the pendulum model, previous work has not examined the extent to which the characteristic increase in infants' strides and step length is due to their growing legs.

Neural maturation. Like body growth, important changes in neural development and experience occur at the same time as walking skill improves. Over the first 2 years of life, the brain grows from 30% to nearly 70% of its adult weight (Thatcher, Lyon, Rumsey, & Krasnegor, 1996). Glial cells multiply at a rapid pace, neural fibers become myelinated, and there is a burst of synaptic growth in visual cortex (Johnson, 1998). There is a surge in EEG activity in the frontal lobes at around 12 months when most infants begin to walk (Bell & Fox, 1996). Maturation of neural structures and circuitry could affect strength and balance by increasing the efficiency and speed with which perceptual information and motor signals are integrated and processed. Neural maturation may underlie improved balance in upright walking by influencing infants' pick-up of perceptual information, the rapidity of their motor responses to perceptual feedback, and the development of anticipatory postural control. Accordingly, some researchers propose that maturational changes in infants' information-processing capabilities between 12 and 24 months explain why infants begin walking toward the end of their first year and why walking skill improves (Zelazo, 1998; Zelazo et al., 1989).

Walking experience. Independent of maturational changes in body and brain, locomotor experience could facilitate strength and balance by providing infants with practice moving in an upright position. For example, 2-month-olds who were provided with daily practice moving their legs in an upright position retained newborn stepping movements longer than infants who only kicked on their backs and the upright-practice group began walking several weeks earlier than their counterparts in the control groups (Zelazo, Zelazo, & Kolb, 1972). Similarly, the regular, physical exercise obtained over days and weeks of walking experience could strengthen infants' leg and hip muscles and provide opportunities for learning to control balance more efficiently. In principle, each wobbly step provides practice coordinating the segments of the leg (ankle, shank, and thigh), stabilizing the torso and head, gathering and using perceptual information, and generating anticipatory and compensatory responses to loss of balance. In addition, each step provides feedback about the extent of the wobble, that is, infants' success at minimizing muscle expenditure, exploiting passive forces, and maintaining the body within its moving base of support while maximizing the over-ground distance covered (Adolph, 2002; Adolph & Eppler, 2002). In line with this argument, previous work shows that everyday locomotor experience facilitates improvements in the speed and size of infants' crawling steps (Adolph, Vereijken, & Denny, 1998) and promotes adaptive responding to treacherous ground surfaces, independent of babies' testing age and body dimensions (e.g., Adolph, 1997, 2000; Bertenthal, Campos, & Barrett, 1984; Campos, Bertenthal, & Kermoian, 1992).

Present Study

The present study expanded on previous work in several ways. We used a revamped footfall method for obtaining measures of foot placement in infants, kindergartners, and adults. We attached inked tabs to the bottoms of participants' shoes and calculated distance measures from the trail of footprints left behind on a scroll of paper. This quick and inexpensive method allowed us to compile a relatively large data set including a large number of infants, some of whom were tested longitudinally. With this data set, we replicated and extended previous findings on what changes in infants' walking. Using both cross-sectional and longitudinal data, we examined developmental trends for step length, step width, and foot rotation and, in addition, contrived a new variable, the dynamic base, which captures walkers' ability to control the path of progression. We formally tested whether earlier investigators' intuitions were correct that improvements are nonlinear during infancy. We compared mean values, measures of variability, and intercorrelations between gait measures in infant, kindergartner, and adult age groups to test whether walking continues to improve after infancy.

Most important, we aimed to advance understanding of why walking improves. To examine whether changes in step length and step width are simply due to the length of participants' legs as predicted by the pendulum model, we normalized distance measures by participants' leg length and compared the results across infant, kindergartner, and adult age groups. To understand better the distal source of change in the development of walking, we obtained measures of participants' body dimensions and used their chronological age and duration of walking experience to capture the effects of neural maturation and practice. Because older children tend to have larger bodies and more walking experience, we teased apart the respective independent contributions of each factor by statistically controlling for the effects of the other factors.

Method

Design and Participants

Participants were 210 infants (101 girls, 109 boys), 15 kindergartners (8 girls, 7 boys), and 13 adults (10 women, 3 men). We culled the infant data from several studies originally designed to test visual guidance of locomotion over risky ground surfaces. Fortuitously, infants' chronological ages and duration of walking experience covered the period of interest suggested by the literature and some of the infants were observed longitudinally from walking onset. Infants were recruited from published birth announcements and purchased mailing lists in the Atlanta, Georgia; Bloomington, Indiana; Pittsburgh, Pennsylvania; and New York City areas. All infants were healthy, term babies; most were White and from middle- to upper-income families. All could walk at least 12 ft (3.7 m) independently on three of four consecutive trials in the laboratory.

We collected the kindergartner and adult data for the current descriptive study to test claims regarding the time course of walking development. Sample sizes were smaller because we expected less variability in more mature walkers. The kindergartners attended a laboratory nursery school in Pittsburgh and each was tested only one time. They were between 5.3 and 6.3 years of age. Adults were researchers in the motor development laboratory and each was tested one time. Twelve were between 18.7 and 21.7 years of age; one was 32.6 years of age.

We tested 165 babies (78 girls, 87 boys) only once, when they were between 297 and 497 days old ($M = 426.0$ days). We tested 45 babies (23 girls, 22 boys) 2 to 10 times, spaced 10 to 89 days apart for a total of 131 sessions across infants (see Table 1). At their first test session, infants in this longitudinal group were between 287 and 504 days of age ($M = 435.5$ days). We defined walking onset as the first day infants could walk at least 10 ft (3.1 m) independently. We followed 28 infants prospectively (16 longitudinal and 12 cross-sectional), and their walking onset dates were determined from weekly telephone interviews and testing during home visits. Parents of the remaining infants provided retrospective reports of their infants' walking experience using calendars and baby books to aid their memories. An experimenter questioned them with a predetermined series of formal questions in a structured interview (e.g., Adolph, 1995; Adolph & Avolio, 2000; Adolph, Eppler, & Gibson, 1993). Infants in the cross-sectional group had between 4 and 187 days of walking experience ($M = 77.2$ days) and infants in the longitudinal group had between 3

Table 1
Number of Sessions at Which Participants Were Observed and Length of Intervals Between Observations

Age group	No. of sessions	No. of participants	Mean interval length (days)
Infants	1	165	—
	2	30	33.3
	3	2	25.5
	4	7	25.0
	5	4	21.1
	7	1	20.3
	10	1	20.7
	Subtotal longit.	45	
	Total cross-sect. and longit.	210	
Kindergarteners	1	15	—
Adults	1	13	—

and 233 days of walking experience ($M = 72.8$ days) at their first day of testing. Figure 1 shows the distribution of infant data by test age and walking experience.

Apparatus and Procedure

Footfall method. First, participants removed their shoes. Then, an experimenter used a stencil to place moleskin tabs on the bottoms of participants' shoes at the base of the heel and in line with the third toe. Tabs were cut from drugstore moleskin or constructed from flannel affixed to double-sided carpet tape. As shown in Figure 2A, 1.5-cm squares and triangles marked the heel and toe on the bottoms of the shoes. After redonning their shoes, participants practiced walking a few times over a long strip of butcher paper (76 cm × 3.7 m for infants, 4.6 m long for kindergartners, and 5.5 m long for adults). Infants walked over a raised platform (116 cm high) to prevent them from running away. Parents stood at the far end of the platform and encouraged infants to walk while the experimenter followed beside them to ensure their safety. Kindergartners and adults walked over the floor, beginning a few steps before the paper and ending a few steps after the paper. They were told to walk normally at a comfortable speed. Infants' footfall sequences were videotaped to provide a back-up record for interpreting idiosyncracies when necessary.

Next, an assistant applied ink to the moleskin tabs with a cotton swab, one color for one foot (e.g., green) and another color for the other foot (e.g., red). Infants were held in an experimenter's arms. Kindergartners and adults sat on a chair. Finally, participants walked over the butcher paper, leaving behind a trail of colored footprints (see Figure 2B). So that we could later assess test–retest reliability, the assistant reapplied ink to the tabs on participants' shoes and asked them to walk over a new strip of paper for a second trial. Every kindergartner and adult contributed two footfall trials. If infants stopped walking or fell, the experimenter repeated the trial. Infants contributed two footfall sequences in 153 of the 165 cross-sectional sessions and in 126 of the 131 longitudinal sessions.

Body measures. After collecting the footfall sequences, an experimenter obtained several measures of participants' body dimensions: weight (on a pediatric scale), recumbent height from crown to heel, leg length from hip to ankle (anterior, superior iliac spine to medial malleolus), head circumference at eyebrows, and crown–rump length. Each measure was obtained twice and results were averaged. As a measure of participants' overall chubbiness, we calculated the Ponderal Index [weight/(height^3)] (Shirley, 1931). Because of fussing, infants had missing data for one or more body measures at 12 sessions.

Data Coding and Calculation of Foot-Placement Measures

Footfall measures are affected by start up and slow down (Breniere, Bril, & Fontaine, 1989; Breniere

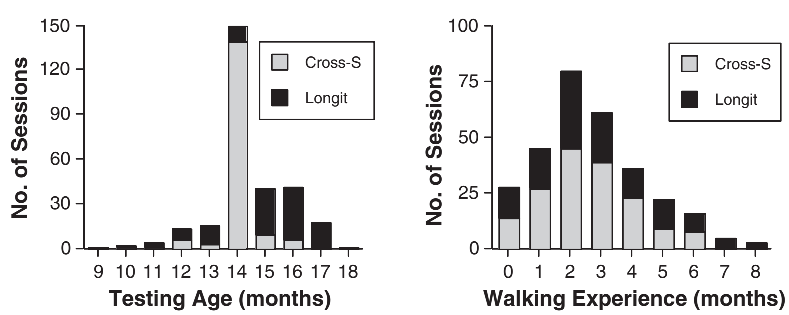

Figure 1. Distribution of cross-sectional and longitudinal infant data by test age and walking experience.

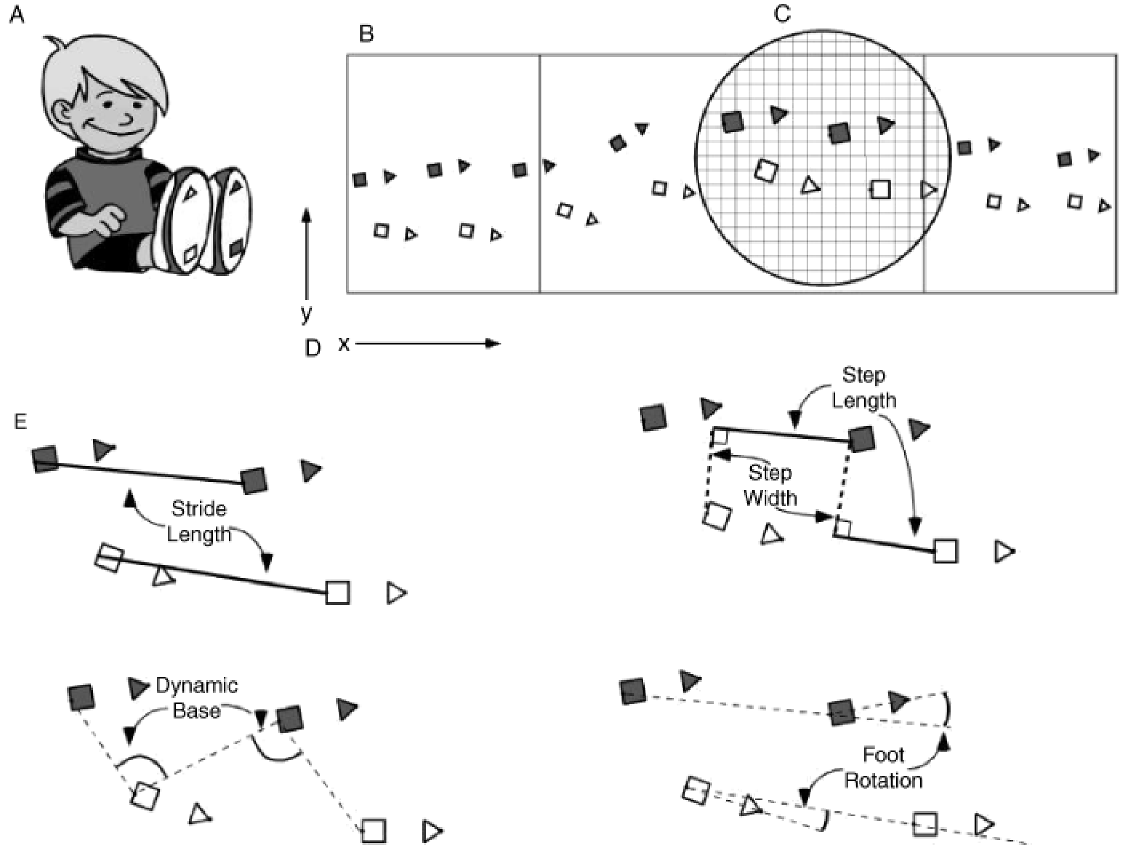

Figure 2. The footfall method. (A) Inked tabs on the bottom of participants' shoes. (B) The trail of footprints on a scroll of paper. Horizontal lines designate the middle portion of the path where participants had reached steady state velocity. (C) The *x* and *y* coordinates of heel and toe prints (shown magnified). (D) The fixed Cartesian reference frame. (E) Calculation of foot-placement measures using a moving frame of reference.

& Do, 1986; Ledebt, Bril, & Breniere, 1998) when walkers initiate a walking sequence and when they come to a stop (step lengths, for example, are shorter on the first or last step of a sequence). Infants' gait patterns are most severely affected. So that our calculations would reflect walking skill during steady state velocity when walkers had hit their stride, coders ignored the first and last few steps of each sequence. Because infants walked from one edge to the other edge of the paper, coders ignored the first 3 steps and the last 3 steps on the paper, leaving between 6 and 17 steps from which to calculate measures of foot placement ($M = 8.05$ steps). The kindergartners and adults began walking 3 to 4 steps before the edge of the paper and continued walking 3 to 4 steps after they had stepped off the paper, leaving 6 to 13 ($M = 9.53$) and 6 to 10 ($M = 7.73$) codable steps for the kindergartners and adults, respectively.

For scoring distance measures, one coder placed a transparent grid over each footfall sequence and identified the x–y coordinates of each heel and toe print with a .25-cm resolution. Figure 2C illustrates an enlarged view of the grid and foot prints. Figure 2D illustrates the x and y axes against which coordinates were identified. A second coder entered the coordinates into a commercial spreadsheet program.

Like previous studies (Bril & Breniere, 1992; Scrutton, 1969; Scrutton & Robson, 1968; Shirley, 1931), we calculated stride length (distance between heel strikes on the same foot), step length (distance between heel strikes on consecutive feet), and step width (lateral distance between feet), using a fixed, Cartesian reference frame. A fixed reference frame assumes that participants always walk along a straight path that is always parallel to the x axis, for example, a line of progression drawn through the sequence of footfalls, or in this case, the bottom edge of the paper. With a fixed reference frame, stride and step lengths are calculated as the difference in values of the x coordinates and step width is the difference in y coordinates drawn perpendicular to the x axis. However, when the path is twisting or veering relative to the x axis, a fixed reference frame will systematically underestimate stride length and step length and overestimate step width. Thus, recognizing that a fixed reference frame cannot take into account twists and turns in the path of progression, we calculated measures of stride length, step length, and step width using a moving reference frame (see Figure 2E). The moving frame uses both the x and y values to calculate stride lengths and determines step lengths and step widths relative to the angle of the accompanying stride. Note that when the path of progression is perfectly straight and parallel to the x axis, the two reference frames are equivalent. Finally, we calculated foot rotation (toe in or toe out) and dynamic base (the angle formed by three consecutive steps). The dynamic base is a new measure that combines information about the base of support and the straightness of walking (Adolph, 1995; Adolph, 1997; Adolph & Avolio, 2000).

Results

Statistical Analyses

We used ANOVA to test differences in mean values, product moment correlations to assess the association between variables, and regression models to describe variation in walking measures as a function of infants' chronological age, walking experience, and body dimensions. The analyses were made more complicated by the fact that we had 296 observations from 210 infants. Including the repeated observations from the 45 infants in the longitudinal group with the single observations from the 165 infants in the cross-sectional group yields more precise estimates of means, correlation coefficients, and regression parameters. However, the usual statistical tests cannot be used with these estimates because the repeated observations are not formally independent of each other.

We approached the problem of analyzing the mixture of longitudinal and cross-sectional infant data in three ways. First, to test mean differences between measures, we constructed a data set with only one observation per infant. For infants with several observations, we selected an observation where the duration of walking experience was relatively uncommon in the total data set. As a result, we tended to select the first or the last available measurement. This selection process made the final sample more informative about developmental processes. The expanded cross-sectional sample had 210 independent observations and could be analyzed with standard ANOVA methods and hierarchical regression analyses. We used Type III sums of squares in significance tests (what Howell, 2002, p. 619, called Method I) to take into account unequal group sizes for comparisons involving infants, kindergartners, and adults.

Second, for analyses of correlations between footfall measures, we used the full set of 296 observations to estimate the coefficients, but we constructed conservative significance tests by assuming that only 210 observations were available.[1] Third, for curve fitting to model the detailed time course of improvements in walking skill, we used random regression models (Byrk & Raudenbush, 1992) that take into account the fact that some observations are repeated measures. The MIXED procedure of SAS Version 8 (SAS Institute, 2001) allowed us to specify that participants have their own intercepts in the regression equation and to analyze repeated measures as deviations from the random intercept. This statistical procedure allowed us to take full advantage of the complete set of observations, but it is less familiar and consequently we used is as an adjunct to more conventional analyses.

Infant boys were larger than infant girls on every measure of their body dimensions. However, body dimensions were poor predictors of infants' walking skill, and no gender differences appeared for any of the analyses. Thus, we report results collapsed across boys and girls.

[1]All of the children were recruited with the same procedure. Those with multiple observations were not systematically different from those seen only once. Thus, statistical results from cluster sampling apply to repeated measures. The child is the first-order sampling unit and the observation within child is the nested (clustered) second-order sampling unit. Sampling statisticians (e.g., Cochran, 1977) show that clustered data do not produce biased estimates of means, correlations, and regression weights, but the standard errors of the estimates can be incorrect. Correction formulas for the standard errors (sometimes called design effects) involve an intraclass correlation (ICC), that indicates the extent to which within-cluster observations are more similar to each other than between-cluster observations. If the within-cluster observations are very similar, ICC = 1, and if the within- and between-cluster variation is indistinguishable, ICC = 0. When ICC = 1, the correction formulas essentially make the sample size the number of clusters (i.e., children in our context); when ICC = 0, the correction formula makes the sample size the total number of observations (ignoring clusters). We chose as the sample size the number of children assumed the worst case scenario of ICC = 1.00, and hence it is conservative.

Evaluation of Footfall Method

Test–retest reliability. We evaluated the reliability of our footfall method by assessing the correlation between footfall Trials 1 and 2 for each measure. Correlation coefficients for both the fixed and moving frames of reference were .97 for stride length, .97 for step length, and .76 for step width. Coefficients were .81 for foot rotation and .87 for dynamic base. In all further analyses, we report the average of both sequences.

Fixed versus moving references frames. A moving frame of reference was more sensitive than a fixed frame of reference for calculating distance measures relative to twists and turns in the path of progression, especially for infants. Table 2 shows mean values of stride lengths, step lengths, and step widths calculated with fixed and moving reference frames. Infants' data included the expanded cross-sectional sample with only one observation per infant. Although mean differences were small, they were highly reliable. The fixed reference frame yielded systematically smaller values for stride and step lengths in 68% to 100% of participants in each age group and systematically larger values for step width than the moving reference frame in 80% to 98% of participants in each age group. A series of 2 (fixed and moving) $\times$ 3 (infants, kindergartners, and adults) ANOVAs showed main effects for reference frame on stride length, $F(1, 234) = 61.4$, $p < .01$, and step length, $F(1, 234) = 45.0$, $p < .01$, and main effects for age on stride length, $F(2, 234) = 600.1$, $p < .01$; step length, $F(2, 234) = 601.6$, $p < .01$; and step width, $F(2, 234) = 9.8$, $p < .01$. In addition, there were interactions between the two factors for stride length, $F(2, 234) = 8.5$, $p < .01$, and step width, $F(2, 234) = 17.1$, $p < .01$. For strides and steps, post hoc comparisons (Tukey's HSD) showed significant differences between fixed and moving reference frames for each age group, but the differences were larger for infants than for adults (all ps $< .05$). For step width, post hoc comparisons showed differences between fixed and moving reference frames only for the infants ($p < .01$).

Because of its greater sensitivity, in all further analyses we report results only for measures calculated with a moving frame of reference. Because information from stride lengths and step lengths is highly redundant ($r = .997$ for infants), in further analyses we report results for step lengths only.

Table 2
Mean Values of Stride Lengths, Step Lengths, and Step Widths Using Fixed and Moving Reference Frames

	Age group		
Measure	Infants	Kindergarteners	Adults
Stride length			
Fixed	49.53	97.54	153.71
Moving	49.79	97.72	153.78
Step length			
Fixed	24.63	48.55	76.48
Moving	24.98	48.95	77.16
Step width			
Fixed	11.75	8.35	8.95
Moving	11.68	8.42	8.95

Development of Walking Skill

We calculated two aspects of change in walking skill: changes in mean values and changes in variability. The former reflects infants' ability to keep balance and make forward progression. The latter reflects their ability to control their walking patterns by reproducing the same behavior from step to step. For each participant at each test session, we calculated the mean value and coefficient of variation for step length, step width, dynamic base, and foot rotation for each walking trial separately. Then we averaged across the two trials so that each participant contributed one data point per measure for each session. Because mean values vary widely among infants, kindergartners, and adults, the same standard deviation can reflect very different levels of variability. Thus, the coefficient of variation (standard deviation and mean) normalizes variability by the mean value to allow for meaningful comparisons across ages. Foot rotation sometimes displayed negative values because of in-toeing, regressing the mean values toward 0. To analyze changes in the amount, rather than direction of foot rotation, we calculated means and coefficients of variation for the absolute values of foot rotation.

There was a wide range in footfall measures in every age group and at every week of infants' walking experience. Despite large individual differences, there were clear changes in walking skill from infancy to adulthood. As shown in the left column of Figure 3 and top panel of Table 3, adults and kindergartners walked better than infants (note, infant data include the expanded cross-sectional sample). Adults and kindergartners took longer, straighter steps, with their feet closer together laterally and pointing more straight ahead. Step length doubled from the infant to kindergartner period, then increased another 50%. Step width

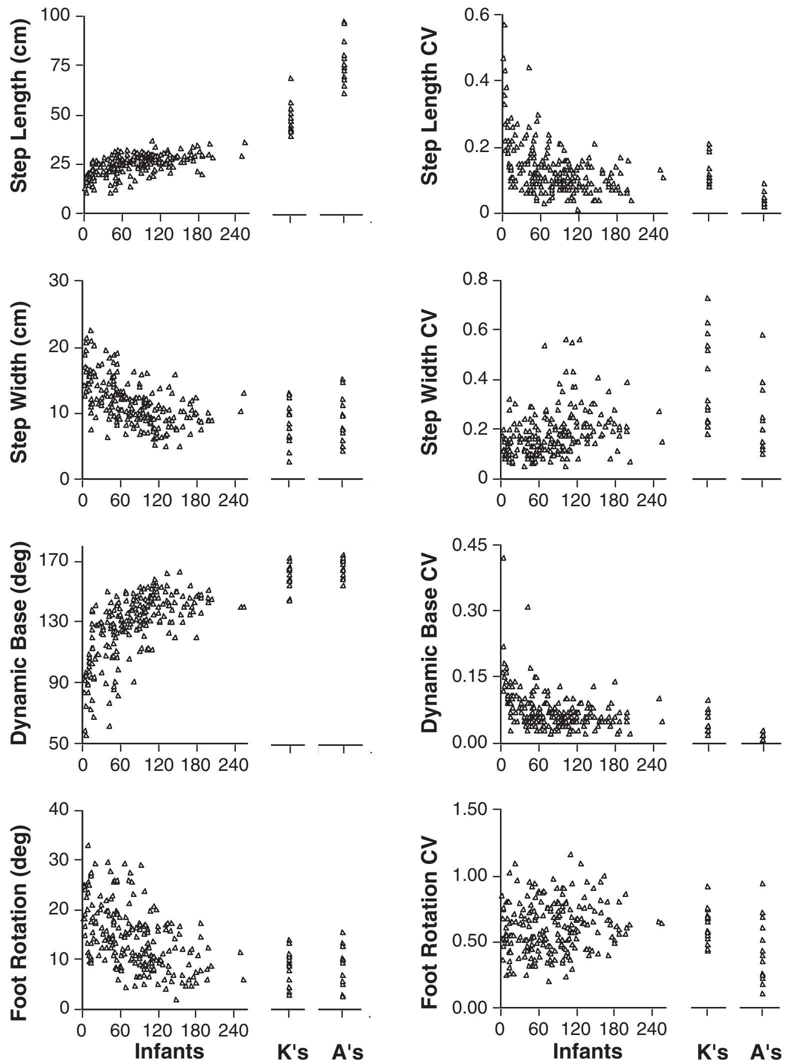

Figure 3. Mean values (left panels) and coefficients of variation (right panels) for foot-placement measures (step length, step width, dynamic base, and foot rotation). Infants are plotted by walking experience. Ks = kindergartners; As = adults.

decreased 25% after infancy. Dynamic base angles approached 180 degrees and foot rotations decreased by 40%. A series of one-way ANOVAs showed significant age differences for each measure. Post hoc (Tukey's HSD) analyses revealed differences among all three age groups for step length, and between infants and the older age groups for step width, dynamic base, and foot rotation (all $ps < .05$).

As shown in the left column of Figure 3 and the middle panel of Table 3, in general, adults and kindergartners were less variable than infants. One-way ANOVAs confirmed age differences for each measure of variability. Post hoc (Tukey's HSD) analyses showed differences in the average coefficients of variation between infants and adults for step length, infants, and the two older groups for step width and dynamic base, and between adults and the two younger groups for foot rotation (all $ps < .05$). The finding that infants showed smaller coefficients of variation for step width compared with kindergartners and adults is counterintuitive and deserves special comment. This finding occurred because infants tended to produce consistently wide steps; that is, small standard deviations (average $SD = 1.9$ cm) normalized by large means (average $M = 11.7$ cm) resulted in small coefficients of variation. In contrast, adults had similar standard deviations in step width compared with infants (average $SD = 2.1$ cm), but these were normalized by much smaller mean step widths (average $M = 8.9$ cm), resulting in higher coefficients of variation. Kindergartners obtained high coefficients of variation for a different reason. Like adults, they

Table 3
Means, SDs, and Results of One-Way ANOVAs on Mean Values of Foot Placement and Coefficients of Variation for Infants, Kindergarteners, and Adults

	Infants	Kindergarteners	Adults	*F*
Mean values				
Step length				
Mean	24.99	48.95	77.16	$F(2, 235) = 595.29^{***}$
SD	5.15	7.36	11.14	
Step width				
Mean	11.67	8.42	8.95	$F(2, 235) = 9.54^{***}$
SD	3.45	3.14	3.61	
Dynamic base				
Mean	127.39	159.92	166.25	$F(2, 235) = 37.70^{***}$
SD	21.47	8.17	6.42	
Foot rotation				
Mean	14.37	8.44	9.03	$F(2, 235) = 10.62^{***}$
SD	6.34	3.53	4.11	
Coefficients of variation				
Step length				
Mean	0.14	0.10	0.04	$F(2, 235) = 10.96^{***}$
SD	0.08	0.04	0.02	
Step width				
Mean	0.18	0.37	0.30	$F(2, 235) = 27.95^{***}$
SD	0.09	0.18	0.21	
Dynamic base				
Mean	0.08	0.05	0.02	$F(2, 235) = 13.28^{***}$
SD	0.05	0.02	0.00	
Foot rotation				
Mean	0.61	0.62	0.44	$F(2,235) = 4.75^{**}$
SD	0.19	0.13	0.25	

$^{**}p < .01$. $^{***}p < .001$

walked with a relatively narrow step width (average $M = 8.5$ cm), but they had higher standard deviations (average $SD = 2.8$ cm).

Figure 3 also illustrates dramatic improvements in infants' walking over days of experience. Step length and dynamic base increased, whereas step width and foot rotation decreased. Simultaneously, variability in step length and dynamic base decreased. As in previous studies, improvements in walking skill were generally faster in the first few months than in subsequent months, especially for mean values. Table 4 shows regression coefficients characterizing a linear model and a power function for each measure of walking skill for the 165 infants who were observed cross-sectionally and a power function for the 45 infants who were observed longitudinally.[2] Comparisons between linear and power functions in the cross-sectional group suggested that the power function fit the data better than the linear function for mean values of step length, step width, and dynamic base (differences in R^2 between linear and power functions were .08, .02, and .10, for step length, step width, and dynamic base, respectively) and for measures of variability in step length and dynamic base (differences in R^2 were .04 and .10 for step length and dynamic base, respectively). The linear model fit as well as or better than the power function for mean values of foot rotation and for measures of variability in step width and foot rotation.

To compare formally the fit of the two models for infants in the cross-sectional group, we regressed each footfall measure onto the fitted values obtained from the linear and power functions of walking experience, thereby making the two patterns of fit compete with each other.[3] For the mean values of step length, step width, and dynamic base, and for the measure of variability in step length, the fitted values from the power function accounted for significant variation in the data, holding constant the fitted values from the linear model, but the linear model did not account for variation beyond the fit of the power function. For the measure of variability in dynamic base, the power function was the stronger predictor but the linear function also accounted for unique variance. For the mean value of foot rotation, the fitted values from the linear function accounted for significant variation in the data, but the power function did not.

In comparing the R^2 values, we used data from infants who were measured only once. With these cross-sectional data, the R^2 can be interpreted as the proportion of between-infant walking variation that can be fit by days of walking experience. The cross-sectional observations are statistically independent, making it possible to apply conventional significance tests. However, functions fit to cross-sectional data are not necessarily the same as those fit to longitudinal data. To verify the consistency of the cross-sectional results with available longitudinal

[2]We were interested in the power function $Y = b0^{*} X^{b1}$, where $b0$ is a scaling factor and $b1$ is the coefficient that determines the shape of the monotonic relation between X and Y. For $b1 = 1$, the relation is linear, whereas for $b1 < 1$, the slope is steeper at first and less steep later. Standard statistical packages such as SPSS estimate these parameters by transforming the problem into one that is log-linear. Taking the log of both sides of the equation gives $\ln(Y) = \ln(b0^{*}\ X^{b1}) = \ln(b0) + \ln(X^{b1}) = \ln(b0) + b1^{*}\ln(X)$. After taking logs, standard linear statistical methods can be used to estimate $\ln(b0)$ and $b1$. We took the antilog of the first estimate to give us $b0$.

[3]We summarize the results of this ancillary analysis rather than showing all the test statistics, but a table showing the details of this analysis is available from Karen Adolph.

data, we used the MIXED procedure of the SAS System to estimate the power function for improvements in walking skill displayed by the 45 infants who were measured two or more times. This procedure provides a generalization of mixed-model repeated-measures analysis whereby within-subject patterns in the data are taken into account by allowing individual infants to have their own intercepts and slopes. Our analyses suggested that only intercepts were variable from infant to infant. The slope was estimated as a constant.

To estimate the power functions, we regressed the log of each footfall measure on the log of walking experience in the 131 observations from the 45 infants tested longitudinally. As shown in Table 4, the estimates of power functions are close across the cross-sectional and longitudinal samples. The results are statistically indistinguishable for all measures except for the mean values of step width and dynamic base (indicated by boldface in the table). For those two measures, the estimated values of the intercept and slope are statistically different, but they are similar in magnitude and sign. Note that Table 4 does not show R^2 values for the random regression models because this statistic does not have the same meaning when considering both between-infant and within-infant variability. Although it is possible to conceive of an R^2 value

Table 4

Regression Coefficients for Linear and Power Functions of Mean Values and Coefficients of Variation of Footfall Measures for Infants Observed Cross-Sectionally and Longitudinally

	b_0	$SE\ b_0$	b_1	$SE\ b_1$	R^2	b_1 test statistic
Step length						
Linear cross-sectional	20.67	0.68	0.05	0.01	0.23	$F(1, 163) = 49.63$***
Power cross-sectional	12.68	0.99	0.16	0.02	0.31	$F(1, 163) = 71.54$***
Power longitudinal	12.19	0.70	0.18	0.01	—	$F(1, 44) = 181.98$***
Step width						
Linear cross-sectional	15.17	0.43	– 0.04	0.00	0.34	$F(1, 163) = 82.93$***
Power cross-sectional	27.25	2.57	– 0.21	0.02	0.36	$F(1, 163) = 90.43$***
Power longitudinal	**20.50**	1.69	**– 0.16**	0.02	—	$F(1, 44) = 76.04$***
Dynamic base						
Linear cross-sectional	104.73	2.69	0.29	0.03	0.36	$F(1, 163) = 90.36$***
Power cross-sectional	63.11	3.71	0.17	0.01	0.46	$F(1, 163) = 139.28$***
Power longitudinal	72.20	2.85	**0.14**	0.01	—	$F(1, 44) = 259.21$***
Foot rotation						
Linear cross-sectional	19.48	0.86	– 0.06	0.01	0.21	$F(1, 163) = 43.27$***
Power cross-sectional	36.38	6.20	– 0.25	0.04	0.18	$F(1, 163) = 36.75$***
Power longitudinal	30.07	5.02	– 0.22	0.04	—	$F(1, 44) = 33.41$***
Step length CV						
Linear cross-sectional	0.19	0.01	0.00	0.00	0.18	$F(1, 163) = 35.33$***
Power cross-sectional	0.42	0.08	– 0.31	0.04	0.22	$F(1, 163) = 46.99$***
Power longitudinal	0.43	0.08	– 0.32	0.04	—	$F(1, 44) = 62.57$***
Step width CV						
Linear cross-sectional	0.12	0.01	0.00	0.00	0.11	$F(1, 163) = 20.23$***
Power cross-sectional	0.07	0.01	0.19	0.04	0.10	$F(1, 163) = 17.26$***
Power longitudinal	0.09	0.01	0.15	0.04	—	$F(1, 44) = 16.40$***
Dynamic base CV						
Linear cross-sectional	0.10	0.01	0.00	0.00	0.13	$F(1, 163) = 24.30$***
Power cross-sectional	0.22	0.04	– 0.29	0.04	0.23	$F(1, 163) = 49.68$***
Power longitudinal	0.21	0.03	– 0.28	0.03	—	$F(1, 44) = 71.74$***
Foot rotation CV						
Linear cross-sectional	0.57	0.03	0.00	0.00	0.01	$F(1, 163) = 1.52$***
Power cross-sectional	0.50	0.07	0.03	0.03	0.01	$F(1, 163) = 0.83$***
Power longitudinal	0.54	0.07	0.02	0.03	—	$F(1, 44) = 0.41$***

Note. R^2 is not available for random regression models.
Boldfaced numbers denote statistically significant differences.
***$p < .001$.

across measurements within infants, our longitudinal data do not have sufficient numbers of repeated observations to obtain an unbiased estimate of that quantity.

The changes illustrated in Figure 3 suggest that individual infants' walking may improve by systematic covariation in the various foot-placement measures. Table 5 shows that such systematic intercorrelation is only partly true. During infancy, dynamic base was strongly correlated with step length and step width. Step length was modestly correlated with step width and foot rotation. However, foot rotation showed only small relationships with step width and dynamic base. The wide range in values of correlation coefficients indicates that individual infants may solve the problems of balance and propulsion using idiosyncratic combinations of gait parameters. Note that although all person-time observations ($N = 296$) were used to obtain the most precise estimates of the correlations, the significance tests were conservatively based on the number of distinct infants ($n = 210$).

Effects of Body Dimensions, Testing Age, and Walking Experience

Although each age group showed a wide range in body dimensions, all measures increased across age groups (see Table 6; note, infant data are drawn from the expanded cross-sectional sample). Leg length, for example, increased 165% from infants to adults, height increased 110%, and weight increased 530%. Ponderal Index, the overall chubbiness index, decreased 30% from infant to adults. Only measures of head circumference and Ponderal Index showed overlap between age groups. Within-group standard deviations increased from infancy to adulthood for every measure except Ponderal Index.

Table 6
Age-Related Changes in Body Dimensions (Leg Length, Height, Head Circumference, Crown–Rump Length) and Body Proportions (Ponderal Index)

	Infants	Kindergartners	Adults
Leg length (cm)			
Mean	33.68	57.30	90.11
SD	1.51	2.47	6.89
Height (cm)			
Mean	79.35	115.36	169.44
SD	3.37	3.66	10.28
Weight (kg)			
Mean	10.24	19.73	65.62
SD	1.13	2.13	13.53
Head Circumference (cm)			
Mean	47.61	52.15	57.76
SD	1.63	1.72	2.36
Crown-Rump Length (cm)			
Mean	50.06	62.69	87.97
SD	2.18	2.04	5.34
Ponderal Index			
Mean	2.03	1.28	1.35
SD	0.22	0.09	0.27

For adults, longer bodies predicted longer steps; leg length, height, and crown–rump length were positively correlated with step length (rs = .80, .82, and .69, respectively, all ps < .01). In addition, chubbier bodies predicted wider steps; Ponderal Index was positively correlated with step width ($r = .65$) and negatively correlated with dynamic base ($r = -.67$), all ps < .05. For kindergartners, there were no correlations between body dimensions and gait measures. For infants, partial correlations controlling for test age showed a significant but small correlation only between leg length and step length ($r = .20$, $p < .01$).

Table 5
Correlations Between Mean Values of Footfall Measures in Infants, Kindergartners, and Adults

Age		Step length	Step width	Dynamic base
Infants ($N = 296$[a])	Step width	−0.48***		
	Dynamic base	0.82***	−0.87**	
	Foot rotation	−0.42***	0.14*	−0.30***
Kindergartners ($N = 15$)	Step width	0.17		
	Dynamic base	0.24	−0.91***	
	Foot rotation	0.09	−0.39	0.44
Adults ($N = 13$)	Step width	−0.32		
	Dynamic base	0.54#	−0.96***	
	Foot rotation	−0.11	−0.05	−0.01

[a]P-values are computed conservatively, assuming only 210 available observations.
*$p < .05$. ***$p = .001$. #$p = .06$

A possibility predicted by the pendulum model of walking is that the large changes in leg length from infancy to adulthood cause consequent changes in step length and step width. On this account, if we normalize step length and step width by leg length, the differences between age groups should disappear. However, as shown in Table 7, normalization removed only the differences between kindergartners and adults (note, infant data are drawn from the expanded cross-sectional sample). One-way ANOVAs comparing the three age groups—infants, kindergartners, and adults—showed significant age effects for normalized step length, $F(2, 223) = 7.76$, $p < .001$, and step width, $F(2, 223) = 59.96$, $p < .001$. Post hoc (Tukey's HSD) tests confirmed that infants differed from the two older age groups for both measures (all ps < .05).

Given that improvements in walking skill during infancy were nonlinear, we subdivided infants into three groups according to their test age and walking experience to determine whether normalized distance measures might approximate those of adults in the older, more experienced infant walkers. Table 7 shows that with an increase in infants' test age and an increase in the duration of their walking experience, values of the normalized distance measures began to approach those of kindergartners and adults. Step length represented an increasingly larger proportion of infants' leg length and step width represented a progressively smaller proportion of their leg length. One-way ANOVAs comparing infants, kindergartners, and adults using the subdivisions in infants' test age revealed significant age differences for normalized step length, $F(4, 221) = 7.29$, $p < .001$, and step width, $F(4, 221) = 41.02$, $p < .001$. Post hoc (Tukey's HSD) tests suggested that the differences in age groups were carried largely by the youngest infants. For normalized step length, infants younger than 14 months differed from infants older than 15 months and from kindergartners and adults; infants between 14 and 15 months of age differed from kindergartners and adults (all ps < .05). Infants older than 15 months were statistically indistinguishable from the older age groups. For normalized step width, infants younger than 14 months differed from all older age groups; infants between 14 and 15 months and infants older than 15 months differed from the babies younger than 14 months and from the kindergartners and adults (all ps < .05).

Table 7
Distance Measures Normalized by Participants' Leg Length

Age group	N	Step length/leg length Mean	Step length/leg length SD	Step width/leg length Mean	Step width/leg length SD
Infants	198	0.74	0.15	0.35	0.11
Test age					
< 426 days (< 14 mos)	75	0.70	0.14	0.39	0.12
426–456 days (14–15 mos)	91	0.75	0.15	0.33	0.09
> 456 days (> 15 mos)	32	0.81	0.10	0.29	0.08
Walking experience					
0–60 days	83	0.65	0.15	0.42	0.11
61–120 days	76	0.79	0.11	0.31	0.07
> 120 days	39	0.83	0.10	0.28	0.07
Kindergartners	15	0.86	0.14	0.15	0.06
Adults	13	0.85	0.08	0.10	0.04

Similarly, one-way ANOVAs comparing infants, kindergartners, and adults using the subdivisions in infants' walking experience revealed significant group differences for normalized step length, $F(4, 221) = 24.39$, $p < .001$, and step width, $F(4, 221) = 69.05$, $p < .001$. Post hoc (Tukey's HSD) tests suggested that differences between infants and the older age groups were carried primarily by the least experienced infants. For normalized step length, infants with less than 2 months of walking experience differed from all of the other groups. Infants with more than 2 months of experience were statistically indistinguishable from kindergartners and adults. For normalized step width, infants with less than 2 months of experience differed from more experienced infants, kindergartners, and adults; infants with 2 to 4 months of experience were indistinguishable from infants with more than 4 months of experience and both groups differed from kindergartners and adults (all ps < .05).

We compared the contributions of measures of infants' changing body dimensions, chronological age at testing, and duration of walking experience with their level of walking skill in a series of correlational and hierarchical regression analyses. Table 8 shows the zero-order correlations among measures of infants' body dimensions, testing age, walking experience, and walking skill based on data from the expanded cross-sectional sample. The measures were highly intercorrelated. Larger babies tended to be bigger on every dimension (values of r ranged from .29 to .78 for correlations among weight, height, leg length, crown–rump length, and head circumference, all ps < .001). Chubbier infants tended to have a larger Ponderal Index ($r = .32$, $p < .001$) and to be taller and have longer body segments (r ranged from –.31 to –.58, all ps < .001). Testing age and walking experience were moderately correlated ($r = .58$, $p < .001$), and both factors were correlated with

Table 8
Correlations Between Measures of Body Dimensions, Testing Age, Walking Experience, and Walking Skill in Infants

	Measures							
	Leg.	Height	Crown–rump	Weight	Head	Ponderal index	Age	Experience
Height	.68***							
Crown–rump length	.47***	.78***						
Weight	.52***	.59***	.59***					
Head circumference	.29***	.38***	.34***	.53***				
Ponderal index	– .31***	– .58***	– .32***	.32***	.06			
Test age	.46***	.42***	.25***	.19**	.21***	– .34***		
Walk experience	.35***	.23***	.16*	.09	.03	– .20**	.58***	
Step length	.35***	.27***	.23***	.17*	.07	– .21**	.43***	.59***
Step width	– .19***	– .08	– .11	– .04	– .04	.13	– .42***	– .55***
Dynamic base	.28***	.15*	.15*	.08	.05	– .18*	.47***	.62***
Foot rotation	– .14*	– .11	– .07	– .02	– .02	.12	– .29***	– .50***

*$p<.05$. **$p<.01$. ***$p<.001$.

several measures of body dimensions. Testing age was negatively correlated with Ponderal Index ($r=-.34$, $p<.001$) and positively correlated with each of the other body measures (values of r ranged from .19 to .46, all ps $<.01$). Walking experience was negatively correlated with Ponderal Index ($r=-.20$, $p<.01$) and positively correlated with height, leg length, and crown–rump length (values of r ranged from .16 to .35, all ps $<.05$). Overall, testing age and walking experience were more strongly correlated with walking skill than were measures of body dimensions. Both age and experience predicted larger step lengths ($r=.43$ and .59, respectively, all ps $<.001$) and dynamic base angles ($r=.47$ and .62, respectively, all ps $<.001$) and smaller step widths ($r=-.42$ and $-.55$, respectively, all ps $<.001$) and foot rotations ($r=-.29$ and $-.50$, respectively, all ps $<.001$). By examining scatter plots of the correlations, we verified that the smaller correlations between walking skill and body dimensions were not due to nonlinear relations.

The intercorrelations among body dimensions, testing age, and walking experience shown in Table 8 suggest that the underlying factors they represent—endogenous body growth, neural maturation, and practice walking—may have bidirectional effects and share common variance in improvements in walking. Thus, we performed a series of hierarchical regression analyses to determine the unique contribution of each variable in predicting respective foot-placement measures. Hierarchical regression involves entering variables sequentially in blocks. The model controls for the effects of variables entered in earlier blocks so that we may assess the unique contribution of the final block of variables based on the size of the change in the value of R^2. To make the interpretation of the R^2 clear as a proportion of between-infant variation, we carried out these analyses on the expanded cross-sectional data set, which includes 210 infants, each measured at one time point.

Because all of the explanatory variables except walking experience have linear associations with measures of walking skill, we carried out regression analyses using linear multiple regression methods. However, because we know that walking experience is better represented by a power function than by a linear model for step length, step width, and dynamic base, we approximated the power function by fitting a segmented linear model for those measures. One segment fits a steep slope between 0 and 120 days of walking experience, and another segment fits a more gradual slope from 120 days onward. We do not claim that the 120-day cut point is optimal, but it appears to be adequate in that it accounts for more than half of the additional variance that the power function fits over the linear model. No single cut point accounted for all of the variance of the power function, and an empirical approach to finding the best cut point suggested that multiple segments were needed to approximate optimally the power function. In the hierarchical regression analysis, we entered both segments together in a single block.

We tested two hierarchical regression models: (a) an age and maturation model, in which we examined the contribution of testing age after controlling for infants' body dimensions and dura-

Table 9
Hierarchical Regressions Comparing Age Model and Experience Model of Effects of Body Dimensions, Testing Age, and Walking Experience on Infants' Level of Walking Skill

Dependent measure	Predictor	B	R^2	
		Final model	Age model	Experience model
Step length				
	Body dimensions		0.16***	0.16***
	Leg (cm)	0.12		
	Height (cm)	− 0.85		
	Crown–rump (cm)	− 0.02		
	Weight (kg)	3.02		
	Head (cm)	− 0.25		
	Ponderal Index	− 13.47		
	Test age (days)	0.01	0.00	0.09***
	Walk experience		0.29***	0.20***
	< 120 days	0.08***		
	> 120 days	− 0.03***		
		$R^2 = .45$		
		$F(9, 163) = 14.93$***		
Step width				
	Body dimensions		0.07	0.07
	Leg	− 0.02		
	Height	0.35		
	Crown–rump	− 0.03		
	Weight	− 0.67		
	Head	− 0.12		
	Ponderal Index	3.33		
	Test age	− 0.01	0.01	0.12***
	Walk experience		0.32***	0.21***
	< 120	− 0.05		
	> 120	0.02		
		$R^2 = .40$		
		$F(9, 163) = 12.26$		
Dynamic base				
	Body dimensions		0.12**	0.12**
	Leg	0.64		
	Height	− 3.29		
	Crown–rump	− 0.04		
	Weight	8.47		
	Head	0.10		
	Ponderal Index	− 41.51		
	Test age	0.06	0.01	0.13***
	Walk experience		0.38***	0.26***
	< 120	0.38***		
	> 120	− 0.16***		
		$R^2 = .50$		
		$F(9, 163) = 18.25$***		
Foot rotation				
	Body dimensions		0.04	0.04
	Leg	0.60		
	Height	2.00		
	Crown–rump	0.04		
	Weight	− 5.59		
	Head	0.09		
	Ponderal Index	28.81		
	Test age	0.01	0.00	0.06
	Walk experience	− 0.06***	0.25***	0.19***
		$R^2 = .29$		
		$F(8, 164) = 8.49$***		

**$p < .01$. ***$p < .001$.

tion of walking experience, and (b) an experience and practice model, in which we examined the contribution of walking experience after controlling for infants' body dimensions and testing age. Table 9 shows the change in R^2 values for the block of variables representing infants' body dimensions, test age, and walking experience for each model, the total explained variance in the final model, the unstandardized coefficients for the final model, and the F statistic for the regression equation with all variables entered into the final model.

For the age and maturation model, we entered the set of body measures in the first block (leg length, height, crown–rump length, weight, head circumference, and Ponderal Index), the two segments characterizing walking experience in the second block, and testing age in the third block. As shown by the change in R^2 values in Table 9, across footfall measures, body dimensions explained 4% to 16% of the variance in the first block and walking experience accounted for an additional 25% to 38% of the variance in the second block. On the third block, after controlling for the joint effects of body dimensions and walking experience, testing age accounted for only a negligible amount of unique variance (0% to 1%).

In the data set restricted to one measurement per infant ($n = 210$), the unique effect of testing age, after adjusting for body dimensions and walking experience, was not statistically significant. We also examined testing age using the full set of available measurements ($N = 251$ when missing body dimension data are taken into account). In this supplemental analysis, we used random regression to take into account the repeated measures of infants observed longitudinally. Testing age was statistically significant when predicting step length and dynamic base in this larger sample, but it still accounted for only minimal variability of these variables.

For the experience and practice model, we entered body dimensions in the first block as before (thus, the change in R^2 is identical in the age and experience models), but reversed the order of entry for age and experience—testing age in the second block and walking experience in the third block. Table 9 shows that after controlling for body dimensions, across footfall measures, testing age accounted for an additional 6% to 13% of the variance. On the third block, after controlling for the joint effects of body dimensions and testing age, walking experience explained an additional 19% to 26% of unique variance. In the final model with all variables entered, none of the body dimensions nor testing age made an important independent contribution in predicting walking skill. Experience retained its predictive value for all measures.

Discussion

Independent walking is one of infants' most important and readily observable achievements. As such, infant walking provides an excellent model system for investigating the process of developmental change—what changes when children acquire new skills, the trajectory of the changes over time, and the underlying factors that drive the developmental trajectory. Despite a century of elegant research on infant walking, we still lack a formal characterization of the developmental process. Previous research was directed toward understanding why infants walk when they do. This study focused on understanding why walking improves.

The Footfall Method

Our method of collecting trails of inked footprints provides quick, inexpensive, and reliable foot-placement measures of walking skill in infants, kindergartners, and adults. We improved on earlier footfall methods in several ways. First, we showed that inked footprints can reliably characterize participants' walking patterns at a particular time. This is especially critical for infants whose walking skill changes dramatically over a short period. Second, we demonstrated that a moving frame of reference provides more sensitive and accurate distance measures than does a fixed Cartesian frame of reference. To the extent that walkers deviate from a straight path, a fixed frame of reference will consistently underestimate stride and step length and overestimate step width. Accordingly, we found small but highly reliable discrepancies between fixed and moving reference frames. The discrepancies were magnified in infants, who are more likely to display a staggering, drunken path of progression than are older children and adults. Thus, we suggest that researchers consider adopting the moving reference frame, especially if testing new or handicapped walkers. Third, we devised the dynamic base measure to index developmental changes in infants' control over the path of progression. The straighter and narrower the path, the more closely the dynamic base angle will approach 180 degrees. Fourth, because our footfall method is nonintrusive and requires no special recording equipment, it is well suited for collecting foot-placement measures in clinical populations and in environments outside the laboratory. Finally, because the method is quick and efficient, we were able to collect data from a relatively large sample of infants, both cross-sectionally and longitudinally. As a result, we were able to use hierarchical regression analyses to test formally the independent effects of distal developmental factors on improvements in walking skill.

What Changes in Walking

Age differences. The footfall method replicated and extended previous findings of characteristic changes in walking skill with age and experience. Mean values of step length increased threefold over the infancy period, step width and foot rotations showed equally dramatic decreases, and the new dynamic base measure showed an increasingly straight path of progression. A lingering argument in the literature concerns the time frame of development. In terms of mean values, we found that infants differed from kindergartners and adults on every gait measure, but there was no evidence of further improvement from the kindergarten to adult age groups. Although mean values of step length doubled from kindergartners to adults, these changes were paralleled, of course, by enormous changes in body growth. As predicted by the pendulum model (Townsend, 1981; Winter, 1995), when we normalized step length by participants' leg lengths, the differences between kindergartners and adults disappeared. However, improvements from infancy to the two older age groups were not simply due to the growth of participants' legs. After normalization, younger, less experienced infants continued to show significant decrements compared with kindergartners and adults, and normalized step length was positively correlated with walking experience ($r = .49$). In contrast to findings for mean values, there were developmental changes beyond the infancy period in children's ability to reproduce their movements consistently over the entire path of progression. Average coefficients of variation differed between kindergartners and adults for step length and foot rotation.

The pattern of intercorrelations among mean values of foot-placement measures also differed between infants and the two older age groups. In kindergartners and adults, only dynamic base and step width were correlated (narrower step widths predicted larger base angles) although the positive correlation between dynamic base and step length approached significance in adults. These findings suggest that the key difference between the older walkers was how far apart they planted their heels laterally. In contrast, all mean values of foot-placement measures were significantly correlated in infants. The pattern of correlations followed the general developmental trend of a narrowing base of support. Larger dynamic base angles tended to be accompanied by a larger front-to-back distance between the feet, a smaller side-to-side distance between the heels, and a greater tendency to point the toes more straight ahead. Longer step lengths and narrower step widths tended to be accompanied by less foot rotation.

The modest size of some of the correlations and the large range of values in footfall measures among infants equated for walking experience points to considerable individual variation in characteristics of early walking and in subsequent paths of improvement. In fact, in the first month of walking, 58% of infants produced step widths within the adult range and 29% produced adult-like values of foot rotations. One potential explanation is that infants differed in the degree to which they had problems with balance and propulsion in early walking and, as a consequence, solved these problems in idiosyncratic ways. For example, McGraw (1945) described one type of infant whose postural control mechanisms may be developed in advance of their leg and hip strength. These ''steppers'' maintain narrower step widths but compensate for weak muscles by taking short slow steps and pointing their toes to the sides like a duck. ''Headlong fallers,'' whose strength develops in advance of postural control, take longer, faster steps but compensate for poor balance by maintaining a wider distance between their legs and collapsing at the end of the path into their caregivers' arms. More recently, McCollum, Holroyd, and Castelfranco (1995) suggested additional walking types, such as ''twisters'' who capitalize on balance skills in the sagittal plane while minimizing forward momentum and vertical movements that require excessive leg strength.

An alternative explanation, also first suggested by McGraw (1935), is that the wide range in infants' performance does not reflect stable compensatory strategies for individual differences in strength and balance. Rather, the variability reflects infants' ad hoc response to the outcome of their last step. On this account, development proceeds from a process of step-to-step recovery to the ability to control the overall path of progression. New walkers may take several long fast steps if they find their bodies leaning too far forward and take a few wobbling duck steps if they find their bodies in a vertical position or tipping sideways. The results of the current study are consistent with the alternative explanation based on ad hoc compensation. Over the first few months of independent walking, there was a dramatic decrease in step-to-step variability as indexed by the coefficients of variation and a dramatic increase in the straightness of path as indexed by the dynamic base angle. Nonetheless, richer longitudinal data would better tease apart whether infants display individual balance control strategies or simply react to the current biomechanical constraints on balance.

Developmental trajectory. As noted by earlier researchers, improvements in the mean values of each measure of walking skill were nonlinear (e.g., Bril & Breniere, 1992; McGraw, 1940; Shirley, 1931). In other words, at certain periods in development infants "get a bigger bang for their buck" than at other periods in development. Typically, developmental trajectories have unspecified time-related mechanisms on the *x* axis (children's chronological age or days of experience). Thus, nonlinearities in the trajectory can help direct researchers' attention to critical periods of change and to constrain theorizing about the underlying mechanisms that are driving the change. In infant walking, the trajectory was negatively accelerated. Improvements appeared fastest in the first few months of infant walking, then began to asymptote over the next few months. A formal comparison between a linear fit of the data and a power function confirmed that the changes during infancy were nonlinear for step length, step width, and dynamic base. The segmented regression analysis suggests that the sharpest bend occurs at approximately 4 months.

In contrast to other developmental trajectories that may spurt upward after a slow start (Fenson et al., 1994) or temporarily regress in a U-shaped function (Bower, 1976), negatively accelerated functions are typical of performance curves in perceptual-motor learning tasks (Schmidt & Lee, 1999). In classic skill-learning tasks such as rotary pursuit, mirror writing, and aiming at a target, improvements in performance are plotted against practice, represented by trials or time on task. The similarity between the formal shape of the trajectory of infant walking with those in perceptual-motor learning tasks suggests that processes similar to those in the skill-learning tasks may underlie improvements in infant walking. For example, in the motor-learning literature, researchers have proposed that the initial phase where the learning curve is steepest may reflect participants' efforts to find the various combinations of parameters that allow them to approximate the target skill (Bilodeau & Bilodeau, 1969; Schmidt & Lee, 1999; Whiting, 1984)—in this case, infants' struggle to discover the various parameters that allow forward progression and balance (Bril & Breniere, 1992, 1993; Bril & Ledebt, 1998). The subsequent period of more gradual change may reflect attunement, honing, and automazation processes (Anderson, 1982; Schmidt & Lee, 1999), where children fine-tune the values of different gait parameters to maximize the biomechanical efficiency of walking.

Part of the honing process in mastering a cyclical activity such as walking involves reproducing movements regularly and consistently from step to step (Bernstein, 1996; Vereijken, van Emmerik, Bongaardt, Beek, & Newell, 1997). Thus, in addition to describing developmental changes in mean values as is traditionally reported, we also describe changes in the variability of walking. To facilitate comparisons across weeks of walking experience and across different age groups, we report the average coefficient of variation (standard deviations normalized by means). Like mean values, coefficients of variation showed significant improvement over the infancy period for step length and dynamic base, and the changes were nonlinear. Toward the end of the infancy period, the consistency and reproducibility of infants' step lengths and dynamic base angles began to approach that of mature walkers (a general rule of thumb for interpreting coefficients of variation is that values less than .10 signify stable behaviors). Coefficients of variation actually increased for step width because standard deviations increased as infants became able occasionally to narrow the lateral distance between their feet.

Underlying Developmental Factors

A central aim of the present study was to further our understanding about the source of change in the development of walking. Our conceptualization of the problem of understanding why walking improves was guided by previous investigations into why infants walk when they do. We begin with the problem of walking onset.

Why infants walk when they do. Since the 1930s, there has been widespread agreement among researchers that strength and balance are the proximal cause of walking onset. However, the same groups of researchers who share consensus about the proximal cause of walking onset have engaged in a heated 70-year debate about the distal cause—the developmental factors that may facilitate increased strength and balance. The debate was sparked by interest in the mysterious U-shaped trajectory of infants' stepping movements (newborns' "stepping reflex," its subsequent disappearance at approximately 8 weeks of age, and the reappearance of upright steps when infants begin walking independently toward the end of the first year). The real fuel on the fire, however, concerns what is at stake theoretically—the respective roles of biomechanical factors, neural maturation, and experience and how we should think about their independent and joint effects.

One possibility is that peripheral, biomechanical factors may play the critical role in determining why infants step and walk when they do. For example, Thelen and colleagues (Thelen, 1984a; Thelen & Fisher, 1982; Thelen et al., 1984; Thelen, Fisher, Ridley-Johnson, & Griffin, 1982) showed that redistribution of leg fat and muscle mass may explain infants' changing ability to display the upright stepping pattern. During the newborn period, slimmer babies produce more steps than chubbier babies. Babies who normally produce stepping movements appear glued to the floor when their legs are weighted to simulate normal gains in leg fat. Babies who have graduated from the newborn stepping stage once again take steps when their legs are submerged in a tank of water to alleviate the effects of gravity. Similarly, babies who are naturally slimmer and more cylindrically proportioned begin walking sooner than do chubbier, more top-heavy infants (Adolph, 1997; McGraw, 1945; Shirley, 1931). New walkers topple over when they are weighted to simulate their earlier, more babyish proportions (Vereijken et al., 2002).

A second possibility is that maturation of the central nervous system may be responsible for newborn stepping and later walking. Some researchers claim that the maturing cortex suppresses the infantile stepping reflex and then regenerates the alternating leg pattern under cortical control (Forssberg, 1985; McGraw, 1932, 1935, 1945). Others propose that the maturing central nervous system co-opts the primitive neuromotor pattern when infants become motivated to move in an upright position and that independent walking becomes possible after sufficient maturation of information processing capabilities (Zelazo, 1998; Zelazo et al., 1989).

A third possibility is that practice is the critical factor for the developmental course of stepping and walking. Daily practice of the newborn stepping pattern delays or eliminates its disappearance and initiates an earlier onset of independent walking (Zelazo et al., 1972). Practice in supported walking (walking while holding onto furniture or a caregiver's hands) typically precedes independent walking by several weeks (Frankenburg & Dodds, 1967). According to practical wisdom, supported walking could teach infants to walk by providing babies with motivation to move in an upright position, strengthening leg and torso muscles through exercise, and giving infants experiences with upright balance control (Haehl, Vardaxis, & Ulrich, 2000; Metcalfe & Clark, 2000).

Why walking improves. Like walking onset, researchers largely agree that strength and balance are the proximal cause of improvements in walking skill. However, in contrast to the controversy surrounding the distal cause of walking onset, assumptions regarding the distal source of walking improvements have gone unchecked. In accordance with shifting intellectual fashions regarding the roles of maturation and learning, researchers have implicitly highlighted one factor over another. The early pioneers in the 1930s and 1940s plotted improvements in walking skill with age along the *x* axis, suggesting that maturation drives the developmental progression (e.g., McGraw, 1945). Since the 1980s, researchers have plotted similar graphs with walking experience along the *x* axis, suggesting that practice is the critical underlying factor (e.g., Bril & Breniere, 1989).

In this study, we aimed to put implicit assumptions about underlying developmental factors to the test. We reasoned that the three purported candidates for driving the onset of independent walking—body build, neural maturation, and practice—are also likely to affect its improvement. We measured body dimensions directly in the laboratory and used the Ponderal Index (a ratio of weight to height) to estimate infants' overall chubbiness. As is customary, we indexed neural maturation and walking experience only indirectly, using infants' chronological age as a crude estimate of neural maturation and days elapsed since walking onset as a crude estimate of the amount of practice walking. Note that the use of number of days to index testing age and walking experience gives us a logical purchase on the direction of causality. Logically, the underlying factor represented by number of days could be responsible for improvements in walking skill. However, it is illogical to suppose that walking skill could affect the number of days elapsed since infants' birth date or walking onset date.

Body dimensions, testing age, and walking experience are intercorrelated; older children tend to have larger bodies and more walking experience. More important, the developmental factors that these measures represent are likely to have bidirectional and interactive effects. For example, practice walking may promote brain development and build muscle strength. Reciprocally, faster perceptual-motor processing and more efficient muscle actions due to neuromuscular maturation and body growth may facilitate walking at earlier ages and thereby allow infants to acquire more days of practice walking. Similarly, brain maturation and body growth may encourage infants to obtain more practice walking after the date of onset.

We teased apart the relative contributions of body growth, neural maturation, and practice walking to improvements after walking onset by statistically controlling for the combined effects of the various factors in a series of hierarchical regression analyses. Changing body dimensions did not explain improvements in walking skill independent of infants' testing age and duration of walking experience. Likewise, testing age did not make an important unique contribution to the observed improvements in infants' walking skill independent of their body dimensions and duration of walking experience. In contrast, walking experience played the single most important role in the development of walking skill. After controlling for body dimensions and testing age, walking experience explained an additional 19% to 26% of the variance. With walking experience in the final model, no measures of body dimensions or test age made significant contributions. Note, however, that because the validity of our indices differed, results must be interpreted with caution. In particular, our use of chronological age to index brain maturation was necessarily the least direct measure and possibly the most noisy. Nonetheless, the results of the regression analyses are especially robust given that seven conceptually plausible variables were entered into the model before testing the effect of walking experience.

Effects of practice. How might practice walking facilitate improvements in strength and balance? One line of suggestive evidence comes from a set of prospective diary studies aimed at describing the actual content of infants' everyday locomotor experience (Adolph, 2002; Adolph, Biu, Pethkongathan, & Young, 2002; Adolph & Eppler, 2002; Chan, Lu, Marin, & Adolph, 1999; Chan, Biancaniello, Adolph, & Marin, 2000; Young, Biu, Pethkongkathon, Kanani, & Adolph, 2002). Using a battery of convergent methods (daily checklists, telephone diaries, tiny foot switches, etc.), the diary studies quantified how frequently infants locomote, the places they go, how often they go there, how far they travel, what surfaces and paths they traverse, and the frequency of mishaps en route.

Despite large individual differences in infants' opportunities for learning, several findings emerge consistently from the diary data. First, the evidence speaks against one-trial learning from serious falls, that is, some sort of fast mapping between perceptual information for disequilibrium and the aversive consequences of falling (Bertenthal et al., 1984). In accordance with previous retrospective studies, few parents reported that their infants incurred serious falls during everyday locomotion and those infants that did fall did not display more mature gait patterns or respond more adaptively in challenging tasks in the laboratory than did infants who did not experience serious mishaps (Adolph, 1997; Scarr & Salapatek, 1970).

In contrast to one-trial learning from negative experiences, the diary data point to epochs of learning from generally positive experiences. Infants' everyday experiences with locomotion occur in truly massive doses, reminiscent of the immense amounts of daily practice that promote expert performance in world-class musicians and athletes (Ericsson & Charness, 1994; Ericsson, Krampe, & Tesch-Romer, 1993). For example, walking infants practice keeping balance in upright stance and locomotion for more than 6 accumulated hours per day. They average between 500 and 1,500 walking steps per hour so that by the end of each day, they may have taken 9,000 walking steps and traveled the length of 29 football fields (Adolph, 2002; Adolph & Eppler, 2002).

Albeit intense, infants' practice regimen is not like an enforced march of massed practice where walking experiences are concentrated into continuous time blocks. If practice were massed, the sheer amounts of daily practice would be even more astounding (the average cadence for a 14-month-old toddler walking over the laboratory floor, for example, is 190 steps per minute). Rather, infants' walking experience is distributed throughout their waking day, with short periods of walking separated by longer rest periods where infants stand still or play. Moreover, experiences with upright locomotion are distributed across days. Most infants take their first independent walking step several weeks before passing criterion for walking onset, and most infants display long transition periods during which they pass criterion for walking on some days but not on others (Adolph et al., 2002; Young et al., 2002). As in laboratory studies showing benefits of distributed over massed practice, infants' intermittent experiences with locomotion within the course of each day and across their first few months of walking may provide them with time to consolidate learning and to allow fatigue and flagging motivation to dissipate (Schmidt & Lee, 1999).

Nor is infants' walking experience equivalent to a dull, rote routine of blocked practice, where infants perform the same movements over and over in the same environmental contexts. Rather, the diary studies showed that infants' everyday walking experiences occur in a wide variety of events, places, and surfaces. Regardless of whether infants grow up in three-story homes in the suburbs or tiny Manhattan apartments, each day babies travel over nearly a dozen different indoor and outdoor surfaces varying in friction, rigidity, and texture. They visit nearly every room and functional area in their homes (Chan, Marin, and Adolph, 1999; Chan et al., 2000). The variety of everyday walking experience resembles variable and random practice schedules, where environmental conditions such as stimulus increment and trial order vary from one attempt to the next. In the laboratory, variable and random practice leads to deficits in performance during learning, but ultimately facilitates greater flexibility and transfer under novel conditions (Gentile, 2000; Schmidt & Lee, 1999). A classic explanation for the differences between blocked and variable or random practice is that blocked schedules lead to the repetition of a particular solution on successive trials but that variable and random schedules lead to a process of continually generating solutions anew.

In sum, the magnitude, distributed nature, and variability of infants' walking experience may lie at the heart of developmental change. Thousands of daily walking steps, each step slightly different from the last because of variations in the terrain and the continuously varying biomechanical constraints on the body, may help infants to identify the relevant combinations of parameters for strength and balance and finally to hone and fine-tune their values. All of these steps in a body and world that are continuously changeable may lead infants to acquire more efficient recruitment of their leg and hip muscles, better exploitation of passive forces, and more refined differentiation of the perceptual information required for maintaining balance.

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