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Learning to Crawl

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The effects of infants' age, body dimensions, and experience on the development of crawling was examined by observing 28 infants longitudinally, from children's first attempts at crawling until they began walking. Although most infants displayed multiple crawling postures en route to walking, development did not adhere to a strict progression of obligatory, discrete stages. In particular, 15 infants crawled on their bellies prior to crawling on hands and knees, but the other 13 infants skipped the belly-crawling period and proceeded directly to crawling on hands and knees. Duration of experience with earlier forms of crawling predicted the speed and efficiency of later, quite different forms of crawling. Most important, infants who had formerly belly crawled were more proficient crawling on hands and knees than infants who had skipped the belly-crawling period. Transfer could not be explained by differences in infants' age or body dimensions alone. Rather, experience using earlier crawling patterns may have exerted beneficial effects on hands-and-knees crawling by shoring up underlying constituents common to all forms of crawling postures.

INTRODUCTION

Independent locomotion is a dramatic arrival in the parade of infants' new motor skills. Most infants' first success at mobility is crawling, beginning with clumsy attempts to move forward with the belly dragging along the ground and ending several weeks later in stable, proficient travel with infants propped firmly on hands and knees (Bayley, 1969; Frankenburg & Dodds, 1967). Between these endpoints are relatively abrupt discontinuities in infants' posture and interlimb coordination. Since the 1930s, researchers have described these discontinuities as a series of distinct postural stages (e.g., Ames, 1937; Burnside, 1927; Gesell & Ames, 1940; McGraw, 1935, 1945; Shirley, 1931). Each subsequent posture marks a small triumph over gravity in an orderly march toward erect locomotion: lifting the head and chest off the ground, pivoting in circles, pulling forward with the abdomen dragging along the ground, hopping forward with the belly alternately on and off the ground, rhythmical rocking on hands and knees, crawling on hands and knees, creeping on hands and feet, and so on. In addition to such stage-like transitions, crawling also involves more continuous, gradual improvements in locomotor proficiency. Although less research has focused on continuous changes in crawling proficiency (e.g., Freedland & Bertenthal, 1994), the current study shows that the entire course of crawling is characterized by continuous improvements in crawling speed and efficiency.

A central puzzle in development is how both stage-like transitions and continuous, gradual improvements may arise in the development of a new skill (e.g., Thelen & Smith, 1994). The current study was aimed at advancing our understanding of skill acquisition by examining potential mechanisms underlying both kinds of change. As in other motor skills, changes in crawling postures and proficiency coincide with interrelated changes in infants' brains, bodies, and motor experience.

Traditionally, researchers emphasized maturation of the central nervous system as the primary impetus for stage-like transitions in motor development (e.g., Gesell & Ames, 1940; McGraw, 1941, 1945). Thus, early research on motor development focused on documenting the ages at which children achieved various motor milestones and normative sequences in their appearance. In addition, neural maturation might also facilitate more continuous improvements in locomotor proficiency. For example, myelinization of the cortico-spinal tract may result in faster muscle actions or increased synchrony between limbs (e.g., Forssberg, 1980, 1985).

Even traditional theorists, however, recognized that change in peripheral factors may contribute to individual differences in movement patterns and to transitions from one postural stage to the next. Burnside (1927), for example, observed that many children at the turn of the century crawled by hitching along on their buttocks because infants' long dresses hampered crawling in a prone position. Shirley (1931) noted that some infants appeared more motivated than others to achieve independent mobility and that slimmer infants crawled and walked sooner than chubbier ones. Gesell (1939, 1946) proposed that fluctuations and asymmetries in infants' muscle tone may spur development of various crawling stages. McGraw (1945) suggested that increases in leg strength and postural control may facilitate development of walking.

Current trends in motor development emphasize such peripheral, biomechanical factors for engendering stage-like developmental change (e.g., Goldfield, 1989, 1993; Thelen & Ulrich, 1991). For example, the transition to reaching may depend in part on infants' ability to stabilize their heads and torsos (e.g., Kamm, 1993; Rochat & Goubet, 1995). The strange appearance, disappearance, and subsequent reappearance of infants' stepping movements over the first year of life may result from changes in the ratio of muscle to fat in infants' legs (Thelen, 1984). Likewise, in their longitudinal study of six infants, Freedland and Bertenthal (1994) concluded that the transition to crawling on hands and knees may result from increases in infants' arm strength. None of the infants rocked on hands and knees prior to hands-and-knees onset, suggesting that the more erect posture depended on sufficient arm strength to support the body in midair.

In addition, many researchers have acknowledged that experience executing various postures and movements may influence stage-like transitions and continuous improvements in motor skill (e.g., Benson, 1993; Freedland & Bertenthal, 1994; Thelen & Smith, 1994). Presumably, practicing the same movements over and over should result in increased motor proficiency. Little is known, however, about how experience might exert beneficial effects when old and new skills involve different movements. One possibility is that experience may facilitate transfer by shoring up "hidden," underlying constituents common to both old and new patterns (e.g., Thelen, 1986; Thelen & Smith, 1994). On this view, transfer should depend on the duration of experience and the number of shared constituents. For example, cross-cultural research suggests that motor experience may contribute to the timing of motor milestones by shoring up limb strength and postural control. Infants raised in communities that encourage practice of upright postures tend to walk earlier than infants raised in Western cultures (e.g., Bril, Zack, & Nkounkou-Hombessa, 1989; Konner, 1976; Super, 1976). American infants receiving daily practice with upright stepping movements maintain the stepping response longer and walk sooner than infants receiving no practice (Zelazo, Zelazo, & Kolb, 1972). In contrast, experience has no beneficial effects on more dissimilar motor skills involving very different postures. Infants receiving practice with newborn sitting responses show no facilitation of stepping movements and vice versa (Zelazo, Zelazo, Cohen, & Zelazo, 1993). Infants in cultures that promote upright postures tend to crawl later (or not at all) compared with infants raised in Western cultures (Bril et al., 1989). Experiences obtained over crawling do not transfer to walking (Adolph, 1997), and experiences obtained in a sitting posture do not transfer to a crawling posture (Adolph, Avolio, Melton, & Arnet, 1998).

A second possibility is that variability of experience may play a pivotal role in facilitating developmental change (Bernstein, 1967; Freedland & Bertenthal, 1994; Gibson, 1988; Goldfield, 1989, 1993; Siegler, 1994; Thelen, 1995). On this view, inconsistent performance impels infants to search for stable solutions; multiple behaviors in infants' repertoires provide more options for a selection process. For example, variable experience with belly crawling may allow infants to discover the most efficient pattern of timing between arms and legs (Goldfield, 1993). In Freedland and Bertenthal's (1994) study, three of the infants crawled on their bellies prior to moving on hands and knees, but their belly gait patterns were idiosyncratic and variable. In their first week on hands and knees, interlimb timing was variable, but by the second week, variability decreased and all six infants converged to a diagonal, "trotting" pattern of interlimb coordination (i.e., right hand and left leg move together and left hand and right leg move together). Although many different gait patterns would allow infants to support their body, keep balance, and propel forward, the diagonal gait pattern is most biomechanically efficient and stable (Alexander, 1992). The authors suggested that variable experience coping with balance after hands-and-knees onset may have prompted selection of the more efficient diagonal gait pattern (Freedland & Bertenthal, 1994).

The present study expands on previous findings in several ways. Like the early researchers such as Gesell and Ames (1940), we observed a relatively large sample of infants spanning the entire period of prone progression, from infants' first, precursory crawling movements until they began walking upright. Using criteria similar to those of the early pioneers, we examined whether changes in infants' crawling postures appear in a series of discrete, obligatory stages. Like the more recent research of Freedland and Bertenthal (1994), we used detailed kinematic analyses to track changes in infants' interlimb coordination and locomotor proficiency. We filled in the gaps left by previous research by documenting change in these measures over the entire belly and hands-and-knees crawling periods.

Furthermore, to better understand potential mechanisms underlying developmental change, we assessed effects of infants' age, body dimensions, and crawling experience on the timing of crawling milestones, transitions in patterns of interlimb coordination, and improvements in crawling proficiency. In particular, we focused on how experience might exert beneficial effects on crawling proficiency. We expected that extended experience with the same crawling patterns would result in increased speed and efficiency of those patterns. More interesting, we tested whether duration of experience with earlier crawling patterns transfers to later, quite different crawling patterns. For example, experience with belly crawling may enhance proficiency of hands-and-knees crawling by shoring up underlying constituents common to both forms (building infants' arm strength, providing perceptual feedback about the consequences of disequilibrium, ensuring practice stabilizing the torso when all four limbs move, reinforcing infants' motivation to move toward a goal, and so forth). In addition, previous research suggested that variability of experience might facilitate improvements in crawling by promoting selection of more optimal movements (Freedland & Bertenthal, 1994). Decrease in variability of crawling patterns as crawling skill improves would suggest that variability prompts infants to select an optimally efficient crawling pattern (as evidenced by the infants in Freedland and Bertenthal's study). In contrast, improvements despite persistently high or low levels of variability would suggest that a selection process is not necessary for improved performance.

METHOD

Participants

Twenty-eight healthy, term infants participated in the study. Most families were White and of middle-class socioeconomic status. Parents visited the laboratory with their infants before consenting to participate, and an experimenter verified infants' locomotor status. Although two infants began belly crawling before they were recruited, they were included in the sample because their first day of crawling was dated accurately from parents' records and home videotapes. Two additional infants were not included in the study. One infant never crawled and instead proceeded directly to walking. The other family withdrew from the study before the baby began crawling. Families received photograph albums, videotapes, T-shirts, and diplomas as souvenirs of their participation.

Longitudinal Design

We tracked the development of prone progression from the day infants were recruited until they could walk independently. We defined crawling onset as the first day when infants crawled forward on belly or hands and knees at least 91 cm on three of four consecutive trials without pausing longer than 3 s between crawling steps. This strict criterion for crawling onset ensured that infants could produce several consecutive crawling cycles for obtaining temporal measures of crawling proficiency and interlimb coordination. Trials were classified as belly crawling if infants moved forward with their bellies touching the ground and as hands-and-knees crawling if infants traveled the entire 91 cm with their abdomens off the surface.

Parents kept daily checklist diaries for the duration of the study noting various milestones in development of crawling: *pivoting* in circles with belly on the ground, moving forward one or two occasional *steps on belly*, *rocking* rhythmically back and forth on hands and knees, moving forward one or two occasional *steps on hands and knees*, and crawling to criterion on *belly* and *hands and knees*. In addition, parents recorded infants' success at postural transitions to and from a prone position: shifting from *sitting to prone* and from *prone to sitting* positions. A research assistant verified parents' diary entries with weekly telephone interviews.

When parents reported that infants moved forward more than three steps, an experimenter tested infants in their homes or in the laboratory every 2 or 3 days until babies passed criterion for crawling onset. Dating from their first official crawling onset day, 15 infants (seven girls, eight boys) were tested every 3 weeks in the laboratory beginning in their first week of crawling until they began walking independently (305 cm on three of four consecutive trials). Thirteen infants (six girls, seven boys) were tested only two times, once in their first week of crawling and once in their tenth week of crawling. The latter, more relaxed testing regimen boosted the sample size for comparisons between beginning crawlers and more experienced ones. All infants were tested within 7 days before or after each target test session.

Apparatus and Procedure

At each test session, infants crawled four times over a raised, carpeted platform (244.5 cm long × 83.6 cm wide × 75.3 cm high). Vertical posts along the sides of the platform marked a 91 cm middle section. Infants began each trial at one end of the platform. Parents stood at the far end of the platform and encouraged infants to crawl over the middle section, using toys and cereal as enticements. An experimenter followed alongside infants to ensure their safety. Trials were repeated if infants stopped midway or fell.

All trials were videotaped at 30 frames per second with a camera located perpendicular to the middle section of the platform. Infants crawled two times in each direction so that each side of infants' bodies was closest to the camera and most easily visible for half of the trials. Portions of the limbs farthest from the camera were also visible and enabled coders to identify all limb movements reliably.

At the end of each session, an experimenter measured infants' head circumference at eyebrows, recumbent height from crown to heel, leg length from ankle to hip, and body weight on a Pediatric scale. In addition, Ponderal index (weight/height^3) provided a measure of infants' overall chubbiness (Shirley, 1931). All infants showed continuous growth for each body dimension, providing a crude indication that measures were reliable.

Available Data

Because of the two testing regimens, varying durations of infants' crawling experience, whether or not infants belly crawled, and occasional missed sessions, different numbers of infants contributed kinematic data to each crawling session. Table 1 shows available data at each week of belly and hands-knees crawling and denotes the number of infants contributing data per session represented in each of the figures. Some infants contributed data to both belly and hands-knees sessions, and other infants contributed data only to hands-knees sessions. In total, we collected 559 crawling trials. On 418 trials, infants crawled continuously between the 91 cm marker posts. On the remaining trials, infants started or stopped slightly before the marker posts; these trials always contained at least three continuous crawling cycles.

Data Reduction

Data reduction focused on changes in infants' *crawling proficiency* and *patterns of interlimb coordination* over weeks of belly and hands-knees crawling. All data were derived from frame-by-frame analysis of videotapes using a computerized coding system, MacSHAPA (Sanderson, McNeese, & Zaff, 1994; Sanderson, Scott, et al., 1994).

Measures of crawling proficiency reflected how quickly infants moved and the size of their crawling movements. To score timing and distance, coders identified the beginning and end of each trial (when infants passed the first and second marker posts), the division between each crawling cycle (when the left arm moved forward), and the beginning and end of each crawling step (when each of the arms and legs moved forward and when they stopped moving forward). Each trial was composed of multiple crawling cycles, and each cycle was composed of multiple crawling steps (cycles always included movement of both arms). Because of the difficulty of coding steps during belly crawling, coders scored only individual steps for infants' last week of belly crawling. Another coder independently scored timing data from the first trial of 51 randomly selected sessions, representing data from each child and 2,616 video frames altogether. Interrater reliability was high: 92.3% agreement within two video frames (.07 s) and 95.6% agreement within three video frames (.1 s). These kinematic data yielded several measures of crawling proficiency: Overall *velocity* (91 cm/trial time between marker posts), number of complete *cycles* to crawl 91 cm, average *cycle time* (seconds/cycle), number of *steps* to crawl 91 cm, average *swing* duration (time that limbs were in motion), and average *stance* duration (time that limbs were stationary on the support surface). Number of steps, and swing and stance durations were calculated only for infants' last week of belly crawling and for each week on hands and knees. Trials where infants did not move continuously between 91 cm marker posts were not used to calculate velocity, number of cycles, and number of steps.

Measures of interlimb coordination reflected more global characterizations of movement patterns for each crawling cycle. Coders identified each unique combination of body parts used for propulsion and balance. Similar to previous researchers' qualitative descriptions of crawling stages (Freedland & Berten-

Table 1 Number of Infants Contributing Data to Each Crawling Session

	Weeks of Crawling								
Crawling Method	1	4	7	10	13	16	19	22	25
Belly	12	7	7	5	1	1	. . .	. . .	. . .
Hands-knees	22	16	14	21	10	7	6	5	4

thal, 1994; Gesell & Ames, 1940; McGraw, 1941, 1945), coders recorded whether infants used their arms and legs to propel them forward and whether infants balanced on their bellies, hands, knees, and feet. Asymmetries between legs and different knee / foot combinations on the same leg were categorized as different crawling patterns. A second coder independently scored crawling patterns from the first two trials of 68 randomly selected sessions, representing 441 cycles in total. Coders were in exact agreement for every code on 97.8% of crawling cycles.

In addition, we analyzed the pattern of timing between limb movements for infants' last week of belly crawling and each week on hands and knees, based on criteria from previous research with animals and human infants (e.g., Freedland & Bertenthal, 1994; Hildebrand, 1967, 1989; Schöner, Jiang, & Kelso, 1990; Sparrow, 1989). The start time of swing in the left arm was used as the reference event so that time lags between start time of swing in the other three limbs were calculated as a proportion of the total cycle time of the left arm. Then, these calculations were converted to absolute deviations from a diagonal gait, the developmentally preferred pattern of crawling identified by Freedland and Bertenthal (1994). For example, right leg movements slightly slower than exact synchrony at .1 of the left arm's cycle, and right leg movements slightly faster than exact synchrony at .9 of the left arm's cycle, both showed absolute deviation from perfect diagonal gait (0 or 1) by .1. Note that interlimb timing reflects temporal patterns of interlimb coordination regardless of body parts used for propulsion or balance.

RESULTS

Postural "Stages" in Prone Progression

Most infants displayed most postural "stages" en route to walking. However, development of prone progression did not follow a strict stage-like progression. Some infants skipped postural stages (see varying sample size in Table 2), most infants straddled multiple stages simultaneously, and there was no rigid order in appearance of each postural stage.

Most important, nearly half of the sample skipped the belly-crawling period. Fifteen infants first passed criterion for crawling onset by moving forward with their abdomen or chest resting on the platform (labeled "former belly crawlers"). The other 13 infants first passed criterion for crawling onset by traveling forward in an erect crawl, without their torsos touching the surface (labeled "non-belly crawlers"). The left panel in Table 2 shows group averages for age at onset of each postural stage. On average, non-belly-crawling infants tended to crawl and walk slightly earlier than former belly-crawling infants; however, variability was high and t tests showed no significant group differences in age at onset of hands-knees crawling or walking (all $ps > .30$). Likewise, t tests showed no differences between former belly crawlers and non-belly crawlers in age at onset of crawling precursors or postural transitions (all $ps > .30$). Despite important deviations from a strict stage-like progression, infants did show consistent trends in the order of appearance of various postural stages. All 28 infants displayed at least one clumsy precursor of prone progression before they passed criterion for crawling onset (pivoting, rocking, occasional steps on belly and hands and knees, shifting from sitting to prone positions). All former belly crawlers eventually progressed to crawling on hands and knees, and hands-and-knees crawling or shifting from prone to sitting positions were always the last milestones to appear in infants' repertoires.

Body Dimensions

Smaller, slimmer, more maturely proportioned infants tended to crawl at earlier ages than larger, chubbier infants. Height, weight, head circumference, and leg length were positively correlated with age at onset of belly crawling and hands-and-knees crawling; correlation coefficients ranged from .57 to .81, all $ps < .07$. Ponderal index, a measure of overall chubbiness, was negatively correlated with age at onset of hands-knees crawling, $r(20) = -.56$, $p < .01$.

Experience

The right panels of Table 2 show group averages for experience with each postural stage. On average, former belly crawlers had 1.62 months experience traveling long distances on their bellies. In addition, former belly crawlers had more experience practicing pivoting, occasional steps on belly, and occasional steps on hands and knees compared with non-belly crawlers before both groups passed criterion for hands-and-knees crawling; values of $t(26) = 2.12$, 6.08, and 2.74, respectively, all $ps < .05$.

Patterns of Interlimb Coordination

After onset of belly and hands-knees crawling, we examined two types of changes in infants' interlimb coordination—the combination of body parts used for propulsion and balance and the relative timing of arm and leg movements.

Table 2 Age at Onset and Experience with Postural "Stages" in Former Belly versus Non-Belly Crawlers

	Age at Onset (Months)[a]				Experience (Months)[b]			
	Former Belly		Non-Belly		Former Belly		Non-Belly	
Postures	*n*	*M* (*SD*)	*n*	*M* (*SD*)	*n*	*M* (*SD*)	*n*	*M* (*SD*)
Pivot	15	6.18 (1.05)	13	6.52 (1.50)	15	2.32 (1.40)	13	1.37 (.88)
Belly steps	15	6.33 (1.31)	5	6.25 (1.53)	15	2.17 (.99)	13	.32 (.49)
Belly onset	15	6.89 (1.35)	0	. . . . . .	15	1.62 (.88)	13	.00 (.00)
Rock	13	6.53 (1.52)	12	6.48 (1.20)	15	1.68 (1.31)	13	1.17 (.69)
Hands-knees steps	15	7.88 (1.77)	12	7.41 (1.34)	15	.63 (.36)	13	.29 (.27)
Hands-knees onset	15	8.50 (1.84)	13	7.87 (1.46)	15	3.82 (1.43)	13	3.87 (1.50)
Sit/prone	15	7.04 (1.06)	13	6.87 (1.34)	15	1.50 (1.10)	13	1.11 (.88)
Prone/sit	15	8.41 (1.65)	13	8.10 (1.32)	15	.42 (.51)	13	.27 (.28)
Walk onset	15	12.32 (1.60)	13	11.75 (1.30)	. . .	. . .	. . .	. . .

[a] Only infants who displayed postures contributed to group averages for age.
[b] All infants contributed to group averages for experience. Infants had 0 days of experience if they displayed a posture after onset of hands-knees crawling or if they never displayed the posture. Experience with hands-knees onset was calculated relative to walk onset. Experience with all other postures was calculated relative to hands-knees onset.

Propulsion and balance. Across infants and sessions, we observed 25 unique combinations of body parts used for propulsion and balance. As illustrated in Figure 1, every observed crawling pattern involved propulsion with both arms and at least one leg. Limbs used for balance were always used for propulsion, but sometimes infants propelled with their legs without balancing on the corresponding knees or feet.

The observed combinations reflect four increasingly erect postures. "Army" belly crawls required the least amount of balance control. Infants used their belly and thighs for support and never balanced on hands, knees, or feet. On average, army crawls represented 63% of each infant's cycles during the belly-crawling period. In "inchworm" belly crawls, infants balanced alternately on their extremities and on their belly. On average, belly-flop inchworm patterns represented 31% of each belly crawler's cycles. In a standard hands-knees gait, infants moved forward with their belly suspended in the air while balancing on both hands and both knees. Occasionally, belly crawlers managed a cycle or two on hands and knees during the belly-crawling period (M = 6% of belly cycles). After passing criterion for hands-and-knees onset, on average the standard hands-knees gait represented 88% of each infant's cycles. In "bear" crawls, infants balanced on hands and feet, sometimes also using one or both knees. On average, bear crawls represented 12% of each infant's cycles during the hands-and-knees period. For each observed crawling pattern, asymmetrical use of the legs favored the right side (M = 69%–84% of cycles where infants showed a side preference).

Variability in crawling patterns. Over weeks of belly crawling, infants showed high variability in combinations of body parts used for propulsion and balance (total height of bars in Figure 2). In fact, many infants used different crawling patterns from cycle to cycle. Persistent variability was due both to continued use of old belly-crawling patterns (striped bars) and discovery of new movement patterns (solid bars). Most important, Figure 2 shows that infants did not exploit experience with multiple belly-crawling patterns to hone in on a preferred or optimal belly-crawling pattern. Instead, belly crawlers continued to use multiple, idiosyncratic, and arduous movement patterns throughout the entire period of belly crawling, and many new belly crawls were side-biased rather than symmetrical. In contrast, low vari-

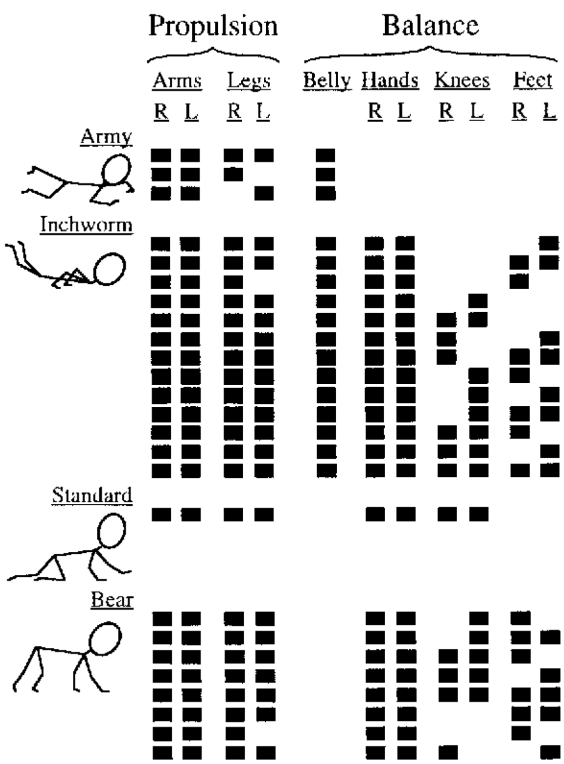

Figure 1 Observed crawling patterns. Left column illustrates four types of increasingly erect postures: "army" belly crawls, "inchworm" belly crawls, standard hands-and-knees crawling, and "bear" crawls. Right columns show observed combinations of body parts used for propulsion and balance. Former belly crawlers contributed to all four categories, and non-belly crawlers contributed only to standard and bear-crawling patterns. Rows represent patterns displayed by at least one infant. Reading down columns shows similarities and differences between crawling patterns.

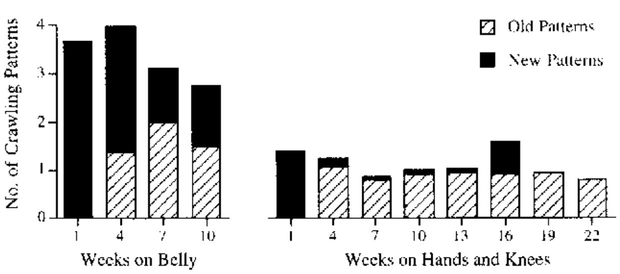

Figure 2 Changes in variability over weeks of belly crawling and hands-and-knees crawling. Striped bars represent average number of old crawling patterns (unique combinations of body parts used for support and propulsion), and solid bars represent average number of new patterns. Old crawling patterns were defined as combinations of body parts used for propulsion and balance exhibited by infants in previous weeks, and new patterns were those not previously exhibited.

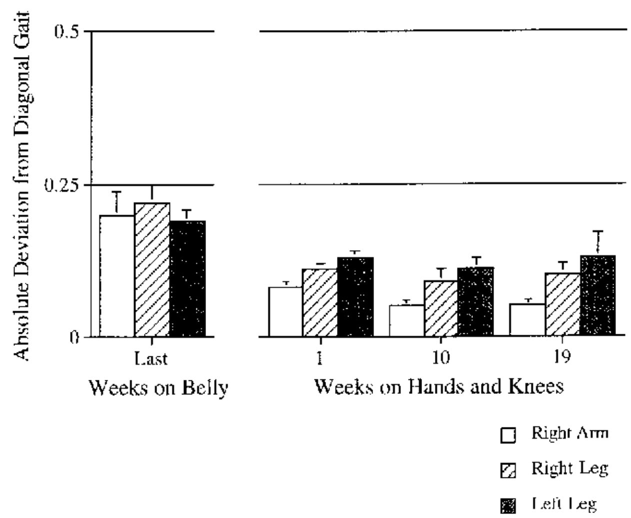

Figure 3 Interlimb timing between arms and legs in infants' final week on belly and first, tenth, and nineteenth weeks on hands and knees. The height of each bar indicates average deviation from perfect diagonal gait, where right arm and left leg move together and left arm and right leg move together. Values close to 0 represent diagonal gait; values close to .25 indicate no consistent timing pattern; values close to .5 indicate ipsilateral or homologous gait patterns. The error bars reflect standard errors.

ability was characteristic of crawling on hands and knees. From their first hands-knees session, most infants consistently used a standard hands-knees gait, and infants explored new combinations only briefly or not at all.

Interlimb timing. A second aspect of interlimb coordination is the timing of arm and leg movements. Note that regardless of limbs used for propulsion and support, infants can move limbs in random orders. Figure 3 illustrates average absolute deviation from a perfect diagonal "trot": the right leg's deviation from perfect synchronization with the left arm (striped bars) and the deviations of the right arm and left leg from perfect alternation with the left arm (white bars and solid bars, respectively).

In their last week of belly crawling, infants showed no consistent pattern of interlimb timing, with large deviations from diagonal gait and high standard errors (left panel of Figure 3). In contrast, from their very first week on hands and knees and in each subsequent session, infants tended toward a uniform diagonal gait (right panel of Figure 3). In general, infants did not execute a perfect trot. Instead, they lifted and placed their front limbs a few video frames before moving their hind limbs, so that three limbs were on the surface for a brief period of each cycle. A 3 (limb) $\times$ 2 (weeks) repeated-measures ANOVA confirmed change in interlimb timing from infants' last week of belly crawling to their first week on hands and knees, $F(1, 8) = 24.67$, $p < .001$, with no differences between limbs. In their first week on hands and knees, former belly crawlers tended to display less deviation from diagonal gait than non-belly crawlers, $F(1, 12) = 6.05$, $p < .03$. After onset of hands-and-knees crawling, repeated-measures ANOVA showed no effect for experience. There were no differences from infants' first to tenth weeks on hands-knees for any of the limbs, $F(1, 12) = 2.06$, $p > .10$. However, there was a significant effect for limbs, $F(2, 24) = 18.20$, $p < .001$. Post hoc (Newman-Keuls) analysis showed that overall, the right arm showed less deviation from a diagonal gait than the right and left legs, $F(2, 36) = 7.87$, $p < .01$.

Changes in Crawling Proficiency

Overall, crawling became gradually more proficient with weeks of experience. As shown in Figure 4, velocity increased and cycle time, swing duration, and stance duration decreased, meaning that infants' movements became faster. Number of cycles and steps decreased, indicating that infants' movements became larger. In general, crawling was more proficient on hands and knees compared with belly, and there was no decrement in proficiency over the transition from belly to hands and knees. As shown in Table 3, statistical comparisons supported these experience-related changes in proficiency. Paired *t* tests showed significant improvement from belly crawlers' first to last available belly sessions (Table 3, first row) and from all infants' first to last available hands-knees sessions (Table 3, second row). Averaged over all available sessions within each crawling period, paired *t* tests showed greater crawling proficiency on hands and knees compared with belly (Table 3, third row). Paired comparisons between the two sessions spanning the transition from belly to hands-and-knees crawling showed no decrement in proficiency (Table 3, fourth row).

Most striking, former belly crawlers generally were more proficient in their first weeks on hands and knees compared with non-belly crawlers (compare solid and dashed lines in Figure 4). Former belly crawlers had faster velocities, cycle times, and swing and stance times and used fewer cycles and steps than non-belly crawlers. In fact, in their first hands-knees session, there was almost no overlap in performance of individual infants in former belly versus non-belly-crawling groups, and the former belly advantage persisted for several weeks. Statistical comparisons between former belly crawlers and non-belly crawlers supported these group differences in crawling proficiency at infants' first week on hands and knees (Table 4).

Experience, Age, and Body Dimensions

The difference in hands-knees crawling proficiency between former belly crawlers versus non-belly crawlers did not result only from differences in infants' age or body dimensions. That is, the former belly crawlers' advantage was not due merely to being older and bigger. When we statistically controlled for age or body dimensions at infants' first hands-knees session, comparisons between former belly crawlers versus non-belly crawlers replicated the belly-crawling advantage. ANCOVAs controlling for infants' age at hands-knees onset showed differences between former belly crawlers and non-belly crawlers for each proficiency measure, all $ps < .05$. Likewise, ANCOVAs using each measure of body dimension as a covariate showed significant group differences for every measure of proficiency, all $ps < .05$.

Table 5 shows zero order correlation coefficients between each infants' age, experience, and body dimensions with each measure of crawling proficiency. The overall pattern of results indicates that age and duration of experience executing various precursory and belly-crawling movements were important predictors of hands-and-knees proficiency, but body dimensions were not. Age showed significant correlations in 5 out of 6 comparisons, experience in 33 out of 42 comparisons, and body dimensions in 5 out of 30 comparisons. Furthermore, most measures of experience retained their predictive power when age at hands-knees onset was partialed out, but measures of body dimensions did not. Table 6 shows partial correlation coefficients, controlling for infants' age at hands-knees onset. Interestingly, practice executing movements quite dissimilar to hands-knees crawling (belly crawling and belly steps) retained their predictive power when age was partialed out.

DISCUSSION

This research examined how both stage-like transitions and continuous gradual improvements may arise in the development of a new skill. Crawling is an ideal candidate for studying development because it involves both types of changes. As in previous research (e.g., Ames, 1937; Burnside, 1927; Freedland & Bertenthal, 1994; Gesell, 1946; Gesell & Ames, 1940; McGraw, 1935, 1945; Shirley, 1931), we found relatively abrupt transitions from less to more erect

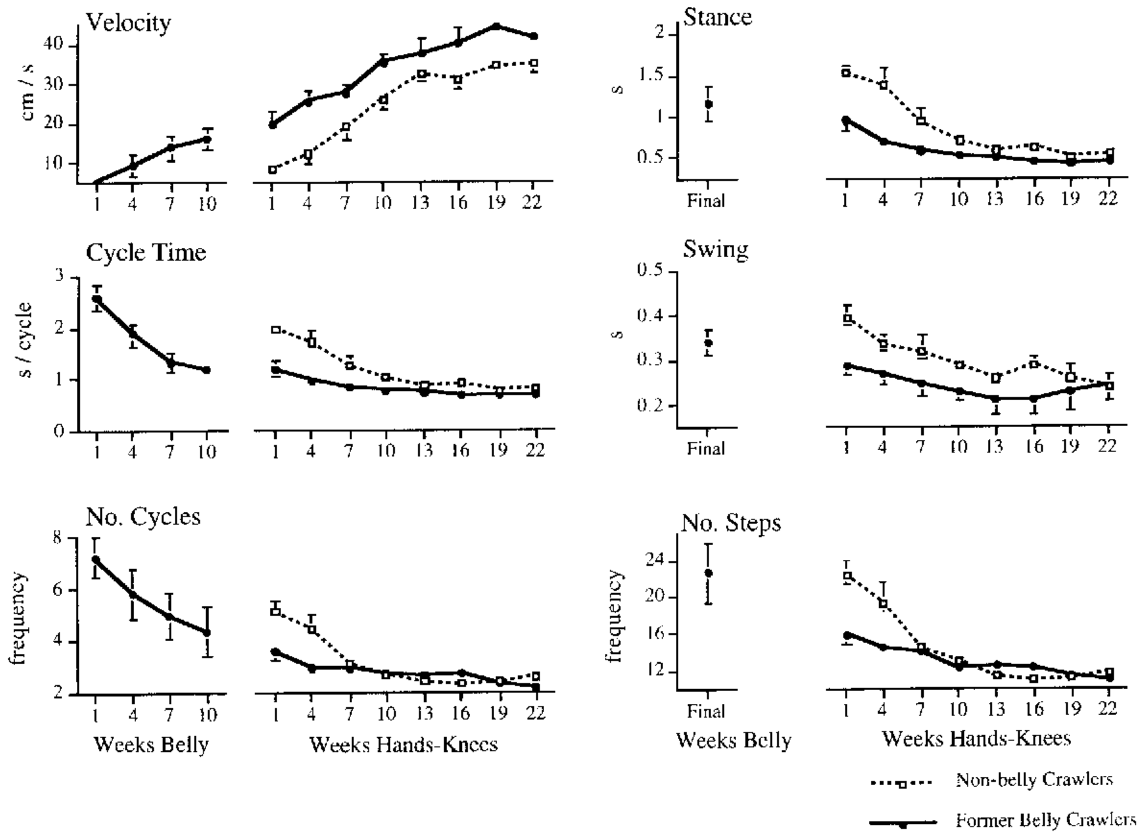

Figure 4 Changes in measures of crawling proficiency over weeks on belly and weeks on hands and knees: overall velocity between marker posts, time to complete each crawling cycle, number of cycles between marker posts, stance duration, swing duration, and number of crawling steps between marker posts. Solid lines and solid symbols indicate former belly crawlers. Dashed lines and open symbols indicate non-belly crawlers. Error bars reflect standard errors.

Table 3 Test Statistics for Paired *t* Tests on Changes in Crawling Proficiency over Belly and Hands-Knees Sessions

	Measure of Crawling Proficiency[a]											
	Velocity		Cycle Time		Swing Time		Stance Time		No. Cycles		No. Steps	
Developmental Changes	*df*	Paired *t*	*df*	Paired *t*	*df*	Paired *t*	*df*	Paired *t*	*df*	Paired *t*	*df*	Paired *t*
Changes within crawling periods:												
First to last belly	5	−3.08*	7	3.02*	. . .	. . .	. . .	. . .	5	2.85*	. . .	. . .
First to last hand-knees	19	−9.56***	20	6.54***	20	5.22***	20	6.80***	19	5.08***	19	5.71***
Changes across crawling periods:												
Overall belly versus hands-knees[b]	13	−8.64***	14	6.36***	. . .	. . .	. . .	. . .	13	4.12***	. . .	. . .
Last belly versus first hands-knees	6	4.39**	7	2.03+	7	1.19	7	1.38	6	2.06+	6	2.59*

[a] *df* reduced for measures requiring infants to crawl 91 cm between marker posts.
[b] *t*-tests calculated by comparing infants' averages of proficiency measures over weeks of belly versus over weeks of hands-knees.
+ $p < .1$; * $p < .05$; ** $p < .01$; *** $p < .001$.

Table 4 **Values of *t* in Comparisons of Crawling Proficiency between Former Belly versus Non-Belly Crawlers at Infants' First Hands-Knees Session**

Measure	*M* (*SD*)		*df*[a]	*t*
	Former Belly	Non-Belly		
Velocity	19.74 (10.22)	8.59 (2.44)	19	3.52**
Cycle time	1.20 (.47)	1.97 (.42)	20	4.06***
Swing	.29 (.08)	.40 (.10)	20	−2.78*
Stance	.95 (.42)	1.52 (.36)	20	3.37**
No. cycles	3.57 (1.07)	5.12 (1.49)	19	−2.70*
No. steps	15.88 (3.46)	22.45 (5.07)	19	−3.43**

[a] *df* reduced for velocity, number of cycles, and number of steps because one infant did not contribute trials crawling 91 cm between marker posts.
* $p < .05$; ** $p < .01$; *** $p < .001$.

crawling postures. However, no particular crawling postures were obligatory. Most dramatically, half of the sample skipped the belly-crawling period. There was no evidence that crawling postures mark discrete stages. Rather, most infants displayed multiple postures simultaneously. In addition, we showed that the entire period of crawling, from belly to hands and knees, is characterized by continuous improvements in crawling proficiency as infants moved more quickly and efficiently from place to place. Although the observational design of the current study precludes definitive answers about developmental mechanisms, the richness of these descriptive data provides suggestive evidence about the roles of infants' age, body dimensions, and experience in promoting changes in infants' crawling postures and crawling proficiency.

Stage-like Transitions: What Makes Infants Crawl?

Infants' first year is characterized by an impressive list of motor achievements. A central question for stu-

Table 5 **Zero Order Correlations of Crawling Proficiency at First Hands-Knees Crawling Session**

Predictor Variables	Proficiency					
	Velocity	Cycle Time	Swing Time	Stance Time	No. Cycles	No. Steps
Age at HK onset	.51*	−.43*	−.25	−.48*	−.50*	.53*
Experience:						
Pivot	.59**	−.57**	−.61**	−.56**	.35	−.46*
Belly steps	.63**	.65***	−.53**	−.58**	.58**	−.66**
Belly crawling	.66***	−.68***	−.56**	.61**	−.53*	−.64**
Rock	.36	−.40	.55**	−.32	−.23	.32
Hands-knees steps	.30	−.44*	.52*	−.39	.39†	−.46*
Sit to prone	.46*	.33	−.39†	−.34	.42†	−.47*
Prone to sit	.65**	−.49*	−.29	.53**	−.50*	−.51*
Body dimensions:						
Height	.45*	−.39†	.33	−.38†	−.27	.28
Weight	.18	−.29	.21	−.24	−.15	−.12
Leg	.31	.24	−.08	−.20	.16	−.14
Head	.21	−.28	−.36	.24	−.13	−.18
Ponderal index	.50*	.29	.27	.35	.27	.33

† $p < .10$; * $p < .05$; ** $p < .01$; *** $p < .001$.

Table 6 Partial Correlations of Crawling Proficiency at First Hands-Knees Crawling Session Controlling for Infants' Age at Hands-Knees Onset

	Proficiency					
Predictor Variables	Velocity	Cycle Time	Swing Time	Stance Time	No. Cycles	No. Steps
Experience:						
Pivot	.39$^+$	−.43$^+$	.62**	−.37$^+$	−.02	.17
Belly steps	.54*	−.57**	−.49*	−.47*	−.46*	−.55*
Belly crawling	.54*	−.60**	−.52*	−.48*	−.37	−.51*
Rock	.19	−.27	−.51*	.15	−.03	−.13
Hands-knees steps	.18	−.35	−.48*	−.28	−.29	−.35
Sit to prone	.17	−.04	.32	.01	−.11	−.15
Prone to sit	.54*	−.36	−.20	−.39$^+$	.35	−.34
Body dimensions:						
Height	.10	−.11	−.23	.01	.22	.24
Weight	−.14	−.07	−.08	.05	.18	.26
Leg	−.16	.16	.17	.27	.42$^+$	.47*
Head	−.25	.05	−.27	.18	.38$^+$	.34
Ponderal index	−.30	.07	.16	.11	.01	.05

$^+ p < .10$; $^* p < .05$; $^{**} p < .01$.

dents of motor development is why infants sit, crawl, or walk, and so on, when they do. Increase in infants' age was associated with increasingly erect crawling postures. Traditionally, researchers attributed such age-related changes to neural maturation. As in previous research (e.g., Freedland & Bertenthal, 1994), however, infants' age at belly and hands-and-knees onset varied widely (*range* = 4.34 and 7.00 months, respectively). Such large differences in age suggest that the timing of crawling onset may not be due entirely to neural maturation (Freedland & Bertenthal, 1994). As recognized by previous researchers (e.g., Burnside, 1927; Freedland & Bertenthal, 1994; Gesell, 1946; McGraw, 1945; Shirley, 1931), various biomechanical and psychological factors also may contribute to the development of crawling. Body dimensions, for example, were related to the timing of both belly and hands-and-knees onset. Slimmer, smaller infants tended to crawl earlier than chubbier, more top-heavy babies, suggesting that crawling may depend in part on how much weight infants must support and propel forward.

Belly crawling consisted of idiosyncratic, arduous gait patterns that were nonetheless functional for mobility. Because the abdomen rests on the ground during belly crawling, balance requirements are minimal and timing of limb movements is relatively unconstrained. One possibility is that changes in infants' arm strength and individual differences in infants' motivation may contribute to the onset of belly crawling. Arm strength is critical to overcome frictional forces from the torso and legs scraping against the ground. In this study and in previous ones (e.g., Ames, 1937), infants always used both arms for propulsion. Motivation may be especially important for belly crawling because forward movement involves abrading the underside in army crawls or crashing onto the chest in inchworm crawls. Former belly crawlers may have been more motivated to move than non-belly crawlers because infants in both groups exhibited occasional belly steps and belly flops as they shifted from rocking to prone positions. Uncomfortable experiences with belly scraping or belly flopping may have led non-belly crawlers to await a more comfortable method of long distance travel.

Apparently, variable experience does not prompt a necessary selection process in a search for optimally efficient or stable forms of crawling. Despite variable experience with multiple belly-crawling patterns, infants showed no evidence of selecting an optimal belly-crawling pattern. As in Freedland and Bertenthal's (1994) study, belly crawlers exhibited variable combinations of arms and legs to propel forward and keep balance and variable patterns of timing between arms and legs. However, in contrast to Freedland and Bertenthal's (1994) study, all infants in the current study displayed a consistent, diagonal gait pattern immediately after hands-and-knees onset, and crawling was restricted primarily to the standard two hands and two knees pattern. There was no subsequent decrease in variability to suggest a necessary selection process for diagonal gait and no evidence that experience was required to perfect its use. However, sporadic practice with diagonal gait during the belly period may have promoted less deviation from diagonal gait in former belly crawlers compared with non-belly crawlers after infants began crawling on hands and knees.

Arm strength, balance, and coordination requirements are high in hands-and-knees crawling because the torso must be stabilized in midair as the limbs move forward (Alexander, 1992). All infants appeared highly motivated to move on hands and knees, and most infants passed criterion for hands-and-knees onset within a month of taking occasional steps on hands and knees. Freedland and Bertenthal (1994) argued that arm strength may be the rate-limiting variable for onset of hands-and-knees crawling because no infant in their sample displayed the hands-knees rocking posture prior to crawling onset. However, most infants in the current study and in previous research rocked for several seconds in extended bouts or took occasional steps on hands and knees prior to crawling to criterion (e.g., Ames, 1937; Gesell & Ames, 1940; Goldfield, 1989). These data suggest that infants do have sufficient arm strength to support the body in midair many weeks prior to onset of hands-and-knees crawling. An alternative possibility is that infants may lack the ability to maintain dynamic balance while generating several consecutive crawling cycles. Infants sometimes misplaced their hands and lost balance in the week preceding hands-and-knees onset, and sometimes they tipped sideways midcycle.

How then might infants settle on the diagonal gait pattern for hands-and-knees crawling? Various patterns of interlimb timing are available long before and after hands-and-knees onset, but apparently diagonal gait is preferred only in particular movement contexts. Katona (1989) elicited homologous crawling movements (both arms and both legs move together) in neonates by placing them prone on a downward slide, and McGraw (1939) elicited diagonal crawling movements in neonates when she immersed them in water. On flat, dry land, belly crawlers produce the diagonal pattern only 16% of the time (Freedland & Bertenthal, 1994), and some adults use an ipsilateral gait (moving right arm and right leg together) to creep on hands and feet (Sparrow, 1989). Possibly, diagonal gait is an immediate response to the biomechanical constraints of keeping balance and moving forward on hands and knees, where infants draw on one of several previously available patterns. Diagonal interlimb coordination may be the most stable solution on hands and knees because it keeps the center of mass moving in a forward direction with minimal destabilizing torques from the center of mass shifting from side to side and to and fro. An ipsilateral gait, in contrast, shifts the center of mass from side to side around the median plane of the body but may be easiest when the hips are elevated during hands-and-feet gait, as in adult creeping.

Continuous Changes: What Makes Crawling Improve?

Duration of experience was related to gradual, continuous improvements in infants' crawling proficiency. When infants practiced the same hands-and-knees movements over and over, hands-and-knees proficiency increased. More interesting, the beneficial effects of experience were not limited to particular crawling patterns. That is, practice executing one type of crawling posture had beneficial effects on postures that used different parts of infants' bodies in different temporal patterns. For example, despite step-to-step and week-to-week variability in infants' inelegant belly patterns, belly crawlers showed continuous improvement in crawling proficiency. Duration of experience practicing belly crawling and precursory postures predicted hands-knees proficiency, and measures of experience retained their predictive power when we controlled for infants' age or body dimensions. Interestingly, postures less similar to hands and knees crawling (e.g., belly crawling, belly steps) predicted more measures of proficiency than postures more similar (e.g., rocking, hands-knees steps). Most impressive, despite structural differences between belly and hands-and-knees crawling, former belly crawlers showed robust, positive transfer from belly to hands and knees. In their first week on hands and knees, former belly crawlers were more proficient than non-belly crawlers, and the belly advantage lasted for several weeks. The difference between former belly crawlers and non-belly crawlers was not due only to infants' age or body dimensions. Rather, the belly-crawling advantage remained for each proficiency measure when we controlled for infants' age and body dimensions at hands-and-knees onset.

These results suggest that facilitating effects of experience may result from shoring up constituents common to all types of crawling. For example, precursory crawling experience may strengthen infants' arms, allowing them to overcome frictional forces on the belly and to resist gravity more easily on hands and knees. Belly flopping from more to less erect postures and taking an occasional step may give infants experience coping with the consequences of disequilibrium, perhaps drawing attention to visual and mechanical information for balance control. Belly crawling transports infants from one place to another, perhaps reinforcing infants' motivation to go. Finally, crawling yields feedback about controlling posture over the entire body while moving both upper and lower extremities (e.g., Reed, 1982). Prior to crawling, infants' experience is limited to controlling head and trunk while they move their arms, for instance in reaching.

Although underlying constituents of various crawling postures remain speculative, the counterintuitive results of this study suggest that experience-related changes can exert beneficial effects on motor development without associative pairing between particular muscle responses. Transfer is not limited to skills where infants practice the same movements over and over. However, the beneficial effects of experience may be specific to postures sharing the same underlying constituents (e.g., Adolph, 1997; Zelazo et al., 1993). In the current study, former belly crawlers walked later than non-belly crawlers and former belly crawlers showed no advantage in other motor skills. These results suggest that by examining situations where experience does and does not show evidence of transfer, we may better understand the factors underlying developmental change.

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