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Go Naked: Diapers Affect Infant Walking

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Abstract

In light of cross-cultural and experimental research highlighting effects of childrearing practices on infant motor skill, we asked whether wearing diapers, a seemingly innocuous childrearing practice, affects infant walking. Diapers introduce bulk between the legs, potentially exacerbating infants' poor balance and wide stance. We show that walking is adversely affected by old-fashioned cloth diapers, and that even modern disposable diapers—habitually worn by most infants in the sample—incur a cost relative to walking naked. Infants displayed less mature gait patterns and more missteps and falls while wearing diapers. Thus, infants' own diapers constitute an on-going biomechanical perturbation while learning to walk. Furthermore, shifts in diapering practices may have contributed to historical and cross-cultural differences in infant walking.

Childrearing practices affect motor development. Cultural and historical differences in how caregivers handle, dress, and toilet their infants can have profound effects on whether infants acquire certain motor skills, the age at which skills are acquired, and the subsequent developmental trajectory (Adolph, Karasik, & Tamis-LeMonda, 2010; Adolph & Robinson, in press). For example, in some African and Caribbean cultures, caregivers use special handling and exercise routines to facilitate the onset of sitting and walking—propping infants into sitting postures, practicing upright stepping, stretching infants' limbs, and suspending infants by ankles or wrists (Bril & Sabatier, 1986; Hopkins & Westra, 1988; Rabain-Jamin & Wornham, 1993). Such daily exercise results in earlier onset of sitting and walking relative to Western norms (Hopkins & Westra, 1989, 1990). Crawling, a skill not exercised or encouraged, may be delayed or skipped altogether.

Historical changes in handling practices within a culture show similar effects. Within a decade, the "Back to Sleep" campaign instituted by the American Academy of Pediatrics reversed the long-time practice of putting infants to sleep on their bellies to putting infants to sleep on their backs (Willinger, Ko, Hoffman, Kessler, & Corwin, 2000). Although successful in reducing the incidence of Sudden Infant Death Syndrome, the change in handling practices had the unintended effect of delaying prone skills such as crawling and rolling (Davis, Moon, Sachs, & Ottolini, 1998). A follow-up "Tummy Time" campaign urged mothers to compensate for the lost prone experience by giving infants playtime on their stomachs. Subsequent research demonstrated a dose-response relation between awake time in a prone position and the onset age of prone skills (Majnemer & Barr, 2005).

Experimental evidence supports the facilitative effects of infant exercise. A few minutes of daily practice can alter the course of motor development (Clark, Kreutzberg, & Chee, 1977; Lagerspetz, Nygard, & Strandvik, 1971). For example, with no intervention, infant stepping has a U-shaped trajectory: Newborns supported in an upright position exhibit stepping movements, but stepping disappears between 2 and 8 months, and reappears when infants begin learning to walk (McGraw, 1932; Thelen, Fisher, & Ridley-Johnson, 1984). However,

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just 12 minutes of daily practice executing stepping movements in an upright position increases the frequency of newborn stepping, maintains stepping during the dormant period when stepping normally disappears, and accelerates the onset of independent walking compared to infants who receive only passive exercise (Zelazo, Zelazo, & Kolb, 1972). Similarly, 15 minutes of daily practice fighting gravity in prone, sitting, and upright positions between 2 and 3 months of age results in earlier onset ages for crawling, sitting, and walking compared to infants who receive comparable amounts of time engaged only in social interactions (Lobo & Galloway, in press).

Various historical and cultural differences in dress also affect motor development. In the 19th century, 40% of American infants skipped crawling, possibly because their long flowing gowns impeded movement on hands and knees (Trettien, 1900). More recently, infants who wear thick winter clothes or sleep under heavy blankets show delays in prone skills such as crawling (Bensen, 1993; Hayashi, 1992), and tight leggings reduce the frequency of upright stepping movements in 2- to 4-month-olds (Groenen, Kruijsen, Mulvey, & Ulrich, 2010).

Toileting practices can also have dramatic effects on motor development. In parts of Northern China where water is scarce, caregivers lay infants on their backs inside bags filled with fine sand for most of each day. The sandbags effectively absorb waste and keep infants clean, but severely restrict infants' movements and lead to substantial delays in sitting and walking compared to children from comparable areas who were not sandbagged (Mei, 1994; Xie & Young, 1999). Here we ask whether a less dramatic solution to toileting—wearing diapers—might also affect infant motor development. Specifically, we asked whether diapers affect the proficiency of early walking. Because diapers introduce bulk between the legs and may constrain infants' leg movements, diapers may exacerbate infants' already immature gait.

In the current study, we compared infants' walking while naked, wearing a modern, thin disposable diaper, and wearing an old-fashioned, thick, cloth diaper. The three conditions provided a crude gradation in overall bulk and were designed to reflect historical and cultural differences in diapering. We collected standard measures of infant walking skill to assess effects of diapers on the maturity of infants' gait. For nearly 100 years, researchers have characterized the maturity of infant gait in terms of step width and step length: A narrower side-to-side distance between the feet and a longer front-to-back distance between feet are indicative of more mature gait patterns (Bril & Breniere, 1989; Shirley, 1931). In addition, we measured functional outcomes—whether infants misstepped or fell—to assess whether diapers make it more difficult to walk.

To test the differential effects of diapers on novice and experienced infant walkers, we observed 13-month-olds, an age when most infants have just begun walking, and 19-month-olds, an age when improvements in walking skill have begun to reach asymptote (Adolph, Vereijken, & Shrout, 2003; Bril & Breniere, 1989; Hallemans, De Clercq, & Aerts, 2006). For novice walkers, falling is common—100 times a day—and gait patterns are notoriously immature; the side-to-side distance between infants' feet may be larger than the front-to-back distance (Adolph et al., in press). Walking in novices is more adversely affected by load carrying (weights strapped to their waists or carried in shoulderpacks) and variations in the ground surface (slopes, cliffs, and so on) compared with more experienced walkers (Adolph, 1997; Garciaguirre, Adolph, & Shrout, 2007; Kretch & Adolph, in press; Vereijken, Pedersen, & Storksen, 2009). Thus, walking may be more disrupted by diapers in the 13-month-olds because a small perturbation could exacerbate their already precarious walking skill. Alternatively, because novice walkers already take wide, immature steps, they may be less susceptible to the bulk of diapers than more experienced infants. Finally, to separate effects of bulk from effects of novelty, mothers reported their normal diapering practices and how much time infants were allowed to walk naked.

Method

Participants

We tested 30 13-month-olds and 30 19-month-olds. Infants were predominantly white and middle class. An additional three 19-month-olds did not complete testing due to fussiness. Mothers reported in a structured interview the first day they saw their infants walk at least 10 feet continuously—our definition of walking onset. Walking experience data from 3 13-month-olds were not available. As shown in Figure 1, the range in walking experience within age groups was considerable, and the overlap between the two age groups was minimal. The 13-month-olds had 8 to 97 days of walking experience (M = 45.25 days); the 19-month-olds had 58 to 289 days (M = 192.07 days); overall, the older group was more experienced than the younger group, $t(55) = 12.44$, $p < .001$.

Outside the laboratory, most infants normally wore disposable diapers (90% of 13-month-olds and 93.3% of 19-month-olds) identical or similar to the brand we used for testing. Only one 13-month-old and one 19-month-old normally wore cloth diapers. Based on mothers' reports, infants were allowed to walk naked M = 41 min a week; 73% had some experience walking naked and 27% never walked naked.

Apparatus and Procedure

Infants walked repeatedly (M = 7.31 trials per condition, SD = 1.53) over a 5.73-m long × 0.92-m wide pressure-sensitive gait carpet (www.gaitrite.com) while wearing each type of diaper (Figure 2A). The carpet had a spatial resolution of 1.27 cm. If infants veered off the carpet, stopped immediately, or fell, we repeated the trial, aiming for at least 6 trials per diaper condition. The order of diaper conditions was counterbalanced.

The disposable diaper used in testing was a common commercially available brand in sizes 3–5, weighing between 32 and 41 g depending on size. Infants were tested in the size diaper they typically wore. Measured flat on a table, all three sizes of disposable diaper were 7.5 cm across by 1.1 cm thick at the crotch. The cloth diaper weighed 170 g and was folded for nighttime use, making the crotch 12.3 cm across and 2.8 cm thick. Infants' diapers were changed if they became soiled during testing.

At the end of the session, an experimenter measured each infant's leg lengths (from hip to ankle) and recumbent height (crown to heel). Due to fussiness and experimenter error, leg length data were missing from nine infants and height data were missing from eight infants.

Data Coding and Processing

Using the video coding software OpenShapa (www.openshapa.org), we identified trials with at least five consecutive steps on the carpet. These trials were then scored for disruptions of alternating gait: falls (when the body dropped to the floor unsupported) and missteps (trips when the swinging foot failed to clear the ground, double steps when the same foot stepped twice, back steps when the leading leg moved backward behind the trailing leg, and lag steps when the swinging leg moved forward but failed to move ahead of the stance leg).

We calculated gait parameters based only on instances where infants took several consecutive steps at a relatively steady state velocity, as is customary (Bril & Breniere, 1989). Thus, we removed portions of trials that included falls/missteps or gait initiation (the first two steps on the gait carpet) and used only the trials with at least five consecutive steps remaining ($M = 9.42$ steps). Gait data from three infants were unavailable due to veering off the carpet and gait disruptions. Figure 2B shows the calculation of gait parameters. Using the raw x-y coordinates generated by the gait carpet, a customized software program calculated *step width* (distance from the heel of the current step to the line of progression formed by the opposite stride), *step length* (distance along the line of progression from the heel of the previous step to the heel of the current step), *dynamic base of support* (angle between the heel points of three consecutive steps), and *walking speed* (distance between the first to last step divided by time). Because previous work showed that infants' walking speed is highly correlated with other gait parameters and generally reflects infants' highest level of walking skill (Garciaguirre et al., 2007), we analyzed each infant's two fastest trials in each condition.

Results

Gait Disruptions

Walking in diapers had a functional cost, especially in the 13-month-old novice walkers. When walking naked, 10 of the 30 13-month-olds fell or misstepped at least once. While wearing the cloth diaper, 21 of them fell or misstepped. In contrast, 19-month-olds rarely fell or misstepped, and 17 walked free of disruptions across all conditions. But when 19-month-olds did display gait disruptions, they usually did so while wearing a cloth diaper: Only four of the experienced infants had a gait disruption walking naked, whereas eight did so in the cloth diaper. In the 13-month-olds, the frequency of disruptions across trials decreased with days of walking experience, $r(28) = -.39$, $p = .04$. Thirteen-month-olds fell or misstepped on $M = 17\%$ of trials while wearing the cloth diaper, 15% while wearing the disposable and 9% while walking naked. Nineteen-month-olds fell less frequently: $M = 5\%$ in cloth, 2% in disposable, and 2% while naked. Table 1 shows the prevalence of gait disruptions in terms of the number of infants who fell or misstepped at least once in each condition (top) and in terms of the proportion of trials that were disrupted (bottom).

Because disruption data were not normally distributed, we analyzed the number of infants displaying at least one gait disruption using a Generalized Estimating Equation (GEE) model with a binomial probit function (Hardin & Hilbe, 2003). The GEE confirmed a main effect of diaper condition, *Wald* $\chi^2(2, N = 60) = 8.62$, $p = .01$. Sidak-corrected pairwise comparisons showed that more infants had a gait disruption when walking in the cloth diaper compared to walking naked, $p = .007$. The number of infants with disrupted gait in the disposable diaper was intermediary and not significantly different from either the naked or cloth diaper conditions. The GEE also confirmed a main effect of age group, *Wald* $\chi^2(1, N = 60) = 22.89$, $p < .001$. The interaction between age and diaper condition was not significant, *Wald* $\chi^2(2, N = 60) = 1.80$, $p = .41$. A GEE on the proportion of trials with gait disruptions revealed comparable effects; *Wald* $\chi^2(1, N = 60) = 19.98$, $p < .001$ for age group, *Wald* $\chi^2(2, N = 60) = 6.89$, $p = .03$ for diaper condition. Replacing age group with infants' individual walking experience as a predictor yielded parallel findings: The GEE on the number of infants who experienced at least one gait disruption showed main effects of walking experience, *Wald* $\chi^2(1, N = 60) = 23.43$, $p < .001$, and diaper condition, *Wald* $\chi^2(2, N = 60) = 7.83$, $p = .02$, but no interaction, *Wald* $\chi^2(2, N = 60) = 2.85$, $p = .24$.

Gait Parameters

In addition to incurring functional consequences, diapers reduced the proficiency of infants' gait. Diapers induced large enough changes in infants' walking to make the condition effect visible to the naked eye. Figure 2A shows footfall patterns from three trials in a typical 19-month-old: Naked steps were straight and narrow; diaper steps were noticeably wider and less mature. Figure 3 shows the diaper effect for the calculated gait parameters. Nineteen-month-olds walked better than 13-month-olds. But while wearing diapers, infants in both age groups took wider, shorter steps and had smaller dynamic base angles—all characteristics of less mature walking—and both age groups were equally affected. Although the cost of wearing a cloth diaper was most severe, even the disposable diaper—worn daily by 92% of the infants—increased step width and decreased dynamic base angles.

All gait parameters were entered into a 2 × 3 repeated-measures multivariate analysis of variance. The MANOVA confirmed main effects of age, $F(4,52) = 20.29$, $p < .001$, partial $\eta^2 = .61$, and diaper condition, $F(8,48) = 11.85$, $p < .001$, partial $\eta^2 = .66$. The interaction between age and diaper condition was not significant, so data were collapsed across ages for follow-up univariate ANOVAs and Sidak-corrected pair-wise comparisons of diaper conditions. The ANOVA on step width confirmed a main effect of diaper condition, $F(2,110) = 32.57$, $p < .001$, partial $\eta^2 = .37$. As shown in Figure 3A, infants took wider (less mature) steps in disposable diapers compared with naked and still wider steps in cloth diapers compared with disposables, *p*s < .001. The ANOVA on step length revealed a main effect for diaper condition, $F(2,110) = 9.23$, $p < .001$, partial $\eta^2 = .14$. As shown in Figure 3B, infants took shorter (less mature) steps in cloth diapers compared with naked and disposables, *p*s < .02. The ANOVA on dynamic base angle confirmed a diaper effect, $F(2,110) = 32.48$, $p<.001$, partial $\eta^2 = .37$. As shown in Figure 3C, infants had smaller (less mature) base angles in disposable diapers compared with naked and smaller yet in cloth diapers compared with disposables, *p*s < .001.

Using infants' walking experience as a predictor instead of age group yielded parallel results, with main effects of walking experience, $F(4,51) = 19.00$, $p < .001$, and diaper condition, $F(8,212) = 2.74$, $p = .007$, and no interaction between walking experience and diaper condition, $F(8,212) = 1.73$, $p = .09$. Follow-up univariate ANOVAs yielded main effects of diaper condition only for step width, $F(2,108) = 8.55$, $p < .001$, and dynamic base, $F(2,108) = 9.21$, $p < .001$. The main effect of diaper condition on step length was no longer significant when using walking experience as a predictor, but none of the univariate tests revealed an interaction.

As in previous work (Adolph et al., 2003; Garciaguirre et al., 2007), leg length and height were not correlated with gait parameters after controlling for infants' age, partial *r*s(44) from −.11 to .04, *p*s > .47. Nevertheless, 19-month-olds had longer legs ($M = 36.67$) than 13-month-olds ($M = 33.70$), $t(49) = 8.44$, $p < .001$, and 19-month-olds were taller ($M = 82.63$) than 13-month-olds ($M = 76.68$), $t(50) = 8.17$, $p < .001$. Thus, as a precaution we reran analyses on step length after normalizing infants' step lengths to their leg lengths. Adjusting for the larger body dimensions of the older infants did not alter the findings: The ANOVA on step length yielded main effects of age group, $F(1,51) = 33.03$, $p < .001$, and diaper condition, $F(2,102) = 8.05$, $p = .001$; the interaction was not significant.

As expected from previous work (Garciaguirre et al., 2007), walking speed was correlated with step width, $r(56) = -.74$, $p < .001$, step length, $r(56) = .95$, $p < .001$, and dynamic base, $r(56) = .86$, $p < .001$. However, there was no main effect of diaper condition on walking speed, $F(2,110) = 2.96$, $p = .06$, partial $\eta^2 = .05$, and the detriment to each gait parameter remained after statistically adjusting for speed, suggesting that changes in speed did not drive the results: step width, Wald $\chi^2(2, N = 57) = 53.97$, $p < .001$; step length, Wald $\chi^2(2, N = 57) = 19.77$, $p < .001$; dynamic base, Wald $\chi^2(2, N = 57) = 47.78$, $p < .001$.

Although the effects of the diaper are statistically significant, inspection of the y-axes in Figure 3 indicates that the detriments to walking proficiency were relatively small. For example, the average step width increased from 9.71 cm when walking naked to 11.05 cm in the disposable diaper and 12.24 cm in the cloth diaper. How substantial is a $M = 2.5$ cm increase in step width? We addressed this question by modeling the relation between walking skill and walking experience using a nonlinear mixed model with an exponential decay function (Burke, Shrout, & Bolger, 2007). As illustrated in Figure 4, for an infant with the median walking experience of 97 days, a 2.5 cm change in step width represents the culmination of 7.5 weeks of walking experience. That is, the 2.5 cm increase caused by a cloth diaper makes infants' walking as immature as it had been nearly eight weeks earlier when walking naked. Similarly, the deficit to step width caused by a disposable diaper is equivalent to losing 4.7 weeks of walking experience.

Discussion

The current results show that diapers reliably alter infant walking, in terms of both function (causing more falls and missteps) and proficiency (inducing less mature walking patterns). Impairments were equally strong for 13-month-old novice walkers and 19-month-old experienced walkers. However, we only documented real-time impairments due to diapers: As soon as infants were naked, they walked better.

Real-time Effects

While wearing a diaper, infants' steps were wider, shorter, and had smaller dynamic base angles—all signatures of less mature walking—compared with walking naked. Albeit statistically significant, are a few centimeters in step width and a few degrees in base angle functionally significant? Simply put: Yes. Infants walked as poorly while wearing a diaper as they would have done several weeks earlier had they been walking naked. That is, in terms of gait maturity, wearing a diaper immediately costs infants several weeks of walking experience. In fact when walking naked, more than half of the 19-month-olds displayed dynamic base angles similar to those of 5- to 6-year-olds (Adolph et al., 2003); only two infants—neither of whom habitually wore cloth diapers—displayed such mature walking while wearing a cloth diaper. Moreover, diapers impair infants' ability to walk from one place to another. Three times as many infants fell or misstepped while wearing a diaper and gait disruptions were three times more likely in the cloth diaper compared with walking naked.

Why might diapers impair walking? One potential explanation concerning the novelty of our experimental manipulation can be ruled out. Although the cloth diaper was novel for most infants, so was walking naked. On average, infants accumulated only 41 minutes per week of naked walking and nearly one third had never walked naked. Nonetheless, infants walked best while naked. Most infants habitually wore the same or an equivalent disposable diaper as the model we used for testing. Nonetheless, their gait was impaired relative to walking naked. Moreover, we found no interaction between diaper condition and age or walking experience. Although the 19-month-olds had been walking in a disposable diaper for several months, they were equally affected as the 13-month-olds.

A second potential explanation is biomechanical. Even modern disposables that are designed to be thin, light, and comfortable introduce bulk between infants' legs. Walking in dirty diapers—a common occurrence in everyday life—would further increase the bulk between infants' legs. By pushing infants' legs apart, step width increases. As step width grows, the dynamic base angle and step length shrink. In addition, diapers may constrain forward movement due to the material wrapped around infants' legs and thereby contribute to deficits in step length and dynamic base. Alterations to the base of support are likely to adversely affect balance and lead to gait disruptions. In addition, wet diapers would increase the weight of the load. Previous work shows that load carriage increases gait disruptions and decreases infants' walking proficiency (Garciaguirre et al., 2007; Schmuckler, 1993; Vereijken et al., 2009). Given that diapers interfere with alternating gait and foot placement, kinematics such as joint angles and limb trajectories and dynamics such as forces and muscle actions are likely to be adversely affected as well.

Taken together, our results suggest that infants learn to walk in the context of an ongoing biomechanical perturbation to their gait in the form of their own diaper. But the immediate improvement in infants' walking when the diaper is removed tells us something more: Infants can exhibit more mature gait patterns when the conditions allow, despite the fact that they do not produce and experience these patterns in daily life when they walk habitually in a diaper.

Developmental Effects

Although we found that diapers cause immediate decrements to infant walking, the current work cannot address whether these real-time changes have more lasting developmental implications. Cross-cultural data raise the provocative suggestion that childrearing practices such as how infants are dressed can alter the course of development. Everyday factors such as wearing heavy clothing or being placed in a constricted posture can delay motor development if spontaneous movement is impeded (Adolph, et al., 2010; Adolph & Robinson, in press). Possibly, infants who learn to walk while naked—without the additional challenge posed by a diaper—might show more rapid gains in posture and coordination, facilitating earlier onset ages and faster improvements. This would be consistent with reported historical changes in infant walking: Infants today walk sooner and better than those of previous generations, when all infants wore cloth diapers (Shirley, 1931).

However, the opposite effect is equally plausible. Cross-cultural practices such as enhanced handling routines and experimental manipulations that encourage infants to fight gravity show us that factors which challenge developing motor skills lead to accelerated onset ages and a faster course of improvements for skills such as sitting and walking (Adolph, et al., 2010; Adolph & Robinson, in press). In the same way, being forced to compensate for the perturbation of the diaper might actually accelerate skill acquisition by actively challenging infants' developing motor skills.

By analogy, many children learn to do homework in front of the television—in the midst of a perceptual and cognitive perturbation. The real-time consequences may be higher levels of distraction, thereby leading to sloppier and less skillful performance. In the long term, children who learn to do their homework in this context may remain at a deficit relative to those who learn in a quiet environment. Alternatively, learning to do homework in the midst of this perceptual-cognitive perturbation may make attention more flexible and focused in the long term, and thereby lead to greater benefits. In the same way, the challenge posed by walking in a diaper could either hinder or facilitate motor development. An experimental study comparing infants reared naked throughout the first two years to infants reared in diapers could help to clarify whether diapers play a facilitative or hindering role in the development of walking.

Concluding Thoughts

The current study provides a cautionary note for researchers because many have not reported what infants were wearing (Bril & Breniere, 1989; Shirley, 1931). Clothes, shoes, and recording devices can affect infants' movements: Pre-walking 2- to 4-month-olds showed equal frequency of alternating upright steps while naked or wearing a diaper, but tight leggings of the sort typically worn to facilitate high-speed motion tracking impeded their movements (Groenen et al., 2010). Lack of information about infants' diapers and other garb is particularly worrisome when attempting to interpret historical changes and cross-cultural differences in walking skill. Historical improvements in infant walking and precocity in nonindustrialized societies are confounded with diapering practices. Much of the previous work on motor development has tested infants while wearing their habitual diaper (Adolph et al., 2003; Bril & Breniere, 1989; Hallemans et al., 2006; Ivanenko, Dominici, Cappellini, & Lacquaniti, 2005; Sutherland, Olshen, Cooper, & Woo, 1980). Our findings suggest that this practice may have led researchers to underestimate infants' abilities: Diapers disrupt the very measures used to index the growing skill that comes with walking experience. How this has impacted our understanding of the underlying developmental trajectory of walking is unknown. Diapers may consistently decrease measures of skill by shifting the learning curve to a later period of development or alter the slope of the developmental trajectory.

It seems that in the search for a pure, context-free description of developing motor skills, it did not occur to researchers that something as non-biological and culturally dictated as diapers might influence locomotion. Whereas biomechanics are the domain of the movement scientist, exotic clothing and toileting practices are considered the realm of anthropologists. The reality, of course, is not that simple. There is no context-free description of movement and no context-free description of development. Locomotion always occurs within an environment, a developing child within a culture.

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References

Adolph KE. Learning in the development of infant locomotion. Monographs of the Society for Research in Child Development. 1997; 62(3) Serial No. 251.

Adolph KE, Cole WG, Komati M, Garciaguirre JS, Badaly D, Lingeman JM, Sotsky RB. How do you learn to walk? Thousands of steps and dozens of falls per day. Psychological Science. (in press).

Adolph, KE.; Karasik, LB.; Tamis-LeMonda, CS. Motor skills. In: Bornstein, MH., editor. Handbook of cross-cultural development science. Vol. 1. Domains of development across cultures. Hillsdale, NJ: Erlbaum; 2010. p. 61-88.

Adolph, KE.; Robinson, SR. The road to walking: What learning to walk tells us about development. In: Zelazo, P., editor. Oxford handbook of developmental psychology. NY: Oxford University Press; (in press)

Adolph KE, Vereijken B, Shrout PE. What changes in infant walking and why. Child Development. 2003; 74:474–497.

Bensen JB. Season of birth and onset of locomotion: Theoretical and methodological implications. Infant Behavior & Development. 1993; 16:69–81.

Bril B, Breniere Y. Steady-state velocity and temporal structure of gait during the first six months of autonomous walking. Human Movement Science. 1989; 8:99–122.

Bril B, Sabatier C. The cultural context of motor development: Postural manipulations in the daily life of Bambara babies (Mali). International Journal of Behavioral Development. 1986; 9:439–453.

Burke CT, Shrout PE, Bolger N. Individual differences in adjustment to spousal loss: A nonlinear mixed model analysis. International Journal of Behavioral Development. 2007; 31:405–415.

Clark D, Kreutzberg J, Chee F. Vestibular stimulation influence on motor development in infants. Science. 1977; 196:1228–1229. [PubMed: 300899]

Davis BE, Moon RY, Sachs HC, Ottolini MC. Effects of sleep position on infant motor development. Pediatrics. 1998; 102:1135–1140. [PubMed: 9794945]

Garciaguirre JS, Adolph KE, Shrout PE. Baby carriage: Infants walking with loads. Child Development. 2007; 78:664–680. [PubMed: 17381796]

Groenen ATK, Kruijsen AJA, Mulvey GM, Ulrich BD. Constraints on early movement: Tykes, togs, and technology. Infant Behavior & Development. 2010; 33:16–22. [PubMed: 19959239]

Hallemans A, De Clercq D, Aerts P. Changes in 3d joint dynamics during the first 5 months after the onset of independent walking: A longitudinal follow-up study. Gait & Posture. 2006; 24:270–279. [PubMed: 16314099]

Hardin, JW.; Hilbe, JM. Generalized Estimating Equations. Boca Raton, FL: Chapman & Hall/CRC; 2003.

Hayashi K. The influence of clothes and bedclothes on infants' gross motor development. Developmental Medicine and Child Neurology. 1992; 34:557–558. [PubMed: 1612218]

Hopkins B, Westra T. Maternal handling and motor development: An intracultural study. Genetic, Social and General Psychology Monographs. 1988; 114:379–408.

Hopkins B, Westra T. Maternal expectations of their infants' development: Some cultural differences. Developmental Medicine & Child Neurology. 1989; 31:384–390. [PubMed: 2753243]

Hopkins B, Westra T. Motor development, maternal expectations, and the role of handling. Infant Behavior & Development. 1990; 13:117–122.

Ivanenko YP, Dominici N, Cappellini G, Lacquaniti F. Kinematics in newly walking toddlers does not depend upon postural stability. Journal of Neurophysiology. 2005; 94:754–763. [PubMed: 15728772]

Kretch KS, Adolph KE. Cliff or step? Posture-specific learning at the edge of a drop-off. Child Development. (in press).

Lagerspetz K, Nygard M, Strandvik C. The effects of training in crawling on the motor and mental development of infants. Scandinavian Journal of Psychology. 1971; 12:192–197. [PubMed: 5170193]

Lobo MA, Galloway JC. Enhanced handling and positioning in early infancy advances development throughout the first year. Child Development. (in press).

Majnemer A, Barr RG. Influence of supine sleep positioning on early motor milestone acquisition. Developmental Medicine & Child Neurology. 2005; 47:370–376. [PubMed: 15934485]

McGraw MB. From reflex to muscular control in the assumption of an erect posture and ambulation in the human infant. Child Development. 1932; 3:291–297.

Mei, J. The Northern Chinese custom of rearing babies in sandbags: Implications for motor and intellectual development. In: van Rossum, JHA.; Laszlo, JI., editors. Motor development: Aspects of normal and delayed development. Amsterdam: VU Uitgeverij; 1994.

Rabain-Jamin J, Wornham WL. Practice and representations of child care and motor development among West Africans in Paris. Early Development and Parenting. 1993; 2:107–119.

Schmuckler, MA. Perception-action coupling in infancy. In: Savelsbergh, GJP., editor. The development of coordination in infancy. Amsterdam: Elsevier Science; 1993. p. 137-173.

Shirley, MM. The first two years: A study of twenty-five babies. Westport, CT: Greenwood Press; 1931.

Sutherland DH, Olshen R, Cooper L, Woo S. The development of mature gait. Journal of Bone and Joint Surgery. 1980; 62:336–353. [PubMed: 7364807]

Thelen E, Fisher DM, Ridley-Johnson R. The relationship between physical growth and a newborn reflex. Infant Behavior & Development. 1984; 7:479–493.

Trettien AW. Creeping and walking. The American Journal of Psychology. 1900; 12:1–57.

Vereijken B, Pedersen AV, Storksen JH. Early independent walking: A longitudinal study of load perturbation effects. Developmental Psychobiology. 2009; 51:374–383. [PubMed: 19365798]

Willinger M, Ko CW, Hoffman HJ, Kessler RC, Corwin MJ. Factors associated with caregivers' choice of infant sleep position, 1994–1998. Journal of the American Medical Association. 2000; 283:2135–2142. [PubMed: 10791506]

Xie, Q.; Young, ME. Integrated child development in rural China. Washington, D. C: The World Bank; 1999.

Zelazo PR, Zelazo NA, Kolb S. "Walking" in the newborn. Science. 1972; 176:314–315. [PubMed: 5019791]

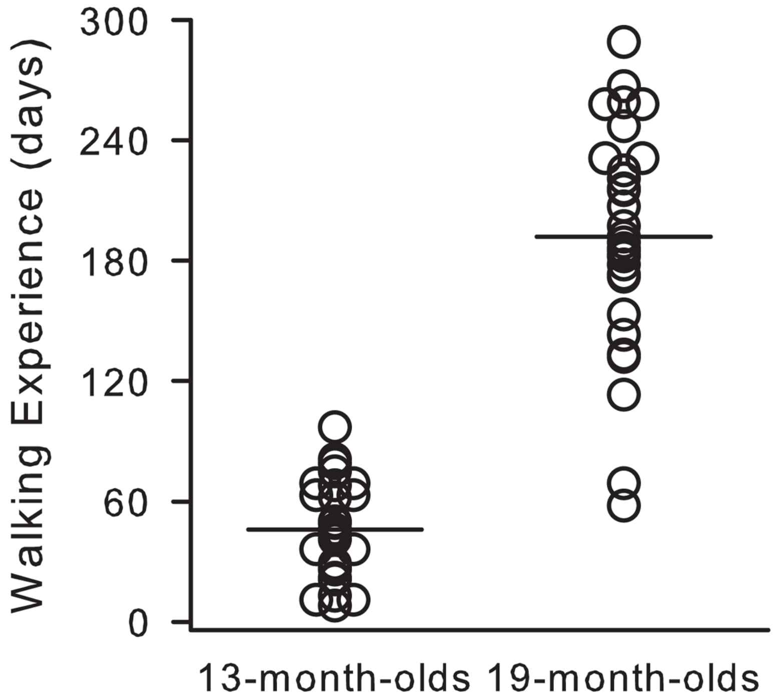

Figure 1.
Infants' walking experience in 13-month-olds and 19-month-olds. Each circle represents data from one infant. The horizontal lines represent group means.

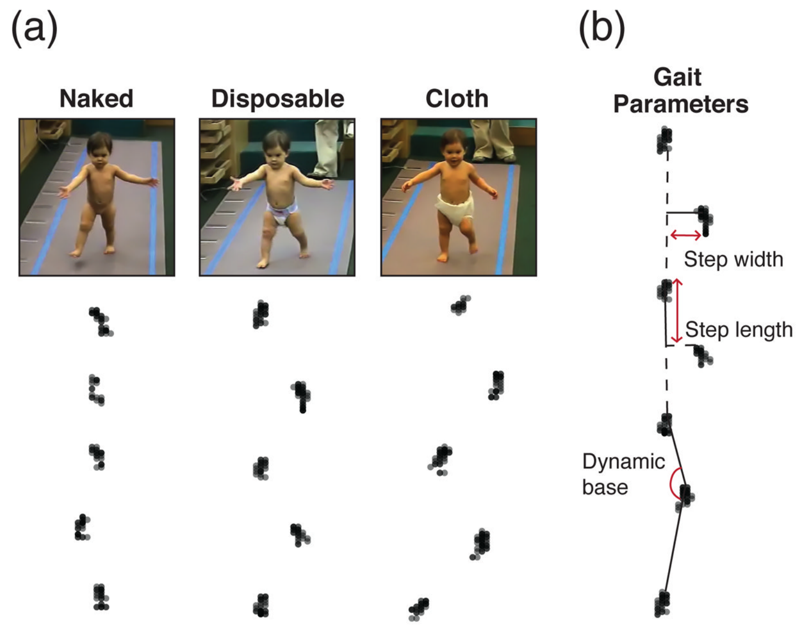

Figure 2.

(A) Sample footprint paths from one typical infant walking while naked, wearing a disposable diaper, and wearing a cloth diaper. Infant is walking from top to bottom. Marks represent the pressure points of each footfall recorded by the gait carpet. (B) Gait parameters illustrated with footfalls recorded by the gait carpet as infant walked from top to bottom. Top: Step width is the side-to-side distance between feet. Middle: Step length is the front-to-back distance between consecutive footfalls. Bottom: Dynamic base is the angle between three consecutive steps.

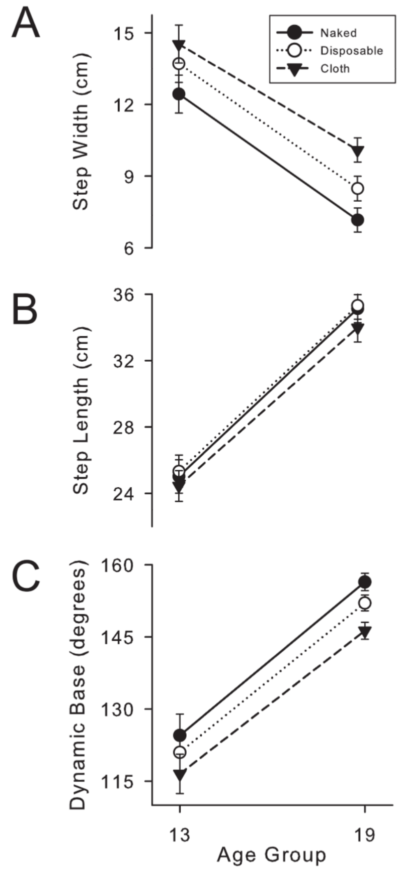

Figure 3.
Average results for each age group in each condition illustrating the main effects of age and diaper condition on (A) step width, (B) step length, and (C) dynamic base. Error bars represent the standard error.

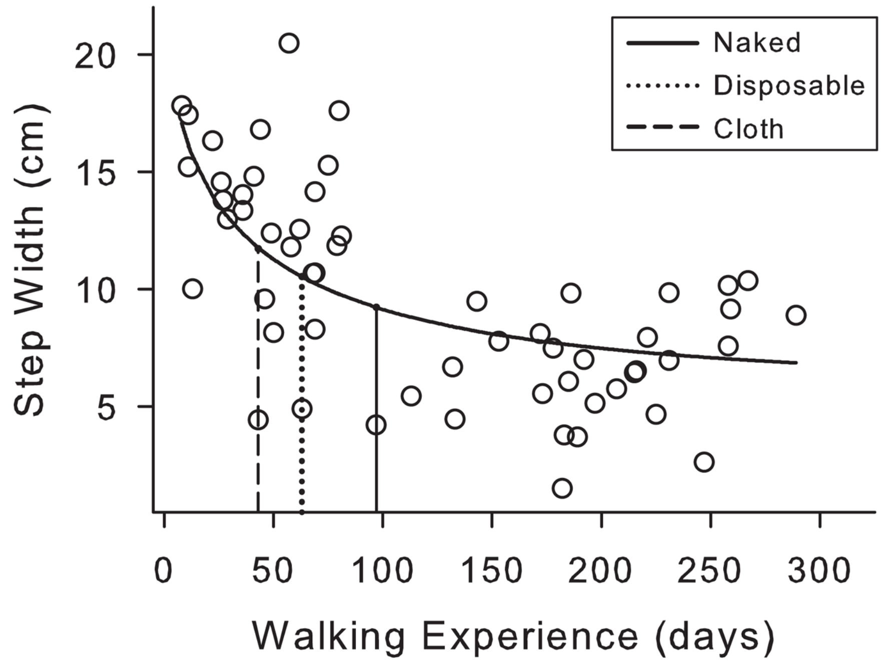

Figure 4.
Infants' step width as a function of walking experience. The curve represents the step width predicted by the exponential decay model. The solid vertical line shows the median walking experience. The dotted vertical line intersects the fit line at a step width 1.2 cm larger (the average increase caused by wearing a disposable diaper). The dashed line intersects the fit line at a step width 2.5 cm larger (the average increase caused by wearing a cloth diaper). The distance from the solid line to the dashed line represents the cost to infants' walking skill from wearing a cloth diaper in terms of the amount of walking experience needed to accomplish an equivalent change.

Table 1

Prevalence of gait disruptions in terms of the number of infants disrupted and the proportion of trials disrupted.

	Naked	Disposable	Cloth
Number of infants disrupted			
13-month-olds	10	17	21
19-month-olds	4	4	8
Proportion of trials disrupted			
13-month-olds	.09	.15	.17
19-month-olds	.02	.02	.05