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Transitions in the development of locomotion

Abstract

Previous research on the development of locomotion has focused primarily on identifying the stage-like milestones en route to independent mobility. In contrast, dynamic systems theory directs researchers' attention to the process of change itself, to the transitions between stages and the mechanisms that underlie the transitions. In this paper, we describe five transitions in the development of independent locomotion. We show that research on transitions provides new insights into understanding long-standing puzzles of developmental change.

Introduction

Decades of research on locomotor development have revealed much about the characteristics of successive locomotor skills. However, we still know surprisingly little about the transitions between new locomotor skills and the mechanisms that underlie developmental change from one locomotor milestone to the next.

Normative studies in the first half of this century focused on identifying the stage-like milestones of locomotor development. Pioneering researchers such as Gesell (e.g., 1939), McGraw (e.g., 1945) and Shirley (1931) provided detailed, qualitative descriptions of ordered sequences of stages for prone and upright locomotion. These descriptions led to developmental inventories of the typical ages and stages when infants begin crawling on their bellies, progress to crawling on hands and knees, pull to an upright standing position, walk with hands held or cruise sideways holding onto furniture for support, and finally walk independently (e.g., Bayley, 1969; Frankenburg & Dodds, 1967). However, the traditional focus on *when* skills develop resulted in little insight into *how* skills develop.

More recently, advances in recording technologies allowed researchers to observe detailed biomechanical and kinematic changes in various locomotor milestones. For example, modern researchers have provided detailed information about the development of postural stability in upright stance (Bril & Breniere, 1993; Shumway-Cook & Woollacott, 1985; Woollacott, Shumway-Cook, & Williams, 1989), the achievement of steady state velocity in independent walking (Bril & Breniere, 1989), and the relation between duration of the gait cycle and walking speed (Bril & Breniere, 1989; Clark & Phillips, 1987; Phillips & Clark, 1987). However, with their focus on collecting detailed kinematics of particular locomotor milestones, modern researchers lost the big picture of how locomotion develops from one milestone to the next.

In contrast to both the normative and biomechanical approaches, dynamic systems theory focuses researchers' attention on the important transitions between milestones. Since its introduction to the behavioral sciences in the early 1980s, dynamic systems theory has captured the imagination of an increasing number of developmental psychologists (e.g., Smith & Thelen, 1993; Thelen, 1984, 1988; Thelen & Smith, 1994). At the heart of this interest lies an explicit focus on the transitions between skills and on the process of change from one stable state to the next. Transitions reveal a system in transit, thereby providing a window into the process of change and its underlying mechanisms.

In the present paper, we combine ideas from dynamic systems theory with the merits of the normative and biomechanical approaches. Our goal is to set the stage for a dynamic systems account of the development of locomotion that provides kinematic descriptions of the transitions between various milestones while preserving the big picture from crawling to independent walking. In the first section, we report a series of studies on the transitions between major milestones of crawling, supported walking, and independent walking. In the second section, we use these data on transitions to address three long-standing puzzles of developmental change: Does development move toward more stable, less variable solutions? What are the mechanisms for spurring developmental change and how can we reconcile underlying continuity with apparent stage-like discontinuity? And finally, how might experience influence developmental change?

Transitions in the development of locomotion

Typically, the major milestones of infant locomotion involve a sequence of increasingly erect postures (e.g., Bayley, 1969; Frankenburg & Dodds, 1967) with accompanying transitions between milestones. As illustrated schematically in the left-hand column of Figure 1, most infants progress from:

1. immobility in a prone position to crawling forward with the belly dragging along the ground;
2. belly crawling to crawling on hands and knees;
3. hands-and-knees crawling to cruising sideways holding onto furniture for support;
4. sideways cruising to cruising frontward gripping onto furniture with one hand or walking frontward with hands held by a parent for support; and
5. frontward cruising/supported walking to independent walking.

Even Gesell (1939) and McGraw (1945) however, recognized that developmental progression is variable and that the sequence of milestones is not obligatory. Infants display large individual differences in the timing of each milestone and some infants skip intermediate milestones, revert to earlier ones, or display multiple milestones simultaneously. For example, as shown in the right-hand column of Figure 1, some infants skip belly crawling or never crawl at all, some crawl and cruise simultaneously, and some regress to earlier milestones before moving on to more advanced forms of locomotion.

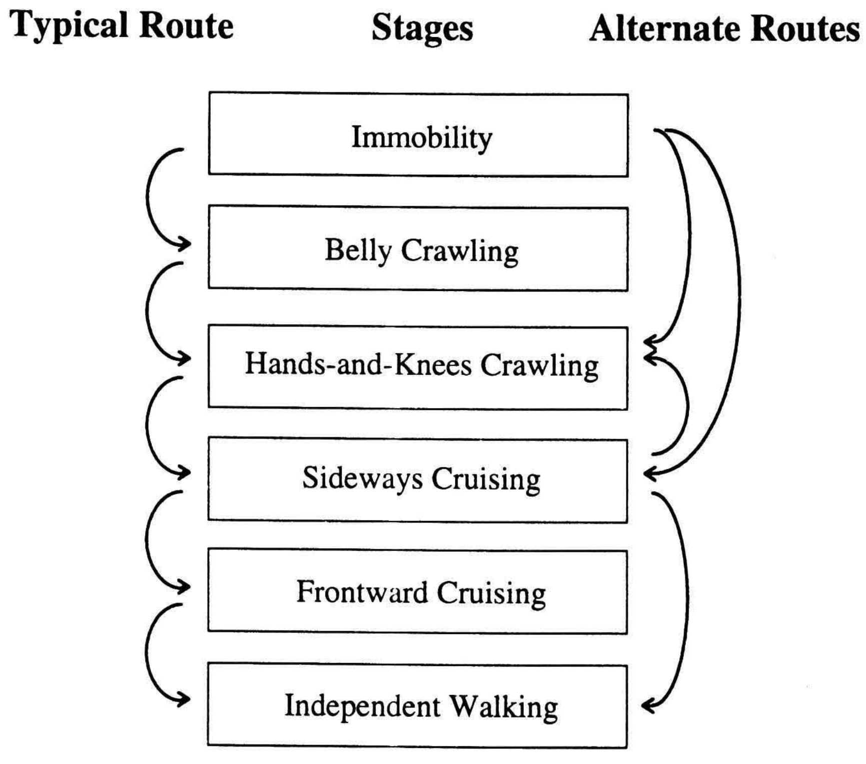

Fig. 1. Routes to independent walking.

The transition from immobility to crawling

For most infants, the first success at independent mobility is crawling. Typically, crawling begins with clumsy attempts to move forward with the belly dragging along the floor, and ends with stable erect movement on hands and knees with the abdomen suspended in the air.

In a recent longitudinal study, we observed 28 infants from their first attempts at moving in a prone position until they walked independently (Adolph, Vereijken, & Denny, 1997; Vereijken, Adolph, Denny, Fadl, Gill, & Lucero, 1995). The transition from immobility to crawling proper (defined as crawling 91 cm on 3 of 4 consecutive trials without pausing longer than 3 s between steps) was marked by a number of precrawling movements: Taking an occasional step or two on belly or hands and knees, pivoting in circles, rocking on hands and knees and moving from prone to sitting positions and vice versa. Prior to crawling proper, 27 of 28 infants pivoted, 20 infants practised occasional steps on belly, 25 rocked on hands and knees, 27 practised occasional steps on hands and knees, 25 shifted from sitting to prone, and 15 from prone to sitting positions. Pivoting or occasional belly steps appeared earliest (M = 6.3 months of age); occasional hands-and-knees steps appeared latest (M = 7.7 months). On average, infants displayed precrawling movements for approximately one month prior to crawling proper.

Fifteen infants displayed a transition from precrawling movements to belly crawling (M = 6.9 months of age). The most striking characteristic of belly crawling was its enormous richness in movement patterns, from step to step, from session to session, and from infant to infant. Across infants and trials, babies used 22 different combinations of arms, belly, knees, and feet for propulsion and balance. On average, 30%-50% of displayed patterns were asymmetrical, favouring the right leg for propulsion and balance. Despite high and continued variability in belly crawling patterns, infants' proficiency at belly crawling increased: They moved faster and took larger steps. And, despite weeks of belly crawling experience, no infant showed consistent patterns of interlimb timing over weeks of belly crawling.

The remaining 13 infants displayed a transition from precrawling movements to hands-and-knees or hands-and-feet crawling (M =7.9 months of age). In contrast to the belly crawlers, these sole hands-and-knees crawlers demonstrated low variability in crawling patterns from the very first week, displaying only 8 different combinations of arms, knees and feet by using primarily two hands and two knees for propulsion and balance. On average, only 0%-10% of displayed patterns were asymmetrical. Moreover, sole hands-and-knees crawlers displayed a consistent pattern of interlimb timing: From their first week of crawling proper, infants used a diagonal gait pattern with contralateral limbs moving simultaneously. A consistent diagonal gait pattern was also found by Freedland and Bertenthal (1994) in a study of the transition to hands-and-knees crawling. As in belly crawling, infants' proficiency at hands-knees crawling increased over weeks of experience.

The transition from belly to hands-and-knees crawling

In our longitudinal study (Adolph et al., 1997; Vereijken et al., 1995), each of the 15 infants who crawled initially on their bellies showed a subsequent transition from belly to hands-and knees crawling (M = 8.5 months of age). Although these exbelly crawling infants displayed no consistent pattern of interlimb timing in their last week of belly crawling, all exbelly crawlers showed the same consistent diagonal gait pattern as the sole hands-and-knees crawlers from their very first week on hands and knees. Overall, hands-and-knees crawling was more proficient than belly crawling: Infants moved faster and took larger steps. Surprisingly, there was no decrement in crawling proficiency across the transition from belly to hands-and-knees crawling. Rather, velocity and step size increased and cycle time, swing and stance times remained at the same level from infants' last week of belly crawling to their first week of hands-and-knees crawling.

Most important, in their first weeks on hands and knees, the 15 exbelly crawlers were more proficient at hands-and-knees crawling than the 13 infants who skipped the belly crawling period. That is, despite dramatic differences in every measure of interlimb coordination and timing between belly and hands-and-knees crawling, prior experience with belly crawling resulted in more proficient hands-and-knees crawling later on. This finding did not result from differences in the age or body dimensions of exbelly crawlers and sole hands-and-knees crawlers. Experience with precrawling movements and belly crawling were stronger predictors of infants' proficiency on hands and knees than their age and body dimensions, and experience retained its predictive power with measures of age and body dimensions partialled out. Moreover, precursors more dissimilar to hands-and-knees crawling (e.g., occasional steps on belly, pivoting in circles, and shifting from sitting to prone positions) were stronger predictors of hands-and-knees proficiency than more similar precursory movements (e.g., occasional steps on hands and knees and rocking on hands and knees).

The transition from hands-and-knees crawling to sideways cruising

Typically, infants' first success at upright locomotion is walking sideways holding onto furniture for support (Frankenburg & Dodds, 1967). After infants can pull themselves to a stand, they experience a period of sideways cruising. Often, the period of pulling up or cruising overlaps with the period of hands-and-knees crawling. For example, in our longitudinal study (Adolph, 1997; Adolph et al., 1997), infants pulled to a stand at an average age of 8.0 months and began sideways cruising at 8.5 months. Despite the frequency of sideways cruising, this form of upright locomotion has received little attention in the developmental literature.

In a recent longitudinal study of cruising (Vereijken & Waardenburg, 1996), we observed 4 infants weekly from their first success at pulling to a stand until they walked independently (defined as walking the length of the rail without touching it with the hands). Each week, infants were placed at one end of a wooden handrail at their chest height and enticed to cross to the far end of the handrail.

The transition from standing immobile to cruising sideways was marked by a sequence of precursory upright movements. First, infants bounced up and down, then they rocked from side to side, and finally, they made an occasional step in a sideways direction. Infants retained a firm grip on the rail with both hands while displaying these precursory movements.

All four infants displayed a transition from precruising movements to cruising sideways (M = 9.7 months of age; range = 8.1-11.1 months). Initially, sideways cruising required the use of both hands and both feet. In other words, infants made a transition from crawling on four limbs to moving upright with four limbs. However, in contrast to the consistent diagonal gait pattern observed in hands-and-knees crawling, cruising was not characterized by a diagonal gait. On average, infants cruised sideways using separate, successive limb movements on 62.1% of the total trial time, interspersed with frequent, long pauses for 23.8% of the total trial time. The typical sequence of limb movements while cruising in a righthand direction was right hand, left foot, right foot, left hand, right hand, etc. When two limbs moved simultaneously (M = 14.2% of trial time), cruising progressed primarily in a diagonal gait pattern (M = 13.7% of trial time).

The transition from sideways cruising to frontward cruising

On average, infants cruised sideways for 14.5 weeks (range = 7-20 weeks). During this period, limb movements increasingly overlapped and pauses between limb movements decreased in length and number, eventually taking only 2.3% of the total trial time. In addition, the sequence of limb movements became more variable. During this period, infants displayed a gradual transition from cruising sideways to frontward cruising. All infants began to turn their feet in a frontward direction but made the transition to full frontward cruising only when one hand released the handrail for the entire trial. This transition was made by 3 of the 4 infants. In their last week of frontward cruising, infants typically moved two or three limbs simultaneously (M = 76.8% of trial time) in variable sequences. On average, when two limbs moved simultaneously, they were the diagonal limbs in 30% of total trial time, ipsilateral limbs in 20.6% of trial time, and the two hands in 9.2% of trial time. Frontward cruising was more proficient than sideways cruising: Infants moved faster and took larger steps.

The transition from frontward cruising to independent walking

In our longitudinal study of cruising, infants maintained balance by gripping the handrail. In other studies of infant locomotion, researchers observed infants as they walked frontward with a parent holding their hands and as they walked independently. Without parents' support, infants modified their walking gait to maintain upright balance. Although some measures show improvement — e.g., newly independent walkers maintain a smaller lateral distance between their feet (Shirley, 1931), less external rotation of the feet and hips (Burnett & Johnson, 1971), and less bending at the hips (Statham & Murray, 1971) — several important measures show a decrement when infants are required to keep balance without manual support. Compared with newly independent walkers, supported walkers take shorter steps (Sutherland, Olshen, Cooper, & Woo, 1980), they show a higher cadence (Statham & Murray, 1971), less synchronization of joint rotations (Thelen & Cooke, 1987), less variability in interlimb phasing and more consistent step lengths (Clark, Whitall, & Phillips, 1988), more reciprocal activation in muscle actions (Okamoto & Goto, 1985) and less co-contraction of muscles (Forssberg, 1989; Thelen & Cooke, 1987).

In a large study of the development of walking, we collected kinematic measures of walking gait from the footprints infants left as they walked over a long strip of butcher paper wearing inked tabs on the soles of their shoes (Adolph, Vereijken, Byrne, & Ilustre, 1996). We observed 156 infants (M = 14.4 months of age, range = 9.4-17.5 months) with 0.1-8.3 months of walking experience (M = 2.8 months). Forty-five of these babies were observed longitudinally. By using a moving frame of reference (see Adolph, 1995), we were able to take into account infants' twists and turns in their path of progression when calculating measures of walking skill.

On average, infants exhibited the transition to independent walking (defined as travelling 321 cm on 3 of 4 consecutive trials without pausing longer than 3 s between steps) at 11.5 months (range = 7.9-14.9 months). From their very first weeks of walking, infants showed strong trial to trial consistency in all gait measures. Over weeks of walking, infants took longer steps, displayed smaller lateral distances between their feet, pointed their feet more straight ahead, and maintained a straighter path of progression while step to step variability decreased. These findings are consistent with reports of earlier researchers who also found improvements in kinematic measures of infants' foot placement with weeks of walking experience (e.g., Burnett & Johnson, 1971; McGraw, 1945; McGraw & Breeze, 1941; Shirley, 1931).

Likewise, measures of interlimb timing and joint angles also show improvements over weeks of walking. Infants show approximate 50% phasing between leg movements from their first weeks of walking, but variability in timing decreases (Clark et al., 1988), and infants spend less time with both feet on the floor during periods of single limb support. Increase in walking speed results primarily from longer step lengths, rather than changes in cadence as is the case with adults (Bril & Breniere, 1992). From their first weeks of walking independently, infants stabilize their head (Bril & Ledebt, 1998; Ledebt, Bril, & Wiener-Vacher, 1995) and hip joints (Assaiante, Thomachot, & Aurenty, 1993).

The well-documented deficiencies in infants' first weeks of walking may result from poor balance control during periods of single limb support (e.g., Adolph, 1997; Bril & Breniere, 1992). That is, infants may have trouble keeping balance on one leg while the other leg swings forward resulting in shorter steps, longer double support periods, shorter swing times, and higher cadence. To maximize their base of support, infants may place their legs laterally and point their toes and hips to the sides.

Understanding the process of development: Clues from transitions

Inspired by a dynamic systems approach, we examined changes in the kinematics of infants' locomotor skill at five major transitions in locomotor development. In the following section, we show how evidence from transitions provides a useful way for testing the tenets of dynamic systems theory and for understanding the process of developmental change.

Does development move toward stable solutions?

Central to the dynamic systems framework is the notion that development is marked by periods of stability with periods of instability and high variability at the transitions between stable solutions (e.g., Thelen & Smith, 1994). Is this indeed the case? And, if so, how might the movement system clamp down on variability with the emergence of a new behavioral milestone?

Eventually, all infants settled on a stable solution for moving their limbs in independent walking. However, evidence from the transitions between locomotor milestones shows that development can progress in both directions — from more to less variable solutions and from less to more variability. Sometimes the transitions are marked by increased variability and sometimes not. For example, in accordance with dynamic systems tenets, the transition from sideways to frontward cruising was marked by increased variability during the period of change. However, in contrast to dynamic systems tenets, the transition from belly crawling to hands-and-knees crawling showed no change in variability prior to the transition and a dramatic decrease in variability of interlimb coordination and timing after the transition. Apparently, changes in stability and variability of performance are not dictated by a developmental principle, but rather are task-dependent.

Two factors may influence variability of performance. First, task constraints may reduce the options available for infants' movements. When constraints are high, whether originating in the infant, the environment, or the goals of the task (Newell, 1986), there is little choice in how to perform the task. Second, infants may recognize the need to maintain control over disruptive reactive forces, either to secure the outcome or to preserve their own safety. One way to keep control is to freeze otherwise uncontrolled parts of the body or degrees of freedom so that extraneous movements cannot contribute to generation of reactive forces (Bernstein, 1967). The literature on adult motor learning points to such reduction of degrees of freedom (e.g., McDonald, van Emmerik, & Newell, 1989; Newell & van Emmerik, 1989; Sparrow & Irizarry-Lopez, 1987; Vereijken, van Emmerik, Whiting, & Newell, 1992; Vincken & Denier van der Gon,1985).

How might task constraints and reactive forces explain bi-directional changes in variability in the development of infant locomotion? During belly crawling, neither factor plays an important role. There are few constraints on how infants can move their limbs and negative effects of reactive forces are negligible because infants rest firmly on their bellies. Thus, belly crawlers are free to discover multiple solutions for moving and there is no reason for infants to settle on a stable solution. In contrast, hands-and-knees crawling has more stringent constraints on balance control and there is risk from falling. The confluence of both factors may lead to a stable, less variable diagonal gait pattern. In sideways cruising, balance constraints are even more serious than in hands-and-knees crawling. There is risk of losing control over reactive forces and falling from an upright position. Thus, beginning cruisers may clamp down on degrees of freedom, showing little variability in performance, but with increasing experience, more degrees of freedom and more variability are allowed into the movement patterns as infants discover that they can cruise in a frontward direction.

What are the mechanisms for spurring change?

One of the enduring puzzles of development concerns the mechanisms that spur developmental change and how this change can appear continuous at the local level of developing components but discontinuous and stage-like at the global level of developing behavior.

According to dynamic systems theory, the emergence of each locomotor milestone requires the functional readiness of many underlying variables, each following its own developmental trajectory and changing continuously at its own rate (Thelen, 1986). New behavioral milestones may appear in a stage-like fashion only when all the underlying components are developed sufficiently. In other words, the last component skill to develop acts as a control parameter to push the behavioral system into a new configuration. At different points in development, different variables can serve as control parameters, and the last component to develop may differ across individuals. The evidence from transitions between locomotor milestones is consistent with this account.

For the transition from precrawling to belly crawling, possible control parameters may be infants' arm strength and their motivation to go somewhere. Arm strength is required to overcome friction when the belly is dragged along the floor. Accordingly, prior to crawling forward on their bellies, most infants pivoted in circles, requiring less arm strength for movement. Motivation may be crucial because belly crawling is uncomfortable and arduous. The sole hands-and-knees crawlers did practice occasional belly steps at the same age as the exbelly crawlers, suggesting that they had the requisite arm strength, but the former group never progressed to travelling long distances on their bellies. Possibly, the sole hands-and-knees crawlers lacked the motivation for arduous belly crawling and awaited patiently a more comfortable method of locomotion.

The ability to keep balance may be the control parameter for the transition to crawling on hands and knees, where the torso must be stabilized in mid-air as the limbs move forward. The stable pattern of diagonal interlimb coordination observed in hands-and-knees crawling may result from these balance constraints because the diagonal pattern keeps the center of mass most stable between the supporting limbs (Freedland & Bertenthal, 1994). Apparently, arm strength is sufficiently developed to support body weight in a more erect posture prior to the transition to hands and knees because most infants rocked on hands and knees prior to hands-and-knees crawling. However, arm preference may serve as a control parameter for hands-and-knees crawling. During the period when infants rocked symmetrically on hands and knees, Goldfield (1989) found that the development of an asymmetrical arm preference in reaching marked the transition to hands-and-knees crawling. Possibly, the symmetry between the two supporting hands needs to be broken in order for infants to crawl forward.

The transitions to sideways and frontward cruising may depend on leg strength and new strategies of balance control. After infants can pull to a stand, continuous changes in leg strength may underlie the ability to support body weight on one leg as they move sideways. Sideways and frontward cruising, and supported walking with an adult holding their hands may require infants to discover new ways to shift and recover balance in an upright position using the arms to bolster their balance. By shoring up the underlying balance component via manual strategies, infants can exhibit more mature patterns of interlimb coordination in their leg movements.

Finally, in independent walking, infants require sufficient balance control and leg strength to move forward on their own. Several investigators have suggested that the control parameters for the transition to independent walking are the ability to keep balance and to support body weight entirely on one leg (e.g., Thelen, 1986; Whitall & Getchell, 1995). In addition, motivational factors also may contribute to the transition to independent walking. Biringen, Emde, Campos, and Appelbaum (1995), for example, suggested that differential experiences in affective communication during and prior to the transition were related to the age at which infants began walking independently.

What is the role of experience?

On a dynamic systems account, developmental change reflects the history of the behavioral system (Thelen & Smith, 1994). In particular, repeated experiences in a specific context build up attractors, making certain behaviors more likely than others in the practised situation. For example, infants quickly learn to kick their legs to activate an overhead mobile in operant conditioning paradigms. The frequency of kicking at later testing depends on reinstating the particulars of the task and the context — mobile elements and crib bumpers (e.g., Borovsky & Rovee-Collier, 1990; Rovee-Collier, Griesler, & Early, 1985; Shields & Rovee-Collier, 1992). Likewise, infants' search behavior in object permanence tasks reflects the frequency of their experience with the particulars of the task — properties of the hidden objects, hiding locations, and distracters (Thelen, Smith, and Titzer, 1995). Infants searched most often in the experienced location and the trajectory of their arm movements became more and more regular with repetition.

Similarly, in locomotor development, repeated experiences can result in context-specific changes. For example, practice moving the legs in an upright position resulted in earlier onset of independent walking (Zelazo, Zelazo, & Kolb, 1972), but practice with one motor skill showed no transfer to new skills with different postural constraints (e.g., Zelazo, Zelazo, Cohen, & Zelazo, 1993). Accordingly, our data revealed improvements in each locomotor skill with repeated practice. With weeks of experience, infants crawled, cruised, and walked more proficiently.

However, our data showed that experience also may produce more generalized effects by shoring up the underlying components of dissimilar motor skills. Most striking, infants showed perfect transfer over the transition between belly crawling and hands-and-knees crawling, despite large differences in movement patterns, interlimb coordination, and interlimb timing in the two forms of crawling. These results indicate that specific experience with particular movement patterns, particular coordinative timing patterns, or even particular muscle actions is not critical for transfer.

Rather, the positive transfer from belly crawling to hands-and-knees crawling may have resulted from shoring up more general factors underlying both forms of crawling, like strengthening the arms, gaining experience coping with the consequences of disequilibrium, and drawing attention to visual and mechanical information for balance control. In particular, generalized experience with postural control may facilitate transfer between the two forms of crawling (see also Reed, 1982, 1989). Before infants execute precrawling or crawling movements, their movement experience is limited to controlling the head and trunk in prone and sitting positions. In crawling, however, infants experience the movement of all their body parts simultaneously as all four limbs move and they stabilize their torsos. Furthermore, experience with belly crawling may reinforce the infant's motivation to go places (Adolph et al., 1997).

Future challenge

Developmental research in the spirit of dynamic systems theory has provided new insights into the process of change. This approach has been instrumental in redirecting developmental inquiry from description of ages and stages to the process of change itself. Changing the focus of investigation and the questions asked, however, is but a first step in a dynamic systems approach. For many investigators, the requisite next step is a mathematical formalization of the transitions and of the control parameter that pushes the system through its respective stages. However, this mandate may reflect too simple a picture for grasping developmental change. First, as we illustrated above, the control parameter in the development of independent locomotion does not remain stationary but changes from transition to transition. Currently, dynamic systems theory has no mathematical language for control parameters that have their own dynamics. Second, even if it were possible to model a succession of control parameters, the control parameters are likely to differ in different individuals. Finally, the component that develops last is given center stage as the control parameter for the transition. It is, however, the functional readiness of several underlying variables that engenders a developmental transition. Thus, the future challenge is to formalize a multi-factor, multi-level system of change if we are to capture the nature of the developmental process.

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