The Road to Walking: What Learning to Walk Tells Us About Development

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Learning to walk is one of the great achievements in human development. One of the dual aims of this chapter is to describe the developmental progression of locomotion, ranging from the spontaneous leg kicks of fetuses and neonates to the seemingly superhuman abilities of African load carriers and Tarahumaran endurance runners. Our chief aim, however, is to use the study of walking as an exemplar and metaphor for the process of development. The century-old study of the ontogeny of walking—from the early case studies and classic descriptions of motor milestones to the modern recognition of the importance of experience in all forms of locomotion—provides one of the clearest, empirically-based illustrations of the pragmatic and theoretical issues, methodological advances and conceptual pitfalls, and general principles and processes of development that is available to psychology.

Keywords: affordances, crawling, developmental stages, fetal motility, locomotion, mobility, motor milestones, navigation, perception-action, posture, walking

Introduction

“Our legs good, two legs better!”

(George Orwell, 1996/1946, Animal Farm, p. 132)

Walking is special. In science, literature, art, and religion, walking upright separates child from infant, man from beast, freedom from slavery, and moral righteousness from turpitude. It is no accident that so much of our developmental iconography depicts upright locomotion as the exalted endpoint on the road of developmental progress.

Walking Upright: Developmental Icons of Progress

The famous picture of “The March of Progress” portraying man ascending from a knuckle-walking ape to erect modern human (Figure 1A) is reminiscent of infants’ ascent from a prone position to upright locomotion on developmental milestone charts (Figure 1B). These iconic images of phylogenetic and ontogenetic progression liken upright walking to a “higher” form in a variety of ways: a dramatic advance in motor development, a triumph in the upward battle against gravity, the attainment of greater stature, and a higher perch on the evolutionary tree.

The orderly march of species in The March of Progress and infants’ normative ascent along the staircase of motor milestones suggest a deterministic sequence toward increasingly more advanced forms. As Gould (1989) points out, the word “evolution” has become a synonym for “progress.” Even the chapter title, “The Road to Homo sapiens,” in the Time-Life book (Howell, 1965) for which The March of Progress was commissioned, suggests a straight path to a mature endpoint. Likewise, the term “milestone” refers to mile markers along a road to a destination. Co-opted by developmental researchers to mark infants’ motor achievements, the word “milestone” has picked up the additional meaning of significant stopping points en route to upright locomotion.

These developmental icons and metaphors are both compelling and dangerous—compelling because they resonate with our hopes for progress and dangerous because iconography has become reified as fact. Gould (1989) criticized The March of Progress for evoking the notion of an evolutionary ladder with upright man on the top rung; rather, he argued, humans are merely a small twig on a branch of the evolutionary bush. The developmental milestone charts misrepresent the process of development in the same way that The March of Progress misrepresents evolution: by implying starting and ending points and a pre-determined link between them. In evolution, as in development, later is not necessarily better. Moreover, pre-human forms reconstructed from skeletal fossils and behavioral forms on a motor milestone chart are not necessarily representative of discrete stages in a progression toward an ideal form or of the diversity of forms actually encountered along the road.

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Aims and Overview

“The beauty of nature lies in details, the message in generality. Optimal appreciation demands both, and I know no better tactic than the illustration of exciting principles by well-chosen particulars.”

(Stephen J. Gould, 1989, Wonderful Life, p. 13)

The title of this chapter reflects the duality of our aims: to describe the road to walking and to show how the ontogeny of walking illustrates general issues of development. Although the data we present involve leg movements, obstacle navigation, and so on, walking is one of the arenas where development plays out most powerfully and the ideas illustrated by research on the development of walking are broadly applicable to development in other domains. The iconography of developmental progress, for example, is not limited to upright locomotion. It is relevant for any field of development that assumes a linear march toward a mature endpoint. Thus, one aim of this chapter is to highlight the developmental issues raised by research on infant locomotion so as to inspire readers from other developmental fields to consider the implications for their topics of inquiry.

Research on the development of walking has a long and colorful history. It contains some of the earliest (Preyer’s 1905 baby biography and Trettian’s 1900 monograph), richest (McGraw’s 1935 descriptions of locomotion in the twins, Johnny and Jimmy), and most excellent research (Thelen’s work on alternating leg movements, Zelazo’s training studies, Gibson’s navigation studies) in the developmental literature. A second aim of this chapter is to impart some of the wonder and excitement of this literature to new readers of motor development.

The first three sections of this chapter focus on the period before infants begin walking. With “Starting Point,” we argue that there is no real beginning for the development of walking; the notion of a starting point for development is misguided. The next section, “Precursors,” examines the distinctions between precursors

Figure 1. Icons of developmental progress. (A) Rendition of “The March of Progress.” (B) Developmental motor milestone chart. Horizontal bars denote normative ranges for age at onset of each skill. Small vertical lines denote median onset ages.
Alternating Leg Movements

Long before infants can walk, they move their legs in an alternating pattern that shares the 50% phasing that is so characteristic of walking: One leg repeats the other leg’s movements halfway through the first leg’s step cycle (think of a person walking on a treadmill). It is this cyclic alternating pattern that distinguishes walking from other gait patterns such as hopping (a synchronous gait) or skipping (an asynchronous gait). Newborn infants cannot walk, of course, but when held upright on their feet on the floor or a tabletop, they sometimes alternate their legs in a slow motion facsimile of walking (Figure 2A). Newborns also execute these stepping movements while held in mid-air, “walked” up stairs or a vertical wall, and even upside down with their feet on the ceiling (Andre-Thomas & Autgaerden, 1966; Peiper, 1963; Thelen & Fisher, 1982; B. D. Ulrich, 1989). This image of “newborn walking” is so powerful that McGraw accorded it the distinction of starting point in her stage-like depiction of walking (1935, 1945), and others have followed suit (Spelke & Newport, 1998).

![Alternating leg movements in infants. (A) Newborn stepping. (B) Supine kicking. (C) Stick diagrams of leg movements in upright stepping and supine kicking in a representative 2-week-old infant. The lines chart the movements of one of the infant’s legs at toe, ankle, knee, and hip every 33 ms.](image)

As shown in Figure 2B, infants also spontaneously alternate their legs while lying on their backs (Thelen, 1979). Supine kicking is relatively common and occurs when infants are mildly aroused, for example, while engaged in social interactions, playing with toys, or fussing (Thelen, 1981). During supine kicking, as in upright stepping, one leg extends while the other bends (Thelen & Fisher, 1982). In fact, upright steps and supine kicks have the same pattern of joint angles, the same temporal structure, and use the same muscle...
groups to initiate the hip and knee flexion that hoists each leg toward the chest (Thelen & Fisher, 1982). If, as you examine Figure 2C, you turn the page 90°, you will see the resemblance between upright steps and supine kicks.

However, upright stepping and supine kicking have different developmental trajectories. Upright steps typically disappear at about 8 weeks of age while supine kicks continue throughout the first year of life (Thelen, 1984). The disappearance of newborn stepping, first described by McGraw (1945), led a generation of developmental researchers to speculate about the neural inhibition of primitive reflexes and the “unlearning” of a pattern that would need to be relearned as toddlers begin to walk (e.g., Forssberg, 1985; Forssberg, 1989; Zelazo, 1983; Zelazo & Kolb, 1972). But the “disappearance” of newborn walking actually results from changes in the body, not just the brain. During the newborn period, infants’ legs increase in mass faster than they increase in strength. Fat, weak legs are difficult to lift in an upright position because infants must fight gravity during the entire flexion motion. While lying supine, gravity helps to pull the flexed knee toward the chest (try marching upright and bicycling supine to see the difference). Various experimental manipulations affirm that a change in the muscle to fat ratio results in different developmental trajectories. With tiny weights attached to their legs to simulate two weeks of growth, 4-month-olds step less. With their legs submerged in a tank of water to alleviate the effects of gravity, they step more (Thelen, Fisher, & Ridley-Johnson, 1984). And if fat non-steppers are held over a motorized treadmill, the upright steps instantly re-emerge. The treadmill does the work of pulling the leg back, which infants are too weak to do on their own (Thelen, 1986).

Alternating leg movements begin even before birth. This has been best documented in experimental procedures with non-human animals. Newborn rats, which are at about the same stage of neural development as human fetuses early in the third trimester of gestation (Clancy, Finlay, Darlington, & Anand, 2007), produce alternating steps after exposure to potent odors or drugs such as L-DOPA (Fady, Jamon, & Clarac, 1998; Norreel et al., 2003; Van Hartesveldt, Sickles, Porter, & Stehouver, 1991). Rat fetuses (Bekoff & Lau, 1980; Brumley & Robinson, 2005) and chick embryos (Bekoff, 1992) also display spontaneous alternating leg movements. The advent of real-time ultrasound imaging in the 1980s revealed that human fetuses begin moving their legs at 7-8 weeks post-conception (de Vries, Visser, & Prechtl, 1982, 1985). However, conventional ultrasound provides only a cross-sectional view of the fetus; the recent introduction of 4-D ultrasound makes it possible to determine the relative timing of movements in both legs. Recent anecdotal reports from 4-D ultrasound images suggest that “walking in the womb” (Piontelli, 2010) appears during the first trimester.

Neurological evidence from animal studies promoted the idea that leg alternation is emblematic of prototypical walking. In particular, studies of the neural mechanisms of animal locomotion attributed rhythmic, alternating patterns of muscle and neural activity to dedicated neural circuitry—central pattern generators—that govern the basic alternating pattern of limb coordination (Grillner, 1985; Guertin & Steuer, 2009; Kiehn, 2006). Central pattern generators for walking are localized in brachial and lumbosacral regions of the spinal cord and are activated by neural pathways descending from the brainstem and cerebral cortex. Bursts of alternating neural activity can be stimulated by sensory feedback from stepping on a motorized treadmill (Forssberg, Grillner, Halbertsma, & Rossignol, 1980), electrical or chemical stimulation of the central nervous system (Forssberg & Grillner, 1973; Shik, Severin, & Orlovsky, 1966), or even application of neurochemicals into a bath containing only the spinal cord in studies of “fictive” locomotion (Clarac, Pearlstein, Pflegger, & Vinay, 2004; Whelan, 2003). These findings led researchers to believe that the development of the neural machinery that produces alternating activity is the starting point for the development of walking.

Given the early appearance of alternation in humans and other animals, its prevalence over the months prior to walking, the generation of fictive alternation by the nervous system, the stereotypic timing of the alternating pattern, and the structural similarities between stepping, kicking, and walking, it is not surprising that prominent researchers in human development (Spelke & Newport, 1998) and movement science (Grillner & Wallen, 2004) have argued that alternating leg movements provide the core of human’s ability to walk. So, is a 50% phasing between legs the core starting point of upright walking? Is a fetus executing alternating leg movements taking its first steps on the developmental march to upright locomotion?

Fetal leg movements may be a starting point, but alternation is not the starting point for the development of walking. One argument against fetal alternation as the starting point is that alternating leg movements do not appear in a developmental vacuum. Even this simple activity has a developmental history. Before rat fetuses and chick embryos express alternation, they move their legs in synchrony (double leg jumps). The transition from synchrony to alternation is associated with crucial changes in the central nervous system, notably a reversal of the effects of some neurotransmitters (including GABA) at synapses (Nakayama, Nishimaru, & Kudo, 2001). Even earlier in development, functional proprioceptive circuits provide fetuses with feedback about the position and pattern of limb
movements. And even before that, fetuses express spontaneous leg activity that contributes to the organization of the developing nervous system, muscles, and bones (Moessinger, 1983).

Other Patterns, Other Dimensions

A second argument against considering fetal and neonatal alternation to be the core starting point of walking is that environmental factors influence the pattern of leg movements. At birth, humans and animals show a distinct bias toward alternating leg movements. But this bias may arise because physical conditions before birth favor alternating leg movements over other patterns, not because alternation is the only possible movement. In the womb, fetuses encounter changes in environmental conditions, such as a reduction of free space in which to move. Extending the legs in utero requires pushing against the amniotic membrane and uterus. Leg extension results in elastic resistance, and moving the legs in alternation is energetically more efficient than pushing simultaneously with both legs (Brumley & Robinson, 2010). These findings suggest that alternation is an adaptive response to moving the legs in a physically demanding environment. Accordingly, other patterns of coordination between the legs should be available to the fetus and neonate.

Indeed, fetuses and neonates spontaneously and deliberately move their legs in many patterns of coordination (single leg kicks, symmetrical double leg jumps, and asymmetrical alternation that differs from 50% phasing). At different points during development, these other patterns may be more common than alternation. Why should alternation receive disproportionate attention when human fetuses are more likely to kick only a single leg, or to flex and extend both together like a fetal jump (Suzuki & Yamamuro, 1985)?

Moreover, human neonates can learn in a few minutes to kick one leg to jiggle an overhead mobile (Thelen & Fisher, 1983). The leg is attached to the mobile by a ribbon such that every kick results in movement of the mobile (Rovee-Collier & Gekoski, 1979). Three-month-olds demonstrate flexible coordination by quickly switching their kicks to the other leg when the experimenter switches which leg is attached to the ribbon (Rovee-Collier, Morrongiello, Aron, & Kupersmidt, 1978), and they alter the topography of their kicking movements if the experimental arrangement is set up with a stricter contingency (Angulo-Kinzler, 2001; Angulo-Kinzler, Ulrich, & Thelen, 2002; Y.-P. Chen, Fetters, Holt, & Saltzman, 2002). Human 3-month-olds and fetal rats also can select among various patterns of leg coordination in the face of changing contextual constraints (Robinson, 2005; Thelen, 1994). Specifically, attachment of a gentle yoke between the two legs causes human infants and rat fetuses to shift from an alternating to a synchronous pattern because the yoke makes the jumping movements less taxing than alternation.

A final argument for why alternation should not be considered the starting point for walking is that functional walking involves much more than generation of a stereotypic walking cycle. Real walking involves flexibility and diversity in patterns of interlimb coordination so as to speed up and slow down, steer and navigate through a cluttered environment, adjust to changes in footing, slope, and loads being carried, and maintain balance through all of these actions. Like alternation, flexibility of interlimb coordination, perceptual guidance, postural control, muscle strength, and the motivation to go somewhere are crucial dimensions of walking. Each has its own developmental history that antedates walking and each contributes to the eventual ability to walk. None (or perhaps all) should be accorded the privileged status of containing the essence of walking.

Precursors

As illustrated in Figure 1, between the first and last images in the developmental progression to walking lies a multitude of increasingly sophisticated forms. How should we consider this parade of forms that precedes upright locomotion? Our developmental iconography suggests that precursory forms are actually prerequisites: In The March of Progress, modern upright man is depicted as the product of a linear evolutionary series; and on the milestone charts, rolling, crawling, standing, and the other developmental milestones are presented as necessary stages en route to walking. In other words, without the earlier forms, you can’t get there from here. In evolution, modern man is the product of a specific ancestral lineage, but the iconography ignores the fits and starts, false leads, and failed experiments along the road. In development, it just ain’t so. None of the depicted forms is an obligatory prerequisite for walking. And an iconic sequence fails to depict the diversity and variability of precursory forms.

Variety of Means for Mobility

Mobility does not wait for walking. Pre-walking infants drag, pull, hoist, and propel their bodies in a wondrous variety of ways (for review, see Adolph & Berger, 2010). Early solutions appear driven by function: Infants will do whatever it takes to move their bodies from one place to another.

The iconic image of crawling on most milestone charts (as in Figure 1B) depicts an infant crawling on hands and knees in a rhythmic near-trot, (right arm and left leg move together and left arm and right leg move
Figure 3. Relative timing of limb movements in a representative infant crawling on (A) hands and knees and (B) belly. Shaded regions represent time when the limb (or belly) was supporting the body. Open regions represent time when the limb (or belly) was moving forward.

together as shown in Figure 3A). In fact, most infants do the iconic crawl. But as illustrated in Figure 4, most infants also “bear” crawl on hands and feet (occasionally switching to an ipsilateral pacing gait where right arm and right leg move together) and in mixtures of hands, knees, and feet (Adolph, Vereijken, & Denny, 1998). They also crawl on hands and buttocks (termed “bum shuffling”) and mixtures of hands, knees, feet, and buttocks (“crab crawls,” where one knee or foot hitches the body forward onto the buttock of the opposite folded leg)—although some of these forms involve more sitting than crawling.

Bear crawls, bum shuffles, and crab crawls are not exotic or rarified forms; approximately 21% of infants bum shuffle (Fox, Palmer, & Davies, 2002). When anthropologist Hrdlicka (1928) proclaimed in Science that he’d discovered African infants who “run on all fours,” the editor was besieged with letters from white, middle-class parents in England, New England, and the American Midwest describing how their infants also crawled on hands and feet. Nearly 100 years later, researchers touted hands-and-feet crawling in a family of Turkish adults as a throwback to an earlier evolutionary stage of walking (Humphrey, Skoyles, & Keynes, 2005). The fact that the Turkish adults crawl on their palms, not on their knuckles like modern apes, was seen as a clue to our evolutionary history—ignoring the fact that infants and children also crawl on palms not knuckles. In fact, Gesell (1946) and McGraw (1941), the two great pioneers in research on motor development, described hands/feet crawling (on palms) and crab crawling as precursory stages of walking. Note that the prone (belly down) and/or sitting (bottom first) positions are not mandatory. Some infants “spider” crawl on hands and feet in a supine position with their bellies up. Even limb movements are not mandatory. Some infants “log roll” from place to place (Trettien, 1900).

Before they are able to suspend their bellies or bottoms off the floor, about half of infants belly crawl with their abdomens on the floor (Adolph et al., 1998). With the belly in the mix, balance constraints are minimal, and a wide variety of forms are possible (Freedland & Bertenthal, 1994). Belly crawls include “commando” styles with the abdomen continually dragging along the floor and bent arms pulling the body, “inchworm” styles where the body raises mo-
mentarily onto knees and/or toes before lurching forward onto the belly, leg-only crawls (sliding forward over folded arms or cheek), asymmetric one-armed and/or one-legged crawls (with the unused limb dragging or held aloft like a flag), and so on (Adolph et al., 1998). Some of these forms are depicted in Figure 4. Propulsion is possible in all directions. Belly crawlers pull forward, push backward, and pivot in circles. Given the possible combinations of limbs, abdomen, and face used for balance and propulsion in belly crawling, patterns of interlimb coordination are extremely variable. Belly crawlers display the near-trot, an ipsilateral camel gait, homologous bunny hops with first front and then back limbs moving together, “swimming” patterns with all four limbs moving together, and various intermediate forms of interlimb timing (see Figure 3B).

Variability in interlimb coordination is unabated over weeks of belly crawling (Adolph et al., 1998; Freedland & Bertenthal, 1994). Infants continually add new variants of belly crawling to their repertoires and frequently switch between forms of belly crawling from one trial (or cycle!) to the next. Nevertheless, belly crawling improves and infants’ limb movements become larger and faster. This developmental pattern defies the typical rule of thumb in motor skill acquisition, in which increases in proficiency of a particular form are accompanied by decreases in (not maintenance of) variability. Belly crawling may prove the exception to the rule because none of infants’ crazy belly crawls are efficient enough to establish a stable, predominant pattern. Yet, all of infants’ arduous, abrading, and chest-thumping belly crawls serve the function of mobility. So, infants try out new forms and proficiency increases by shoring up constituents common to all forms of crawling. Moreover, belly crawlers enjoy benefits that are not available to infants who forego these early forms. When ex-belly crawlers begin crawling on hands and knees or hands and feet, they are twice as proficient in terms of the size and speed of their movements as infants who skip belly crawling entirely (Adolph et al., 1998). The more experience infants have with belly crawling and pivoting, the more proficient they are in their first week on hands and knees.

A variety of upright forms of mobility also precede walking. Most infants convince their parents to participate in their quest for upright mobility, so parents walk stooped over holding infants’ hands overhead, while infants careen and stumble along. Some infants discover that they can “walk” on their knees keeping both hands in the air. They knee-walk to carry objects and to travel short distances between handholds, like Japanese monkeys or chimpanzees transporting armfuls of food. Most infants “cruise” by moving sideways while hanging onto furniture for support (Adolph, Berger, & Leo, 2011; Vereijken & Adolph, 1999). Over weeks of experience, cruisers display less side-to-side wobble (Haeih, Vardaxis, & Ulrich, 2000), transfer more of their weight from their arms to their feet (Vereijken & Albers, 1998), and become more sensitive to the haptic information for balance that they get through their hands (Metcalfe & Clark, 2000). After a period of sideways cruising, some infants turn their body to face forward while cruising with one hand free and only one hand holding the support (Vereijken & Waardenburg, 1996).

### Stages and Transient Forms

Despite tremendous variability in precursory forms of mobility, the development of walking is typically portrayed as a sequence of universal stages. The notion of universal stages requires that infants cannot skip a stage and stages cannot occur concurrently or in different orders. The pervasive assumption of an invariant, obligatory sequence of discrete events underlies the iconography of the milestone charts and the logic of developmental screening tests. Infants’ scores on the Bayley Scales of Development (2006), for example, are determined by failures on three consecutive skills in the sequence. This scoring criterion assumes that infants will not succeed on a later appearing skill or fail on an earlier appearing skill.

However, precursory forms of mobility do not adhere to the criteria for universal developmental stages. Although the general age trend is toward increasingly upright forms (e.g., from lifting the head in a prone position shown at the bottom of Figure 1B to walking shown at the top of the figure), the “average” infant depicted in milestone charts is only a statistical average and is no real child at all. Individual infants forge their own paths, and the sequence of expression is variable (Adolph, Berger et al., 2011; Adolph, Karasik, & Tamis-LeMonda, 2009; Berger, Theuring, & Adolph, 2007). Postural development is often more like an up-and-down roller coaster ride than a strictly uphill climb, such that infants may display upright skills at earlier ages than prone skills (e.g., sit before they roll and cruise or walk before they crawl). Stationary postures need not precede moving ones; for some infants, solving the problem of dynamic equilibrium may be easier than trying to stay in one place. For example, infants may rock rhythmically on hands and knees before assuming a stationary quadrupedal posture or take their first walking steps before standing without support.

Typically, infants straddle multiple skills simultaneously (e.g., crawl, cruise, and bum shuffle during the same time span), meaning that milestones are concurrent, not discrete events (Adolph, Berger et al., 2011). Even in Gesell’s (1946) esoteric formulation of 23 stages of mobility prior to walking, he reported that
most infants exhibited several crawling stages simultaneously. Infants continually discover new forms, but they don’t immediately drop the old ones. Instead, old and new forms coexist for extended periods in infants’ repertoires. One possibility for the overlap is that new skills are initially more effortful and less functional than older skills with which infants have more practice, so infants rely on the older skills while working on the newer ones (Adolph, Robinson, Young, & Gill-Alvarez, 2008). A second possibility is that different skills (e.g., crawling and cruising) serve different functions (e.g., different vantage points for exploring the layout of the environment) and thereby retain their niches in infants’ repertoires.

Although most infants in present-day, Western cultures crawl on hands and knees and cruise sideways along furniture before walking, some normal, healthy children do not (Adolph, Berger et al., 2011; Berger et al., 2007). Cross-cultural and historical data provide compelling demonstration proofs that particular, precursory forms of mobility are not obligatory prerequisites for walking (Adolph, Karasik et al., 2009; Super, 1976). For example, in a sample of Jamaican infants whose mothers used traditional infant massage and exercise regimens, a sizable proportion (29%) skipped crawling altogether, and the infants who did crawl did so when they began walking: 10.1 months and 10.0 months for crawling and walking, respectively (Hopkins & Westra, 1989, 1990). A few decades ago, Robson (1984) reported that 17% of British infants skipped crawling (10% bum shuffled and 7% simply stood up and walked). In one of the earliest and most beautifully detailed descriptions of the development of mobility, Trettien (1900) reported that 40% of middle-class, American infants skipped crawling. Instead, these late nineteenth century infants bum shuffled, crab crawled, spider crawled on their backs, or log-rolled, perhaps to avoid catching their knees and feet at the edge of their long gowns.

A final argument against a retinue of connected stages is that critical aspects of what infants learn while crawling and cruising do not transfer to walking (Adolph, 2005, 2009). For example, when infants first begin crawling, they do not distinguish safe from risky ground. New crawlers plunge headlong over the brink of impossibly steep slopes and high cliffs, requiring rescue by an experimenter (Adolph, 1997, 2000; Bertenthal, Campos, & Barrett, 1984). Over weeks of crawling, infants learn to perceive affordances for locomotion and judgments gradually bear in to the limits of their abilities (Adolph, 1997). Experienced crawlers make impressively fine distinctions between surfaces that are navigable and those that are not (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Kretch, Karasik, & Adolph, 2010). Similarly, experienced cruisers distinguish navigable from impossibly wide gaps in a handrail they use for support (Adolph, Berger et al., 2011). But when ex-crawlers or ex-cruisers first begin walking, they go right over the edge of a cliff and step right into impossibly wide gaps in the floor as if they have not learned that they need a floor to support their bodies (Adolph, Berger et al., 2011; Adolph, Tamis-LeMonda et al., 2008; Kretch et al., 2010). Learning must begin anew and the process is no faster the second or third time around (Adolph, 1997, 2008).

An alternative interpretation of precursory locomotor forms is that they represent transient expressions of an immature motor system that are functional in a particular context (log rolling serves to move the infant from point A to point B), but are not needed after more efficient methods of locomotion become available. In this way, crawling, cruising, and other alternative patterns are akin to the umbilical cord of the fetus or the tail of the tadpole, which are vitally important before birth or metamorphosis, but are irrelevant and discarded afterward. Such transient expressions have been termed “ontogenetic adaptations” (Alberts, 1987; Oppenheim, 1981) to emphasize their temporary but important role in the developmental process. According to this view, transient forms are functionally relevant, but are not necessary building blocks in an obligatory developmental sequence.

Although the evidence argues against interpreting precursory forms of mobility in terms of a strict progression of connected, functionally dependent stages, their transient nature does not preclude an important contribution to the developmental process. Many threads of psychological continuity must bind development across time. It is the same infant at each time point after all. The various precursors may serve general functions that would be of benefit to any form of mobility: to build strength and coordination among body parts; to facilitate increases in balance, control, and sensitivity to various sources of perceptual information for maintaining balance; to promote a sense of efficacy as infants use travel to generate changes in the environment or their relation to it; and to support new ways of exploring the environment and learning about places and surfaces.

**Milestone Metaphor**

Iconography and convenient labels can help to organize scientific thinking, but unfounded metaphors can misdirect our thinking. For example, the notion of developmental milestones provides a convenient label for highlighting important behavioral events that mark developmental progress. “Milestone” is so broadly used by developmental researchers and parents that Random House (2009) lists “a significant event or stage in the life, progress, or development of a person”.
as the second meaning of the word. The first meaning, and in older dictionaries the only meaning, is “a stone set up beside a road to mark the distance in miles to a particular place.” It is this first meaning that gives force to the metaphor—the notion of linear progress, marked by discrete events, toward a final destination.

The milestone chart with its ascending postural forms says in a picture what has taken us more than 1000 words. It is the most pervasive metaphor for progress in motor development, but the underlying message is more fable than fact. The actual process of development is typically nonlinear with more and less upright forms intermixed, multiple skills expressed concurrently, and none of the forms obligatory prerequisites. In fact, given the diversity of precursory forms, the vast individual differences in which forms are expressed, and the differences between cultures and historical periods, it is only tradition that reifies particular forms to “milestone” status. Which skills are selected for the pantheon of milestones depends on the particular sample of subjects and proclivities of the researchers. Hands-and-knees crawling, for example, was not included in the 1992 version of the Denver Developmental Screening Test, and cruising was not added to the Bayley Scales until 1993. None of the major scales or milestone charts currently includes belly crawling, hands-and-feet crawling, pivoting, or hitching on the buttocks. Even the assumption of a discrete onset age is problematic because expression is inconsistent from day to day (Adolph, Robinson et al., 2008).

A more neutral term such as “benchmark,” meaning simply an arbitrary standard or point of reference, would serve the same descriptive and diagnostic functions for researchers, clinicians, and parents without distorting our view of motor development. And an iconography that highlights diversity and individual differences (as in Figure 4) would avoid the misleading connotations of the milestone chart.

**Onset**

“Q: Dear Mr. Dad: My sister and I have toddler girls who are only a week apart. Hers started walking at about 9 months, but at 16 months mine still hasn’t taken a step. Our pediatrician isn’t worried and I know I shouldn’t compare my baby to anyone else’s, but it’s hard not to. Is there anything I can do encourage my baby to walk?”

“A: No. On average, babies take their first steps at about 12 months. But, the range is pretty big, from 9 to 18 months. How early—or late—a child starts to walk depends on a number of factors…. Bottom line? Your baby will learn to walk when she’s good and ready and there’s nothing you can—or should—do to change her schedule.” —Armin Brott, “Mr. Dad”

(Brott, 2005, February)

Eventually, every healthy infant walks. In every known culture, walking is an expected and valued developmental achievement, on par with talking and toileting. For parents, the most commonly asked question about walking is when their child should walk. The easy answer is around 12 months of age, give or take a few months. For researchers, the most commonly asked question concerns why infants walk when they do. The easy answer is that changes in infants’ brains and bodies and external factors that affect infants’ brains and bodies determine the timing of walking onset. But easy answers gloss over the technical and theoretical issues involved in determining an onset age for any skill and the factors that influence onset.

**Onset Ages**

The notion of an onset age is a necessary corollary of the milestone metaphor and is integral to the iconography of the milestone chart. The median ages (represented by small vertical lines in Figure 1B) are a guideline for when infants should sit, crawl, walk, and so on, and the size of each upward stage (horizontal bars in Figure 1B) reflects the range in onset ages in typical development.

The notion of an onset age so ingrains our view of motor development that we take it for granted that there is an identifiable day when infants begin walking or pass some other developmental benchmark. However, developmental researchers rarely collect observations on a daily basis. Instead, researchers typically rely on retrospective reports from parents and, in prospective studies, use cross-sectional designs to compare various ages (e.g., 9 vs. 12 months), or longitudinal designs with assessments spaced months apart. Even the most ambitious sampling regimes in studies with human children involved observations at weekly or monthly intervals (Adolph, 1997; Corbetta & Bojczyk, 2002; Thelen, 1979; Thelen et al., 1993; Thelen & Ulrich, 1991; Vereijken & Thelen, 1997), with few exceptions (e.g., Mcgraw, 1935).

The problem of widely spaced observations is two-fold. First, estimates of an onset date are likely to be “guessimates” mired in noise. The Gesell Inventory (Gesell & Armatruda, 1941) and Bayley Scales (2006), for example, include only pass/fail grades for walking at 12 and 15 months. The second, more serious problem is that widely spaced sampling intervals presuppose that the shape of the developmental trajectory is stage-like. That is, in the case of motor skills, widely spaced sampling intervals presuppose that walking turns on like a faucet from one day to the next. However, without adequate sampling intervals, we can have
no idea of the underlying shape of developmental change (Adolph, Robinson et al., 2008; Adolph & Robinson, in press). It may be stage-like or not.

We are not the first to raise this issue. The problem of how often behavioral samples should be collected to accurately describe the underlying pattern of developmental change has been discussed in a general way for decades (e.g., Burchinal & Appelbaum, 1991; L. M. Collins, 2006; Hertzog & Nesselroade, 2003; McArdle & Epstein, 1987). But apart from vague recommendations about microgenetic methods, and encouragements to collect frequent samples relative to the rate of developmental change (Siegle, 2006), we have little information about how small a sampling interval is small enough.

Physical growth provides a dramatic illustration that developmental data require frequent sampling. The conventional depictions in textbooks and parent guides show smooth and gradual growth curves, with steep slopes in the early years that gradually asymptote at later ages (U.S. Department of Health and Human Services). However, when height is measured on a daily basis (hundreds of daily home visits over a period of many months), the trajectory does not look smooth and gradual (Lampl, 1993; Lampl, Veldhuis, & Johnson, 1992). Growth appears stage-like, with spurts up to 1.65 cm in a single day, followed by long periods of stasis where infants’ height does not change for days or weeks.

Sampling at even shorter intervals reveals nested epochs of stasis and growth. Newborn lambs were fitted with transducers across the tibial growth plate in their legs and their activity was recorded with time-lapse video (Noonan et al., 2004). Measurements spaced less than 3 seconds apart over a period of three days displayed a pattern of burst and stasis embedded within each day: 90% of bone growth occurred when lambs were lying down, with little or no growth while standing. Aside from the remarkable empirical finding that physical growth proceeds by fits and starts on multiple time scales, the general implication of these studies is that none of this developmental pattern would have been discovered if measurements had been collected at conventional monthly or yearly intervals.

In fact, we recently showed that even small deviations from a daily sampling rate misrepresent the developmental trajectory (Adolph, Robinson et al., 2008). Parents used a daily checklist to track 32 postural and locomotor skills over infants’ first 18 months of life. At the daily sampling rate, only 16% of the 261 developmental trajectories showed onset on a single day, with the skill absent on all previous days and present on all subsequent days. By contrast, for 84% of the trajectories, skills stuttered in and out of infants’ repertoires, initially expressed for a day or two, then absent for a day or two, and so on, with multiple transitions from absence to presence over the course of weeks or months. Variable trajectories were characteristic of every skill, including sitting, standing, crawling, and walking. But variable, sputtering patterns of skill acquisition erroneously appeared abrupt and stage-like when we simulated sampling at longer 2- to 31-day intervals: 51% of variable trajectories erroneously appeared stage-like when observations were conducted at a simulated rate of once per week; 91% of the variable time series appeared abrupt and stage-like at a simulated rate of once per month.

These findings about sampling intervals and variability raise the unpleasant specter that onset ages are empirically intractable. In our study of motor skill development, a simulated monthly sampling rate resulted in average errors greater than two weeks in estimates of onset age relative to daily samples, and some estimates were delayed by more than three months. Such errors are relatively huge for motor development.

Although daily sampling is impractical for many developmental phenomena, identifying benchmarks of development remains a useful tool in both research and clinical settings. But how are such benchmarks to be measured? Researchers could adopt arbitrary criteria for operationally defining an onset age, such as the earliest age at which the skill is first observed or estimate an onset age based on analyzing the actual, daily pattern of expression. (We suggested one such method by applying a neurally inspired activation function to developmental time series in Adolph, Robinson et al., 2008). Thus, easy answers about when infants should walk or achieve any other skill provide only rough, ballpark estimates. Accurate estimates of onset age or any other developmental benchmarks require frequent sampling.

Experience

The catch phrase “learning to walk” implies that experience plays a significant role in when infants begin walking. And so it does. Like precursory forms, onset ages are hugely affected by historical changes and cultural differences. These factors exert their influence through differences in child rearing practices—what infants eat and wear, how they are held, handled, and encouraged, and the physical environment that supports or hinders walking. Van Gogh’s (1890) painting, “First Steps,” beautifully illustrates the role of caregivers in learning to walk (Figure 5).

Modern day infants walk earlier than their grandparents and great-grandparents did. For example, in the 1920s and 1930s, the average, middle-class, American infant began walking between 13 and 15 months (Gesell & Armatruda, 1941; Gesell & Thompson, 1934; Shirley, 1931). In the 1960s, the Denver Developmental Screening Test (Frankenburg & Dodds,
1967) accelerated the average age of walking onset to just over 12 months and the Bayley Scales (Bayley, 1969) found a slightly earlier onset age. Recent norms indicate an average age of walking onset between 11 and 12 months (Berger et al., 2007).

In fact, onset ages for the entire panoply of motor milestones have shifted to dramatically earlier ages from the norms established by the early pioneers of motor development (Bayley, 1935; Shirley, 1931). It is likely that this historical trend is not merely methodological: Definitions of various skills have been remarkably stable across the last century. Pubertal events and physical growth exhibit similar historical trends (Adolph & Berger, 2010; Euling et al., 2008), suggesting that accelerated motor development may reflect general improvements in nutrition and living conditions (Kukлина, Ramakrishnan, Stein, Barnhart, & Martorell, 2004).

Based on Gesell’s early norms (Gesell & Armatruda, 1941; Gesell & Thompson, 1934) and the later Bayley Scales (1969), cross-cultural researchers were astounded to find communities of infants in Africa who achieved benchmarks of sitting, standing, and walking weeks or months before the expected norms. In the Kampa region of Uganda, for example, Geber and Dean (1957) reported: “At 7 months the children could stand without support, at 8 months they began to walk holding on to the wall, and at 9 months they took their first steps alone. At 10 months they could walk well, but with a certain stiffness, and at 1 year they could run” (p. 1058). Replications of accelerated onset ages in African infants are widespread (Iloeje, Obiekwe, & Kaine, 1991; Kilbride, Robbins, & Kilbride, 1970; Leiderman, Babu, Kagia, Kraemer, & Leiderman, 1973; for review, see Werner, 1972); infants of African descent in the Caribbean (Hopkins & Westra, 1988, 1990) and United States (Bayley, 1965; Capute, Shapiro, Palmer, Ross, & Wachtel, 1985) show similar patterns of acceleration.

So-called “African infant precocity” is linked with differences in childrearing practices. In communities where walking onset is accelerated, mothers (or grandmothers) massage and exercise their infants beginning in the newborn period using ritualized daily routines performed expressly for the purpose of facilitating the onset of walking (for review, see Adolph, Karasik et al., 2009; Bril & Sabatier, 1986; Hopkins, 1976; Rabain-Jamin & Wornham, 1993; Super, 1976). Mothers rub infants from head to toe and vigorously stretch their limbs by crossing their arms behind their backs and pulling their knees to their chests—all the while supporting them on a knee or outstretched arm so that infants must fight gravity to keep their heads from lolling (Figure 6A-C). They toss infants into the air and hold them by the head, ankle, or wrist, and shake them (Figure 6D-F). They sit and stand infants on their laps or the ground, bouncing them, and encouraging them to assume upright positions (Figure 6G-I). Mothers rarely lie infants down, even to nap, instead carrying them in slings, which results in additional, shaking, rocking, and gravity resistance (Bril & Sabatier, 1986; Konner, 1976; Super, 1976).

How much mothers rub, shake, and bounce their infants makes a difference for motor development. Facilitation shows a dose-response relation with onset age: the more frequent and consistent the stimulation, the earlier infants begin walking (Hopkins & Westra, 1988, 1990; Rabain-Jamin & Wornham, 1993; Super, 1976). Moreover, only the skills that receive special practice are accelerated, and children from the same cultures do not enjoy the African advantage if reared in a more modern, Western way (Hopkins & Westra, 1988, 1990).

At the other end of the spectrum, restricted practice can delay the onset of walking. For example, in the rural Shandong and Hebei regions of China, “sandbag rearing” is a traditional common practice until infants are toilet trained. In their first 12 to 24 months of life, infants lie on their backs inside a small bag filled with fine sand for 16 to 20 hours per day (Mei, 1994; Xie & Young, 1999). The sand acts as a diaper and is changed once per day. By 13 months of age, only 13% of infants can walk, and at 15 months, the percentage increases only to 72% (compared with 71% and 89% of infants at these ages, respectively, from the same regions not reared in sandbags). Infants in the Ache, a foraging society in Eastern Paraguay, are held nearly constantly to ensure infants’ safety in the dense dangerous forests through which families travel. Ache infants therefore have little opportunity for independent movement or practice and begin walking between 23 and 25 months of age (Kaplan & Dove, 1987). More
severe rearing conditions result in longer delays. Iranian orphans, spending most of their day lying supine in cribs without toys, pictures, or solid food, and cared for by underpaid, overworked, and undereducated staff, did not walk until 3 to 4 years of age (Dennis, 1960).

One need not travel to exotic locations in search of such natural cross-cultural experiments. We’re currently in the midst of one in middle-class America. In response to research linking a prone sleep position with sudden infant death syndrome, in 1994, The American Academy of Pediatrics launched a “Back to Sleep” campaign advising parents to put their infants to sleep on their backs rather than their bellies. Subsequently, prone sleeping decreased dramatically (Kattwinkel, Hauck, Keenan, Malloy, & Moon, 2005), but so did awake prone time (Majnemer & Barr, 2005). An unintended consequence of limited experience with the prone position is that back-sleepers achieve prone skills a few weeks later than prone-sleepers (Davis, Moon, Sachs, & Ottolini, 1998).

One needn’t even pore through obscure studies in the anthropological and medical literatures in search of natural experiments. Since the 1930s, developmental psychologists have conducted actual experiments with human infants to study effects of enrichment and deprivation on motor development. Most famously and rigorously (including random assignment to training and control groups), Zelazo (1976; Zelazo et al., 1972) showed that a few minutes of daily practice of upright stepping movements over a few weeks results in more steps, longer retention of upright stepping, and earlier walking onset ages in the trained groups (10.1 months) relative to controls (11.8 months), even when training is instigated beyond the normal cut-off point for newborn stepping. In the Zelazo household, training became a family affair. The experimenters’ own son was exercised beyond the 8 week cut-off, and he began walking at 7.5 months (Zelazo et al., 1972); the experimenters’ twin daughters were exercised until 36 weeks of age, and they began walking at 8.8 months (Zelazo, 1983).

Most impressive in the motor development literature, McGraw (1935) showed that with training, infants can learn amazing locomotor skills: swimming underwater at 9.5 months, diving headfirst into a pool at 13.8 months, roller skating at 12.3 months, and climbing 70° inclines at 21.4 months. Similarly, 4 months of training facilitated swimming behaviors in 12- to 16-month-old

Figure 6. Formal exercise and massage practices used in Africa, India, and the Caribbean that are used to facilitate infants’ motor development: (A-C) massage and molding of infants’ head, face, and body; (D-F) suspension and shaking by arms, head, and ankles; (G-I) practice of sitting and upright postures.
infants compared with untrained controls (Zelazo & Weiss, 2006). Most disturbing in the developmental psychology literature, under severely restricted and highly controlled rearing conditions conducted with two infant girls in his home, Dennis (1935, 1941) replicated the off-the-chart motor delays he had observed in the Iranian orphans. The girls began walking at 17 and 26 months.

The various training studies described above converge on a common fact: The timing of walking onset and other motor skills is extremely malleable. This fact has several implications. First, any argument for the primacy of neuromuscular maturation as a causal factor for the onset of walking runs aground on the reality that experience can move the onset ages outside the expected range. Normal, daily activities—how infants are held, bathed, dressed, and played with—affect the time course of motor development. Second, physical growth and neural development are plastic and receptive to experience. The developmental relations between behavior and other biological factors (e.g., genetic, morphological, physiological, and neurophysiological factors) are bidirectional. A third implication is clinical: Enhanced experiences can facilitate motor development in children with impairments. Practice stepping on a motorized treadmill accelerates onset age for walking by several weeks in children with Down Syndrome (D. A. Ulrich, Ulrich, Angulo-Barroso, & Yun, 2001).

Many Resources

How does experience cause African infants to walk earlier and Ache infants to walk later? More generally, why do infants walk when they do?

Behavioral development is a process. Changes in behavior are influenced by many resources at all levels of organization including genes and tissue-level interactions in the CNS, learning by the organism, variations in the environment that afford different kinds of behavior, and various kinds of self- and other-imposed stimulation that contribute to the richness of experience (Greenough, 1987). Actions are embodied in the biomechanics of the body and the physiology of the brain and embedded in a particular physical and social context (Adolph & Berger, 2006). The nervous system contributes to the generation and regulation of behavior, but infants’ abilities and the details of their motor actions are also the product of the biomechanical constraints of the rest of their bodies—bones, joints, muscles, and soft tissue—and the gravitational and physical environment surrounding the body (Bernstein, 1967). As a consequence, the resources that contribute to developmental change can include unique and universal aspects of the environment, growth and other changes in infants’ bodies, plasticity within the developing nervous system, and one’s own and others’ behavior (Blumberg, Freeman, & Robinson, 2010). This unified “developmental systems” view of neurobehavioral development (Gottlieb, 1997; Johnston & Edwards, 2002; Lickliter & Honeycutt, 2003; Oyama, Griffith, & Gray, 2001; West, King, & Arberg, 1988), emphasizes the multiple resources underlying development and provides a framework for addressing more specific questions about the roots of behavioral change.

So, returning to the specific problem of walking, is it possible to identify a single factor that is responsible for determining the age of onset of walking? Not without ignoring the reality that walking is dependent on multiple resources, each of which must be in a state of readiness for infants to walk (Thelen, 1995; Thelen & Smith, 1994). Alternation and many other patterns of leg movements, for example, are ready to go long before walking onset (Thelen & Fisher, 1982). Many neural systems also exhibit rapid development during the perinatal period and contribute to the production and coordination of walking, including pattern generating circuitry in the spinal cord, dedicated executive regions in the midbrain and motor cortex, and integrative networks necessary for coordination and fine motor control in the cerebellum. Sensitivity to visual flow begins before the onset of mobility, but improves over the first year of life (Bertenthal, Boker, & Xu, 2000; Bertenthal, Rose, & Bai, 1997; Gilmore, Baker, & Grobman, 2004; Gilmore & Rettke, 2003). Typically, motivation to locomote precedes walking—partly explaining the idiosyncratic and arduous forms that infants adopt—but energetic efficiency may help to push infants over the edge into upright walking (Alexander, 2003). An overall slimming of infants’ body dimensions, from their initially top-heavy shape to a more cylindrical one, contributes to walking (Thelen, 1984).

But generally, researchers agree that the rate-limiting factors for walking onset are muscle strength and balance control (McGraw, 1945; Thelen, 1984; Woollacott, Shumway-Cook, & Williams, 1989). Infants must be strong enough and have sufficient postural control to support their body and maintain balance on one leg while the other leg swings forward.

Any or all of these resources can be affected by experience. For example, exercise stimulates the growth of bones and muscles. Motor activity creates physical stress on bones that activates genes involved in converting cartilage into bone within epiphysial growth zones (Carter, Orr, Fyhrie, & Schurman, 1987; Muller, 2003). Muscles are stimulated to grow by similar physical stress applied on a microscopic scale to muscle fibers (Charge & Rudnicki, 2004). Even “soft” resources such as motivation are affected by experience. For many infants, the support provided by furniture or a parent’s hand provides more moral support than balance. Some take their first independent steps with one
hand in the air, as if they were holding their parents’ finger. Trettien (1900, pp. 41-42) provides a wonderful description of how G. Stanley Hall’s daughter found the motivation to walk:

One day the father came home to dinner and placed his cuffs upon a table.... The child, seeing the cuffs, crept to the table, pulled herself up by the leg of the table, took the cuffs...and slipped them over her wrists, standing unsupported while doing it.... Then, to the great surprise of the father, she walked with great confidence with a pleased expression on her face.... Without the cuffs, however, she could not be induced to take a single step. She was given an old pair of cuffs and she seemed greatly delighted; she walked and ran as before. She used the cuffs for two days, after which she walked without them and did not revert to crawling.

Improvements

In 1986, engineers at Honda Corporation set out to build the world’s most advanced humanoid robot. After 20 years of heroic effort marked by increasingly sophisticated experimental and prototype models, the amazing Asimo was finally unveiled: a robot that can walk, run, turn, carry objects, and climb and descend stairs and slopes—usually without missteps and catastrophic collapse. But most 18-month-old toddlers can easily outperform Asimo. What they have that the robot lacks are fluency, flexibility, and the ability to continually improve.

Fluency and flexibility are the hallmarks of skilled performance (Adolph, 2005, 2009; Adolph & Berger, 2006; Bernstein, 1996; MacKay, 1982). Fluency is what makes skills efficient, coordinated, and beautiful to observe. It is the ability to execute movements smoothly, accurately, and rapidly. Consistency and automaticity—performing the same movements in the same way over and over—are the signature attributes of fluency that allow for more efficient use of psychological and neural resources. The early versions of Honda’s humanoid robot, for example, were so utterly lacking in fluency that the robots took more than 5 seconds to complete each forward walking step. Walking in even the most sophisticated iteration of Asimo looks stilted and forced.

Flexibility is what makes skills truly functional. It is the ability to adapt to changes in local conditions by selecting, modifying, discovering, and creating movements appropriate to the current situation. Variety of means and generativity—finding new motor solutions and coping with new motor problems—are the critical factors underlying behavioral flexibility. The environment, body, and task goals are continually changing. Biomechanical constraints and supports are always in flux. Without flexibility, we would be stymied by variability and novelty. Asimo is stuck if a stair is too high to support walking. But toddlers can create new climbing and descent strategies on the fly.

Typically, in skilled performance, fluency and flexibility are both apparent. When a fashion model walks gracefully and seamlessly down the runway, that’s fluency. When she does so while wearing 4-inch heels, swinging a cape over her shoulders, and managing not to trip over a heavy train, that’s flexibility. Improvements in motor skill reflect increases in both fluency and flexibility.

Fluency

Figure 7 provides a dramatic illustration of improvements in fluency. The two panels show footprints from two infants as they walked over a mechanized gait carpet that registered the location of each step. Both infants were 14 months of age and approximately the same size, but the messy disarray of footprints in the top panel were made by an infant who had been walking for only 2 weeks and the neatly sequenced footprints in the bottom panel were made by an infant who had been walking for 2 months. New walkers’ steps are small, jerky, and uneven because they have difficulty maintaining balance on one leg while the other leg swings forward (Bril & Breniere, 1993). Essentially, infants are falling downward rather than propelling forward during periods of single leg support. The vertical acceleration of the center of gravity is negative at foot contact, rather than positive as it is in older children and adults (Bril & Breniere, 1993). Double support periods with two legs on the floor are long (40% to 80% of the gait cycle) and swing periods with one leg in the air are short (Bril & Breniere, 1993; Ledept & Bril, 2000; Vereijken, Bril, & Ledept, 1998); as a consequence, overall velocity is slow and infants land flat-footed or on their toes because there is no time for them to dorsiflex their ankles (Thelen, Bril, & Breniere, 1992). Hips and knees are held in a flexed position, failing to cushion the downward fall at foot contact and failing to fully extend the leg at toe-off (Sutherland, Olshen, Cooper, & Woo, 1980). Muscle actions in the legs are so inconsistent and working at odds with one another (flexor and extensor muscles co-contract) that it is a wonder that infants can walk at all (Chang, Kubo, Buzzi, & Ulrich, 2006). The head and trunk wobble in every direction (Bril & Ledept, 1998; Ledept & Bril, 2000).
To compensate for poor balance control and deficiencies in strength, infants take short steps with their legs splayed wide apart (Adolph, Vereijken, & Shrout, 2003; Bril & Breniere, 1992). Often, the side-to-side distance between the feet is larger than the front-to-back distance between consecutive steps. To increase the base of support, infants’ hips are externally rotated and their toes point out to the sides (Adolph et al., 2003; Ledebt, van Wieringen, & Savelbergh, 2004). Arms are raised above the waist and held stationary like balance poles (Corbetta & Bojczyk, 2002; Ledebt, 2000). The timing of steps and the distance between them are variable and asymmetrical across the feet, suggesting that new walkers must recover balance from step to step (Clark, Whitall, & Phillips, 1988). Even when balance is augmented with an experimenter’s helping hand, infants have trouble reproducing the path of the swinging leg from cycle to cycle (Ivanenko, Dominici, Cappellini, & Lacquaniti, 2005).

Figure 8 illustrates the characteristic time course and direction of improvements in walking skill over infancy and early childhood. The negative value of the vertical acceleration of the center of gravity at foot contact slowly decreases until the sign of the function becomes positive (Bril & Breniere, 1993). Double support periods eventually decrease to 20% of the gait cycle and swing periods increase until the proportions of the gait cycle spent in stance and swing approximate the 60:40 ratio of adult gait (Shumway-Cook & Woollacott, 2007). Overall walking velocity increases and infants have time to pull their toes up during swing so that they land on their heel at foot contact (Thelen et al., 1992). Muscle actions become more reciprocal, and infants stabilize the pitch and roll of their head and trunk (Assaiante, 1998; Ledebt & Bril, 2000). Steps grow longer as infants keep their legs closer together laterally and point their toes more to the front (Adolph et al., 2003). Arms lower to infants’ sides and swing in alternation with leg movements (Ledebt, 2000).

As depicted in Figure 8, changes in the fluency of infant walking show the negatively accelerated performance curves that are characteristic of improvements in most motor learning tasks (Schmidt & Lee, 1999): an initial period of rapid and dramatic change followed by a protracted period of subtle, gradual improvements. Most researchers put the sharp bend in the performance curve between 3 and 6 months after infants first begin to walk (Adolph et al., 2003; Bril & Breniere, 1993; McGraw, 1945) and most agree that the function doesn’t reach asymptote (adult-like levels of fluency) for some measures until 5 to 7 years of age (Bril & Ledebt, 1998; Sutherland, Olshen, Biden, & Wyatt, 1988). The initial process involves discovering the relevant parameters that control balance and forward progression. Variability is endemic at this point because infants try everything—visiting all the corners of the problem space as they explore and test the various configurations of their bodies that produce walking. The subsequent process involves honing and fine-tuning the values of the parameters to maximize the biomechanical efficiency of walking (Adolph et al., 2003; Bril & Breniere, 1992, 1993; Bril & Ledebt,
Figure 8. The characteristic time course of improvement in several measures of children’s walking gait over the first 60 months of independent walking. Step length = distance between consecutive steps. Step width = lateral distance between steps. Foot rotation = absolute value of in/out-toeing from path of progression. Velocity = overall distance/time. Swing time = amount of time with one foot moving through the air. Double support = amount of time that both feet are on the floor. Vertical acceleration of the center of gravity = rate of change in velocity of the center of gravity along the vertical axis.

than powered robots such as Asimo, yet they walk more naturally, fluently, and efficiently.

The benefits of increased fluency are immense. Walking becomes increasingly effortless and automatic. Automaticity of skilled action allows highly practiced actions to be performed in concert with other behaviors that require attention or concentration. When first learning new motor skills, the motor cortex is heavily involved. But with frequent practice, as skills such as walking become “overlearned,” cortical activity decreases and the neural mechanisms for motor control are delegated to subcortical regions. In particular, the basal ganglia are important for automaticity of skilled movements and sequencing of simple motor acts (Aldridge & Berridge, 2003; Poldrack et al., 2005). With enough practice, simple component actions, such as lifting one leg to climb a stair, shifting the center of gravity over the supporting leg, and lifting the second leg to mount the next riser become organized into larger “chunks” that allow new sequences—walking smoothly up a flight of stairs—to be performed quickly and efficiently with fewer demands on attention. Stroke patients with damage to the basal ganglia have difficulty breaking strings of simple actions into more complex movement sequences (Boyd et al., 2009). Similarly, at first, toddlers can only climb stairs by “marking time,” bringing the trailing leg up to the same riser to join the leading leg. With sufficient practice, the components are chunked into a whole sequence of alternating steps, and children become fluent stair climbers.

Despite nearly 80 years of robust, replicable, and programmatic research on the development of fluency in infant walking (McGraw, 1935; Shirley, 1931), a great irony is that children actually don’t walk in the ways studied by researchers. To study fluency across infants and time points, researchers need infants to perform the same standardized task. And the logical task is to ask infants to walk as fast as they can over a flat, straight path. However, cajoling infants to produce repeated trials of fast straight walking is exceedingly difficult (Adolph & Berger, 2006). Infants stumble and fall, of course. But more to the point, they deliberately stop, veer off the path, and vary their speeds. They change the location of their center of gravity by holding their arms out to mother or carrying toys. They sit down. They switch to crawling. Infants’ spontaneous path through an open play room is a twisting, winding, curling, back-and-forth jumble of fits and starts (Adolph, Komati, Badaly, Garciaguirre, & Sotsky, 2011). Even their typical path along a sidewalk at their caregivers’ sides is not straight and uneventful; they stop to examine a piece of litter, they turn to watch a person pass, they fall despite holding their caregivers’ hands. Like standardized tests of cognition and lan-
guage, the standard lab test of walking fluency is reliable but lacks external and ecological validity.

A second irony is that infants deliberately contribute to their own disfluency by choosing to carry objects as they walk. Load carriage is extremely difficult for infants (Adolph & Avolio, 2000; Garciaiguire, Adolph, & Shrout, 2007; Schmuckler, 1993; Vereijken, Pedersen, & Storksen, 2009). The load shifts the location of infants’ center of gravity, making balance more precarious. The additional mass creates greater destabilizing torques, requiring more muscle strength to generate compensatory sways. As a consequence, infants’ gait is disrupted. For example, when experimenters load infants with lead-filled packs (7%-25% of infants’ body weight) on the shoulders, hips, or ankles and encourage them to walk over a straight, uniform path, infants lose balance more frequently. And on trials when they manage to walk, infants’ step length decreases, velocity decreases, double support periods increase, and so on, resembling the walking patterns of less mature walkers. The problem is exacerbated for asymmetrical loads (all the weight on the front, side, or back of the body), and infants with less walking experience are more adversely affected.

Most striking, infants do not compensate for the disruption in their functional body dimensions. Adults wearing a backpack, carrying a suitcase, or holding a child with both arms lean away from the load, maintaining their new center of gravity well within the base of support (Garciaiguire et al., 2007). In contrast, infants lean into the load and maintain their balance the best they can. If the load is on their back, they lean backward. If the load is on the right, they lean to the right. Because leaning toward the direction of the load shifts the center of gravity much closer to the edge of the base of support, the load pulls infants off-balance, making falls more likely. Nonetheless, these impediments to walking do not dissuade infants from deliberately carrying loads. During free play in their homes, new walkers spontaneously carry objects at an average rate of 43 bouts of carrying per hour (Karasik, Adolph, Tamis-LeMonda, & Zuckerman, 2011).

**Flexibility**

“No man ever steps in the same river twice, for it is not the same river and he is not the same man.”

*(Heraclitus)*

Flexibility is imperative because the constraints on action are continually changing. Motor actions must take changing circumstances into account because changes in infants’ bodies, skills, and environments alter the possibilities, or affordances, for action (Adolph, 2005, 2008, 2009). One-day growth spurts, a heavy object in hand, or subtle shifts in the center of gravity induced by turning the head or drawing a deep breath pose continually changing demands on balance control. Rapid improvements in crawling and walking skill and discovery of new movement strategies bring new possibilities into play. The location and condition of objects and surfaces in the environment—including animate objects such as people—create new obstacles and opportunities for action. Variable and novel circumstances are the norm, not the exception. What makes skills adaptive and functional is not the ability to reproduce movements consistently. Rather, it is the ability to modify ongoing movements, select from among a variety of movements in the repertoire, and generate new forms of movements to cope with a changeable body in a variable world. Creatures whose lives are full of surprises would be ill served by a fixed and rigid set of behaviors that cannot respond to change (Klopfer, 1988).

An important difference between fluency and flexibility is that the latter involves prospective control of movements—preparing and guiding actions into the future (von Hofsten, 1993, 2003, 2004). Thus, to test flexibility in infant action, researchers present infants with novel challenges to locomotion and observe how infants plan their movements: barriers to step over or duck under (Schmuckler, 1996; van der Meer, 1997), openings to squeeze through (Franchak, Sadanand, & Adolph, 2011), squishy waterbeds and deformable foam pits to traverse (Gibson et al., 1987; Joh & Adolph, 2006), slippery slopes and high-friction surfaces to navigate (Adolph, Joh, & Eppler, 2010), and so on (for reviews, see Adolph, 1997; Adolph & Berger, 2006, 2010). Figure 9 illustrates some test paradigms.

The classic paradigm for studying flexibility is the “visual cliff” (Figure 9A), a glass table with a patterned surface directly beneath the glass on the “shallow” side and the floor visible far below the glass on the “deep” side (Gibson & Walk, 1960). Because of the safety glass, the drop-off is only an illusion—hence the visual-only ascription. Mothers stand at the far corner of the apparatus and encourage their infants to cross first one side and then the other. Newly mobile infants cross both sides of the visual cliff, but experienced crawlers avoid the apparent drop-off on the deep side (Bertenthal & Campos, 1984; Bertenthal et al., 1984). However, although the glass is invisible, infants can feel it, and after one trial on the deep side, infants learn the trick and cross (Campos, Haht, Ramsay, Henderson, & Svejda, 1978). As a consequence, researchers cannot test infants over repeated trials to assess the accuracy of their decisions or observe them longitudinally to examine developmental change.

To circumvent the methodological problems with the visual cliff, researchers recently have used actual cliffs (Figure 9B) and gaps in the surface of support...
Figure 9. Paradigms for testing infants’ perception of affordances as they encounter variable and novel challenges to balance and locomotion: (A) approaching an apparent drop-off on a visual cliff; (B) approaching an actual drop-off on a real cliff or (C) adjustable gap in the surface of support; (D) descending an adjustable slope; (E) crossing bridges of various widths and heights; (F) using wobbly or rigid handrails to augment balance on narrow bridges. An experimenter (shown) followed alongside infants to ensure their safety. Caregivers (shown only in Figure 9A and Figure 9B) encouraged infants from the far side of the obstacle.

(Figure 9C), where the height of the drop-off or width of the gap are adjustable (Adolph, 2000; Kretch et al., 2010). In lieu of the safety glass, an experimenter follows alongside infants to ensure their safety. Infants do not rely on the experimenter to catch them, so it is possible to observe each infant over dozens of trials at various increments of risk. Novice crawlers and walkers blithely attempt impossibly risky cliffs and gaps—including those that are the size of the visual cliff. But after a few months of everyday crawling or walking experience, infants show evidence of flexibility by selecting their actions in precise accordance with the affordances for locomotion. On easy increments, they crawl or walk without breaking stride. On challenging increments, they modify their gait by slowing down at the brink and taking careful steps to descend the drop-off or span the gap. On risky increments, they refuse to crawl or walk. Typically, rather than avoid crossing
altogether, they find alternative strategies to navigate the obstacle such as backing feet first into the precipice. Infants’ perception of affordances is impressively accurate—within 1-2 cm of their individual abilities.

Apparatuses with adjustable slopes (Figure 9D) and bridges (Figure 9E-F) have proven especially useful for studying flexibility for several reasons. Slant and bridge width can be varied parametrically, allowing researchers to assess the accuracy of infants’ judgments. Slopes and bridges allow for multiple alternative strategies so that researchers can observe infants’ discovery and use of a variety of means to solve the problem. Moreover, infants must take multiple walking steps to traverse the obstacles, providing a fertile ground for studying gait modifications. On steep slopes and narrow bridges, experienced infants modify their walking gait by shortening step length and decreasing step velocity (Adolph & Avolio, 2000; Berger & Adolph, 2003; Berger, Adolph, & Kavookjian, 2010; Berger, Adolph, & Lobo, 2005; Gill, Adolph, & Vereijken, 2009; Quon, Kretch, & Adolph, 2010). The exemplar infant shown in Figure 10A took 22 steps to walk down a steep 32° slope, compared with 5 steps to walk the same distance down a shallow 6° slope (top right and bottom left data points in scatter plot). As illustrated in Figure 10B, gait modifications are planned prospectively. The footprints cluster into a tight knot as infants approach the brink of the obstacle, meaning that infants shorten step length before putting their feet on the obstacle and then maintain small steps as they traverse it. Infants brace between steps to curb forward momentum on steep slopes, and they turn their bodies sideways and slide along with one leading leg to augment their balance on narrow bridges. Moreover, gait modifications are geared exquisitely to changes in the environment—2° increments in the degree of slant (Figure 10A) and 2-cm changes in bridge width.

Flexibility requires that infants take both sides of the body-environment relation into account. For example, changing infants’ bodies with manipulations such as lead-weight shoulder packs or Teflon-soled shoes dramatically decreases their ability to walk down slopes (Adolph & Avolio, 2000; Adolph, Karasik, & Tamis-LeMonda, 2010). Accordingly, experienced walking infants correctly treat formerly safe slopes as risky: They walk down steep slopes while wearing feather-weight shoulder packs or rubber-soled shoes, but they correctly refuse to walk down the same slopes moments later while wearing the lead packs or the Teflon shoes. Likewise, infants adapt their actions to naturally occurring changes in their own bodies and skills by updating their assessment of their own abilities (Adolph, 1997). A steep slope that was safe for belly crawling might be impossible for crawling on hands and knees. A slope that was impossibly difficult last week might be easy this week after walking skill improves.

Perhaps the strongest evidence for flexibility is infants’ spontaneous search for new means and the retention of a variety of means in their repertoires. Infants are consummate problem solvers and they view previously conquered challenges as an invitation to search for new problems to solve. For example, on impossibly steep slopes, infants explore alternative means of descent by testing different positions—sitting at the edge of the starting platform, peering down the slope from a crawling posture, assuming a backing position—frequently punctuated with returns to a standing position as if reassessing the problem from a familiar posture (Adolph, 1995, 1997). Discovery of a new strategy might result in several trials of the delighted child sliding down in a backing or sitting position, but soon the search is back on. Over the course of a session, infants are likely to use multiple methods of descent (Figure 11A). Strategies are maintained across weeks and months, decreasing in frequency as more efficient
strategies are adopted, but never disappearing completely.

Similarly, on impossibly narrow bridges, infants seek out new means for crossing. If a sturdy handrail is available, they cross holding the rail (Berger & Adolph, 2003). When the handrail is adjacent to the bridge, infants turn sideways to fit on the bridge, press their chest against the handrail, and drape their arms over the railing (Berger, Adolph, & Kavookjian, 2010). When the handrail is separated from the bridge by some distance, they lean forward at the waist and grip the railing with both hands. Even a wobbly foam handrail does not pose an insurmountable problem (Berger et al., 2005). Although too flimsy to support their entire weight, infants devise clever strategies for using a wobbly handrail to augment balance on a narrow bridge—leaning backward as if mountain climbing, hanging onto the rail in a sideways wind-surfing position, leaning over the rail in a hunchback position, and so on (Figure 11B). Discovery of new strategies, main-

tenance of a variety of means in the repertoire, and selecting strategies based on their efficacy is also emblematic of strategy choice in cognitive tasks and holds true across the life span (Ishak, Adolph, & Lin, 2008; Siegler, Adolph, & Lemaire, 1996).

What allows for flexibility in motor action? In real time, flexibility depends on information; and information, in turn, relies on exploratory activity (Adolph, 1997, 2009; Adolph & Berger, 2006). A library of static facts (“I’m a poor walker,” “18° slopes are dangerous”) won’t work because local conditions are too changeable. Information must be generated and collected on the fly. Each moment may require infants to newly assess the current status of their bodies and skills relative to the current configuration of the environment.

Fortunately, multiple sources of information are available, and most of the information is redundant. But infants don’t produce all possible exploratory behaviors all of the time. It would be too exhausting to continually look, touch, test, and scan, with all antennae on high alert. Instead, information that was obtained moments earlier guides and directs subsequent exploration moments later (Adolph & Berger, 2006; Adolph & Eppler, 1998; Adolph, Eppler, Marin, Weise, & Clearfield, 2000). A hint of something unusual prompts more focus on a particular problem. A suggestion that things are off-kilter leads to a broader search of the problem space. An indication of the status quo allows relaxation to a less vigilant mode.

Infants obtain visual information as they approach an obstacle—optic flow from head and body movements, motion parallax from peering over the edge, and depth cues about the location, size, and configuration of the obstacle. If visual information indicates safe going, infants continue without breaking stride. If the initial looks suggest that something is amiss, infants collect additional information from physical contact with the obstacle. They stretch their arms over the gap to feel the extent of the reaching space. They place their foot on the edge of the bridge and tug or bite the wobbly handrail. They stand with their feet on the brink of the slope and rock back and forth, generating torque around their ankles. Tactile exploration is accompanied by concerted looking so that each wobble at the edge of the slope or gap also generates visual information relevant for balance. Frequently, physical contact reassures infants to continue walking, but typically they modify their walking gait. It is only after infants have exhausted the possibilities for their current method of locomotion that they begin to explore alternative strategies.

Information allows for flexibility, but it is only a necessary, not a sufficient, condition (Adolph & Berger, 2006). Occasionally, errors result from lack of the requisite information. New walkers, for example,
sometimes hold their heads stiffly upright like Frankenstein, and miss obstacles on the floor near their feet. But typically, information is readily available and detected. Nonetheless, novices at locomotion display astounding errors of judgment. Inexperienced crawlers hesitate for long periods gazing down a steep slope with both hands touching the slanted surface, then plunge down headfirst (Adolph, 1997). Beginning cruisers dip and dangle their foot into an impossibly large gap for several seconds, then shift their weight over the empty space and fall (Adolph, Berger et al., 2011). New walkers stop at the edge of a cliff, look down, then step right over the brink (Kretch et al., 2010). As with experienced infants, novices typically display elevated levels of exploratory activity on risky increments, indicating that they differentiate the changes in slant, gap size, or whatnot. The problem is that novices have the information available, but fail to use it to guide their movements adaptively.

Learning to Walk

“Learning to walk” is not merely a convenient euphemism for a maturational process. Infants really do learn to walk. That is, improvements in walking skill depend on practice. In terms of fluency, experience underlies the identification of relevant parameters and the subsequent honing process. In terms of flexibility, experience facilitates more efficient exploratory activity and adaptive use of the resulting perceptual information for selecting, modifying, and discovering appropriate movements to suit the current situation. Although experience and age are highly correlated (older children tend to be more experienced), experience, not age, is the strongest predictor of improvements in both fluency (Adolph et al., 2003) and flexibility (Adolph, 1997, 2000). In Figure 8, it is experience, not chronological age on the x-axis, that best predicts the negatively accelerated performance curves that characterize fluency. And similar figures of learning curves in studies of flexibility depict experience on the x-axis.

In a classic paper on the age variable in developmental psychology, Wohlwill (1970) criticized researchers for treating age as an independent variable in statistical and conceptual treatments of development. Using age as a predictor or grouping variable in an analysis of variance or regression analysis infuses it with the causal quality of an independent variable. But it is not. Children are not randomly assigned to age groups and their group membership is not stable (younger children will soon be a member of the next oldest age group). Age is merely the passage of time. Age cannot explain development because time is conceptually empty.

As currently represented in the literature, experience fares no better than age (Adolph & Berger, 2006). Human infants are not exposed to controlled experience regimens, as may be the case with animal models. Rather, experience simply denotes the number of days that have elapsed between an estimated onset date and the test date. Thus, researchers sometimes refer to walking experience as “walking age.” Like age, experience is merely a convenient proxy for time-related factors that are currently unspecified or difficult to measure. Moreover, punctate estimates of onset dates are likely to be erroneous and consistent expression of locomotor skills cannot be assumed (Adolph, Robinson et al., 2008). Instead, new skills stutter in and out of infants’ repertoires from day to day and old skills slowly die out, meaning that experience is not a continuous function of time.

A first step toward identifying putative factors that covary with experience—amount of practice, exposure to particular situations or events, and so on—is a detailed, naturalistic description of infants’ opportunities for learning. The preliminary reports are clear: Infants acquire immense amounts of variable and distributed practice with walking (Adolph, Komati et al., 2011). During each hour, the average 14-month-old toddler takes approximately 2000 steps, travels an accumulated distance of 7 football fields, and incurs 15 or so falls. Bouts of walking are short and interspersed with long rest periods where infants stop to play or look around. Each bout is likely to occur in a different social and physical context with different tasks and goals. Visual experience accompanies locomotion, and toddlers fixate most obstacles just prior to traversal, sometimes visually tracking their feet as they navigate up, down, or over the surface (Franchak, Kretch, Soska, & Adolph, in press). However, researchers are still many steps away from replacing experience on the x-axis of their fluency and flexibility graphs with quantitative measures of practice or exposure such as the number of walking steps, frequency of walking bouts, distance traveled, number of falls, and the like.

How might all these experiences with walking, falling, and exploring the environment translate into actual learning? Young children and young animals appear to learn best when operating near the limits of their current skill level. Kittens engage in object play by self-handicapping—batting at a ball among the legs of chairs and tables instead of in the center of an open floor (Martin & Caro, 1985). New foals leap and twist, accelerate and slow down, instead of walking in a steady direction. Infants push themselves to try new means of descending slopes and stairs, even when old methods work perfectly well. Despite weeks of expertise as fluent and flexible crawlers, infants choose to stand up and face the world as clumsy and haphazard novice walkers.

It would seem that infants learn best when challenged slightly beyond their abilities. In cognitive de-
velopment, this idea is famously captured in Vygotsky’s (1978) concept of a “zone of proximal development,” or “ZPD”—the range of performance between what children can do currently and the level they are likely to achieve next. “Scaffolding” is a complementary concept, wherein support from an external source (typically a more knowledgeable person or a cultural tool) can move children through their ZPD to the next level.

The development of sitting provides a compelling and literal illustration of scaffolding and the ZPD. The illustration is compelling because the scaffold is a physical support structure rather than the metaphorical system of cultural support described by Vygotsky. The ZPD is literally a measurable region of space rather than the metaphorical status of the cognitive system. The spine is segmented and infants acquire the sitting posture one vertebra at a time: first gaining control of the head and the uppermost cervical region of the spine, then the upper and lower thoracic regions at the armpits and waist, and finally the lumbar region at the hips (Saavedra & Woollacott, 2009a).

Children with cerebral palsy have difficulty controlling their sitting posture because they cannot stabilize the various spinal segments (Saavedra, Woollacott, & van Donkelaar, 2009). Without a stable postural base, they cannot use their eyes and head for looking, talking, and eating, and they cannot use their arms and trunk for reaching and manipulating objects. The most severely affected children are like the youngest infants; they can only hold their heads steady if provided with support at the upper cervical region. By providing these children with an external scaffold—a metal and cloth device that supports their spines—precisely adjusted to the edge of their ZPD, and encouraging children to make eye-contact, talk, laugh, and play with objects, the children learn to control the sitting posture by slowly moving through each zone of development, one spinal segment at a time (Saavedra & Woollacott, 2009b; Saavedra, Woollacott, & van Donkelaar, 2007).

Sequelae

In a chapter on learning to walk, it is reasonable to consider walking as the outcome of a developmental process: What are the origins of walking, when do infants walk, how does walking improve, and so on. But in the larger scheme of development, walking is not a final product. Rather, infants’ acquisition of walking has secondary consequences, sequelae with downstream effects far removed from locomotor development. In other words, walking can also be considered as a potential causal factor, mediator, or moderator, rather than as an outcome variable.

Look again, for example, at The March of Progress (Figure 1). Later species of hominins are drawn walking upright and brandishing increasingly sophisticated tools. On the typical reading, the hand-held implements signify the evolutionary superiority of the guys at the end of the parade. (Of course, the tools were a bit of a cheat. Whether animals lower on the totem pole are true tool users (Emery & Clayton, 2004; Weir, Chappell, & Kacelnik, 2002) and the causal role of carrying objects in the evolution of upright walking (Stanford, 2003) are matters of hot debate.) But the picture of progress can be viewed in another way: Walking can be considered as a context-setting event that facilitates or even instigates achievements in other domains. Upright walking frees the hands from supporting the body, thereby advancing the use of hand-held implements, the extension of the body via tools, and the specialization of hands and feet for different functions. Such downstream consequences, in turn, can reverberate through the system in a developmental cascade of subsequent events over multiple time scales.

Downstream Effects

It is no accident that developmental theorists have focused on infant locomotion as a catalyst for change in other domains of development (Bertenthal et al., 1984; Campos et al., 2000; Gibson & Pick, 2000; Mahler, Pine, & Bergman, 1975; Piaget, 1952; Thelen & Smith, 1994). The ability to transport one’s whole body at will has potentially powerful downstream effects. In Gibson’s (1988) words, “A kind of cognitive revolution must result when an infant’s horizons are expanded by the acquisition of self-initiated, self-controlled locomotion. A new field of knowledge is opened up and a whole new set of skills must be mastered. A new kind of activity that is both exploratory and perforatory becomes available for learning about the larger world” (p 27). This “revolution” would also seem to recruit additional motor developments, perception, affect, social behavior, and social understanding.

Prior to independent mobility, infants depend on caregivers to cart them from place to place. They are carried or wheeled to places of the caregivers’ choosing. Often, infants are not even positioned facing forward. But as passengers, there is no pressure for infants to steer and navigate or to remember locations and routes to destinations. They need not look where they’re going or where they’ve been.

Passive locomotion can, in principle, expose infants to a changing view of the environmental layout, global patterns of optic flow, and correlated visual and vestibular inputs. However, infants do not produce these experiences on their own and the resulting information is not linked with self-generated movements. In fact, passively carried infants in a forward-facing infant carrier see a very different view of the world than their actively walking parents as revealed by head-mounted
eye-trackers worn by both infants and parents (Kretch & Adolph, 2010).

Pre-locomotor infants are like the passive kittens who were pulled around on a cart by an active littermate in Held and Hein’s (1963) classic “kitty carousel” experiments. The active kittens could see and feel their legs move during locomotion and they could see and feel the consequences of self-produced movement. The passive kittens did not obtain such correlated perceptual-motor inputs. Although they could survey the scene and were exposed to optic flow, their leg movements did not produce locomotion (instead, they stood on the cart), and an Elizabethan collar prevented them from seeing their paws. As a consequence, active kittens exhibited adaptive, placing, reaching, and avoidance responses to a drop-off, but the passive kittens did not. Like the passive kittens, pre-locomotor infants do not respond adaptively in various motor tasks because they lack self-generated locomotor experience (Campos, Bertenthal, & Kermoian, 1992).

The advent of independent mobility brings about new and widespread opportunities for learning. Locomotion provides new ways to learn about the “movability” of one’s own body, others’ bodies, and detached objects relative to the immovable and permanent aspects of the environment (Gibson, 1988). How to move is one corollary of independent mobility. The layout of the environment offers new affordances for action—opportunities for crawling, climbing, walking, and so on—and new dangers from falling and entrapment. New affordances may shift infants’ attention to action-relevant properties of surfaces and objects (Gibson, 1988). Can this surface bear weight and support balance and propulsion? Is that object an obstacle to be navigated, an invitation to explore, or a trivial element in the scene?

Where to move is another corollary. Places become tied to locations relative to the current and previous location of the body and to landmarks or other places visited (Bushnell, McKenzie, Lawrence, & Connell, 1995). Self-produced locomotor experience (crawling, walking, or pushing themselves around in mechanical walkers) enhances performance on spatial search tasks (Bertenthal et al., 1984; Kermoian & Campos, 1988) and on place learning and cue learning tasks (Clearfield, 2004). Moreover, crawling infants better remember locations when they crawl through the environment on their own instead of being carried along the same path by an adult (Acredolo, Adams, & Goodwyn, 1984; Benson & Uzgiris, 1985). Apparently, the experiences engendered by mobility encourage infants to attend to a larger pool of available cues for location and to weigh various types of information (landmark-based versus body-based cues) more efficiently and adaptively (Newcombe & Huttenlocher, 2000). What experiences are most relevant? Infants are more likely to visually track hiding locations while crawling than while carried (Acredolo et al., 1984), and thus are more likely to encode and retain the relevant information. While crawling or walking, infants can feel themselves moving as they see the places they go (Clearfield, 2004). Mobility has additional benefits for memory. Crawling is associated with more flexible memory retrieval, suggesting that crawling supports learning that is dissociable from the immediate environmental context (Herbert, Gross, & Hayne, 2007).

Independent mobility is self-perpetuating. By expanding the accessible environment, it gives infants new reasons to move. New motivations are another corollary of acquiring mobility. Things at a distance become more interesting, instigating more visual, locomotor, and manual exploration of distal objects (Clearfield, Osborne, & Mullen, 2008; Gustafson, 1984; Karasik, Tamis-LeMonda, & Adolph, in press). Infants can now bring themselves to an object that catches their eye. They can retrieve objects and transport them. Carrying becomes especially relevant for walkers. Bouts of carrying increase by 520% over the transition from crawling to walking (Karasik et al., in press). Moreover, walking changes infants’ social interactions with objects. Instead of waiting for an adult to come to them to share objects, infants transport objects to caregivers in order to share them (Karasik et al., in press). Walking infants are so delighted to carry objects that they happily walk back and forth in experimental studies toting objects between the experimenter and the caregiver (Schmuckler & Gibson, 1989).

Walking is a particularly potent force for social agency. Although crawlers can leave their caregivers to explore the surrounds and seek proximity to caregivers when frightened, walking begins infants’ psychological separation and individuation from caregivers—their “love affair with the world” (Mahler et al., 1975, p. 140). Compared with crawling, walking covers more ground more quickly. Learning to walk is a time of both exhilaration and frustration, marking a new step in emotional independence and a reorganization of the family structure. Parents report an increase in infants’ testing of wills; both parties increase the frequency of saying “No” (Biringen, Emde, Campos, & Appelbaum, 2008; Biringen, Emde, Campos, & Applebaum, 1995). Parents alter their use of language, manual gestures, and facial affect to communicate with pre-locomotor, crawling, and walking infants (Campos et al., 2000; Karasik, Tamis-LeMonda, Adolph, & Dimitropoulou, 2008; Tamis-LeMonda, Adolph, Dimitropoulou, & Zack, 2007). New forms of communicative exchanges may facilitate joint attention to objects and new appreciation for others’ agency (Iversen, in press).

As Gibson (1988) pointed out, the availability of information about the self, the environment, and the relations between them depends on the opportunities for
learning. Without information, these routes to knowledge are closed off. Some researchers argue that independent mobility is not a necessary or sufficient condition for the widespread changes that ensue (Campos et al., 2000; Iverson, in press). Children could assert psychological independence, widen the scope of their exploration, use more advanced location cues, and so on without crawling or walking. But the fact that locomotor development normally sets this global revolution in motion has spurred researchers to develop robot-powered mobility devices to provide independent mobility for children with motor impairments who are otherwise immobilized and dependent on others to go somewhere (Lynch, Agrawal, & Galloway, 2009, Chen, Ragonesi, Galloway, & Agrawal, 2011). Without independent mobility or its surrogate, infants do not get the consequent opportunities for learning provided by locomotion.

Note, however, that not all changes move the system forward. Recent evidence suggests that walking may temporarily reorganize the neural underpinnings of the motor system such that infants can backslide in their earlier motoric achievements. For example, in the same time period when new walkers take steps with their arms in a frozen, high guard position, they revert to bimanual reaching for small objects (Corbetta & Bojczyk, 2002). Although researchers assess reaching in a sitting position, both of infants’ arms are activated, as if the exigencies of bilateral arm activation during walking have spilled over into the activity of reaching. Similarly, new walkers revert to less mature postural responses when tested in a sitting position, as if the demands of keeping balance while upright have temporarily interfered with their balance control while sitting (L.-C. Chen, Metcalfe, Jeka, & Clark, 2007).

The Developmental Cascade

The notion of developmental sequelae fits well with images of flowing streams and sweeping cascades. Indeed, Thelen (2005) likened human development to a mountain stream: a continuous ever-changing flow of activity, with patterns (whirlpools, eddies, waterfalls) and differences (rapids, reflecting pools) at various time points arising from and contributing to the structure of the underlying streambed. As in development, a stream carries its entire history, from the geological history of the region to the immediate conditions of the streambed, the water running through it, and the weather surrounding it. Various actions on the stream (e.g., throwing a rock into the water) have different effects depending on the immediate conditions (causing ripples in a deep part of the stream, but diverting the path of the flow in a shallow part). And like development, a stream creates history: There are downstream effects, some immediate and some far afield from the original course—corridors for fish and wildlife migration, runoff, groundwater recharge, pollutants, droughts—and these effects, in turn, carry and create their own histories in a continual cascade of events.

The most familiar metaphor of this type is Waddington’s (1957) epigenetic landscape (Figure 12A). The landscape presents the image of a weathered hillside, with bumps and furrows, ridges and valleys. A rolling ball represents the current state of the organism, which begins its developmental journey at the top. The surface contours determine the path of descent of the rolling ball, but only probabilistically. As any pinball player knows, small variations early in the path can lead to substantial differences in destination. But Waddington also realized that much of development is self-corrective, leading to predictable endpoints. He depicted this process of canalization in the convergence of many small furrows into fewer deep valleys at the bottom of the slope.

In its original formulation, the surface of the landscape rests on a supporting scaffold, which consists of manifold interactions among genes as they are expressed during development. Although

Figure 12. Metaphors of development. (A) Waddington’s (1957) epigenetic landscape. (B) Banyan tree with diverging and merging roots and branches.
Waddington’s landscape metaphor has been criticized for its genetic bias and its too-rigid view of developmental sequences (Gottlieb, 1991), later in his career as a developmental geneticist, Waddington (1977) broadened his conception of the supporting under-layer to include complex gene-environment interactions. The image of Waddington’s landscape has been reprinted many times to argue for canalization or an epigenetic perspective on developmental change. The general landscape metaphor and iconography have also inspired a dynamic systems account of probabilistic epigenesis (Muchisky, Gershkoff-Stowe, Cole, & Thelen, 1996). Perhaps the most valuable insight provided by the landscape metaphor is that the current status of the organism is determined by its path across the surface. Small nudges early in development—stemming from the under-layer or the landscape—can produce important and unexpected downstream consequences. In this way, the new opportunities for learning afforded by the onset of crawling and walking can provide crucial influences on development, pushing the infant into one nascent valley rather than another, as the child descends the landscape.

New Metaphors

Developmental science has always relied on metaphors to express the complexity, contingency, interdependence and directionality of developmental change (Klopfer, 1988). The criteria for a good metaphor are accessibility and accuracy. The March of Progress and the milestone metaphor, for example, are widely accessible, but largely inaccurate. A host of “infant as” metaphors—infant as blank slate, infant as mini-computer, infant as scientist in the crib (e.g., Gopnik, Meltzoff, & Kuhl, 1999), and so on—convey various theoretical perspectives about infants’ role in development, but fail to capture the process of developmental change. The mountain stream and landscape metaphors focus on the process of development, but the child’s role is utterly missing. Unlike a ball passively rolling downhill or water coursing through a streambed, children seek out and change features of their environments through active exploration and interactions with caregivers.

A more appropriate metaphor might be the growth of a branch or a root of a tree: “As the twig is bent, so grows the child” (Klopfer, 1988). Beginning as a flexible and relatively weak twig, the branch grows in substance as it extends into the environment. When an obstacle is encountered, the branch may alter the direction of its growth, or overcome the obstacle by growing around or through it. In this way the tree can break up soil and rocks with its roots to optimize access to water and nutrients, and can develop its highly individualized and idiosyncratic form, while adhering to the defining features and functions of its kind.

A particularly apt image (although perhaps not widely accessible) is a banyan tree. The banyan begins life as an epiphyte, growing upon a parent tree, deriving its moisture initially from the air and the rain until its roots descend to the ground. Aerial roots drop from the branches to form new trunks. The roots and branches diverge and merge. Banyans can grow to tremendous size and diversity, defying any easy notion of developmental endpoints; a single, famous, banyan tree fills most of a city block in Maui.

Nonetheless, the tree metaphor will surely have unintended meanings that will mitigate its usefulness. Perhaps no metaphor can do justice to the multiple facets of developmental processes and to the many issues that are raised by developmental research (Adolph & Berger, 2006). Cairns (1991) suggested that we simply stick to the facts. He argued that developmental metaphors are a misguided economy. They buy too much too cheaply, substituting “simple images for the hard-won gains of empirical science” (p. 24).

Ending Point

Most developmental researchers assume a mature endpoint, the apex of normal, healthy development. And most developmental researchers characterize the endpoint by the behavior of 18- to 21-year-old undergraduates. That is, a comparison sample is drawn from the undergraduate students who fill the rosters of our universities’ subject pools. For example, arguments about the continuity of development hinge on comparisons between the abilities of infants or young children and those of young adults (Speake & Newport, 1998). Claims about the time course of development assume that deviations from the abilities of young adult undergraduates are evidence for incomplete development in younger participants (Bril & Breniere, 1993) or subsequent degeneration or learning in older participants (Shumway-Cook & Woollacott, 2007). Developmental psychologists are in good company; most of our colleagues in perception, cognition, cognitive neuroscience, and social psychology study undergraduate participants drawn from our introductory courses based on practical considerations and the assumption that their behavior provides adequate insight into normal psychological competence (Henrich, Heine, & Norenzayan, 2010).

Despite the practicality of using undergraduates as the gold standard, the undergraduate assumption is problematic in several ways. First, assuming an endpoint in development leads to teleological research programs (Sugarman, 1987): Deviations from later points in development are viewed as deficits rather than achievements—most famously, Piaget’s (1954)
pre-operational stage is defined in terms of failures in relation to concrete operations. Second, even if the facts bore out the assumption that undergraduates display the mature form, studying the mature capacity in the undergraduate age group is arbitrary: Children could peak before entering college and adults could maintain the capacities long after graduation (Adolph & Robinson, 2008). Third, it is possible, of course, that our undergraduates are not representative of all people in the world; tongue-in-cheek, Henrich et al. (2010) termed them “WEIRD,” Western, Educated, Industrialized, Rich, Democratic young adults. That is, normal development in other cultures could stop short of, continue beyond, or go in a different direction compared with the abilities of WEIRD undergraduates (Karasik, Adolph, Tamis-LeMonda, & Bornstein, 2010). Fourth, for developmental researchers interested in process and mechanism, the focus on “normal” outcomes can blind us to the developmental factors that lead to a diversity of possible solutions and can allow us to ignore the remarkable flexibility of developmental process (Blumberg, 2009).

Beyond the Norm

Hundreds of articles describe normal upright walking and running in young adults. “Normal” here has two important meanings: a statistic derived from or compared with normative data collected under controlled conditions, and typical ordinary people doing the things that they normally do. As described earlier, cross-cultural data show that normal, everyday child-rearing practices in other cultures can accelerate or delay the onset of walking relative to western norms. Likewise, normal, everyday activities in some cultures lead to motor skills in young adults that greatly exceed the expected norms generated from the behaviors of typical undergraduates. Indeed, normal walking and running in some cultures can vastly exceed the abilities of elite athletes in Western industrialized cultures in terms of coordination, strength, and endurance.

How people walk while carrying heavy loads provides a striking example of endpoints that exceed our Western-centric expectations. Normally—that is, in Western cultures—it is energetically costly to carry a heavy load. The additional cost of carrying a load (using rate of oxygen consumption to index energy expenditure) is directly proportional to the magnitude of the load (Taylor, Heglund, McMahon, & Looney, 1980). In other words, a load amounting to 20% of body weight increases energy use by 20% in humans and in four-legged animals such as horses, dogs, and rats.

But East African women in the Luo and Kikuyu tribes can carry 20% of their body weight for free, that is, with no increased energetic costs (Heglund, Willems, Penta, & Cavagna, 1995; Maloiy, Heglund, Prager, Cavagna, & Taylor, 1986; Taylor, 1995). Loads larger than 20% incur a cost, but always at rates far below that of Western walkers and four-legged animals: Increasing loads from 20% to 70% of body weight increases the energetic cost linearly from 0% to 50% (Maloiy et al., 1986), meaning that the relation between load and energy consumption in the African women is offset by a free 20% of body weight. Both male and female Nepalese porters (ages 11 to 68) routinely carry more than their body weight barefooted for many kilometers up and down steep mountain paths in the high altitudes near Mount Everest. Like the African women, they carry loads lighter than 20% of their body weight for free; with heavier loads, they are more economical than the African women, carrying loads 30% of body weight heavier than the maximum loads carried by the African women for the same metabolic cost (Bastien, Schepens, Willems, & Heglund, 2005). Some animals are also freeloaders: Female wallabies can hop along carrying 15% of their body weight (the size of a fully developed pouch-young) without increased energetic costs (Baudinette & Biewener, 1998).

So how do these extraordinary load carriers do it? The manner of load carriage and years of practice are important elements. Women of the Luo tribe carry loads equivalent to 70% of their body weight balanced on top of their heads. Women of the Kikuyu tribe carry the same size loads supported by a strap across their foreheads, frequently boring a groove into their skulls and raising a “Kikuyu bursa” on their backs (Koten, 1986; Maloiy et al., 1986). The Nepalese porters carry even larger loads on their backs supported by a strap around their foreheads. People in these cultures begin carrying head-supported loads as children to accomplish daily chores and as practice for later employment as porters. Untrained Westerners can only manage loads up to 15% of body weight on their heads (Maloiy et al., 1986). Instead, we carry loads in our arms or in packs on our backs. Our “training” also begins in childhood, with the typical backpack in elementary school children loaded at 20-30% of body weight (Goodgold, Mohr, Samant, Parke, & Gardner, 2002; Negrini, Carabalona, & Sibilla, 1999). Indeed, years of leaning forward to offset the torque created by heavy backpacks (loads exceeding 10-15% of body weight) leads to injuries such as back pain, scoliosis, and hyperlordosis in children (Brackley & Stevenson, 2004). Backpack training, however, does not lead to freeloading. Young, fit army recruits carrying backpacks cannot manage relatively small loads (20% of body weight) without increased metabolic cost (Maloiy et al., 1986).

The most extraordinary difference from Western load carrying is the way that the freeloading carriers exploit the biomechanics of their normal gait patterns.
by capitalizing on the pendular motion of alternating bipedal gait. During normal walking, the body’s center of mass accelerates and decelerates in a forward direction and rises and falls in a vertical direction. Gravitational potential energy is stored as the center of mass rises during a step (like a roller coaster nearing the top of its climb). This potential energy is then transformed into kinetic energy as the body gains speed and falls forward (like the cars of a roller coaster, reaching maximum kinetic energy at the bottom of the track). The kinetic energy is subsequently converted back into potential energy as the center of mass rises over the other leg, and the process continues (Carrier, 1984; Cavagna, Heglund, & Taylor, 1977). In a perfect pendulum, the energy transfer would be complete (100%) and no muscular work would be needed. In Western walkers, the exchange is pretty good (about 65%), but it is not complete, so muscles must do work (Taylor, 1995). The freeloading African women and Nepalese porters are more effective than Westerners in synchronizing the forward and up/down motions of the body. The amount of energy recovered from the pendular motion of their bodies can exceed 80%, making their walking gait more energy efficient than the 65% return of “normal” Western walkers (Heglund et al., 1995). Wallabies freeload with a similar trick: They recover the elastic potential energy stored in their stretchy hindlimb tendons at landing to help to propel their bodies (and the load in their pouch) during the next hop (Baudinette & Biewener, 1998).

In other cultures, the norm for endurance during long distance walking and running exceeds most Western elite ultra-marathoners. Persistence hunting by native peoples of Africa, North America, and Australia provides dramatic examples. The Tarahumara Indians of north-central Mexico, for instance, chase deer through the mountains of the Sierra Madre Occidentale, often for 1-2 days, until their prey, hooves completely worn away, drop from exhaustion and are then throttled by hand (Bennett & Zingg, 1935). The Paiute Indians of the American southwest use the same technique to hunt pronghorn antelope (Lowie, 1924). Among !Kung Bushmen in the central Kalahari of Botswana, groups of hunters jog continuously for 3-6 hours over distances of 25-35 km as they track antelope (Liebenberg, 2006). The hunts occur during the dry season, with daytime temperatures exceeding 40°C. Although the antelope quickly outrun their pursuers for short distances, the hunters relocate them before they can recover from their dash, eventually causing them to collapse from fatigue and heat exhaustion.

But the limits of human endurance may be approached through sport, not hunting. The Tarahumara engage in a pastime of kickball racing, which may have been part of their culture for nearly two millennia (Balke & Snow, 1965; Groom, 1971). Participants include men and women of nearly all ages. Teams of competitors maneuver the kickball—a hard wooden ball about the size of a baseball—with their feet over circuits of 10-40 km that wind along rocky trails, over mountains and through canyons, across streams—in fact, over some of the most rugged terrain in North America (Balke & Snow, 1965; Bennett & Zingg, 1935). Informal races and those involving young children, women, or the elderly may require completion of just one or two circuits of the course. But on special occasions such as interpueblo races, men 18-48 years of age race over much larger distances, up to 150-300 km, requiring 24-48 hours to finish (Bennett & Zingg, 1935). During a race, competitors run without stopping, typically at a slow jog; longer races continue through the night. Racers often run 100 miles or more in a day and burn nearly 11,000 kcal in the process, considered to be near the maximum metabolic capacity of humans (Balke & Snow, 1965; Groom, 1971).

In what sense is this extreme ultra-marathon ability “normal” or achievable by normal folk? Tarahumaran children who are acculturated in mission schools rather than reared traditionally display similar physiological work capacity as children from non-running cultures (Balke & Snow, 1965). As Groom (1971) wryly noted when comparing abdominal fat folds of Tarahumaran runners versus those of mission-reared Tarahumarans and the experimenters’ own (10 times) larger bellies, it is the extreme, daily, physical conditioning and diet that results in the runners’ uniquely lean bodies and tremendous endurance.

Other Roads

What about walking in people who are not normal, people whose bodies are deformed and misshapen by
cultural practices, injury, or birthright? The remarkable adaptability of walking in people with physical disabilities provides further evidence that the form of walking movements is the outcome of a flexible developmental process.

How people walk is constrained by the facts of the body, but it is not prespecified or dictated by a genetic program. Blumberg (2009) illustrates this point with two remarkable cases of "freaks": Johnny Eck, the celebrated sideshow performer, learned to walk using only his arms. He was born with a truncated torso and greatly shortened, unusable legs, which he tucked under his clothing. Nonetheless, as astonished viewers can see from archived movie clips, Eck flew across rooms with speed and grace, navigating ladders and stairs, walking, climbing, and balancing—all on his hands. Faith, a dog born without forelimbs, learned to walk and hop upright by balancing on her two back legs.

Footbinding in China provides an extreme example of how cultural practices affect the form of walking movements. For more than 1000 years, mothers intentionally deformed their daughters’ feet to give them the walking gait of a “tender young willow shoot in a spring breeze” (Ebrey, 1999). The practice, typically beginning between 3 and 8 years of age and lasting for several excruciating years, involved breaking the four small toes on each foot, bending them under the ball of the foot, and then binding them in place with bandages until the ball and heel of the foot were touching (Ebrey, 1999; Fang & Yu, 1960). The optimal “lotus blossom feet” were three inches in length and half an inch wide at the front. Relearning how to walk on radically shorter, thinner feet necessitated substantial changes in posture and coordination. Foot-bound women walked on their heels with short, tottering, mincing steps, keeping their legs stiff and straight (Ebrey, 1999; Fang & Yu, 1960). The practice was finally eradicated in the 1920s.

Obesity—whether the result of culture, diet, or genetics—requires adaptations in the way that people walk. Increased weight requires more energy to move the body. But obese people use considerably less energy to walk than would be expected based on biomechanics (Browning & Kram, 2009). They don’t accomplish more mechanical work like the African women head-load carriers, but they do learn to reduce the relative costs of swinging their heavier legs. Increased body mass produces greater ground reaction forces, thereby putting greater stress on muscles, joints, and bones (Browning & Kram, 2007). To reduce the ground reaction forces, obese people walk slower, increase periods of double support with both feet on the ground, and decrease periods of swing with one foot in the air (Browning & Kram, 2007). They minimize lateral ground reaction forces by widening the side-to-side distance between their feet and swinging their legs more to the side than to the front (Abdulrahman & Zebas, 1993). Also, as in infant walking, the wider base and lateral motions add to stability.

Elephants solve a similar problem of curtailing ground reaction forces to prevent their leg bones from shattering. At high speeds, instead of running with a whole-body flight phase and coping with the associated vertical oscillations in their center of mass as their body crashes downward, elephants use extremely fast ambling gaits, always keeping at least one foot on the ground (Hutchinson, Famini, Lair, & Kram, 2003; Schmitt, Cartmill, Griffin, Hanna, & Lemelin, 2006). Small animals such as marmosets and squirrel monkeys don’t have to worry about the effects of ground reaction forces on their own limbs, but they do have to worry about effects on the substrate: While running on thin branches, monkeys do the elephant trick of minimizing oscillations in the center of mass to keep the branches from breaking (Schmitt et al., 2006; Young, 2008). A useful byproduct of minimizing the vertical movements of the center of mass is increased stability. This may be why young children frequently speed walk—termed “Groucho running”—to eliminate the flight phase component of normal running (McMahon, Valiant, & Frederick, 1987; Whitall & Getchell, 1995).

Variations in body proportions affect the form of walking gaits. People with achondroplasia dwarfism that results in short stature, a long torso, and relatively short arms and legs exhibit a bouncing, waddling gait. The pelvis is tilted forward, double that of normal walkers, to aid in propulsion and increase step length (Egginton et al., 2006). The ankle is flexed excessively to help the long foot to clear the ground as it swings forward on the short leg. The knees are bent and bowed outward, as a consequence of the excessive ankle dorsiflexion. Crawling and walking are delayed in infants with achondroplasia, but like children with "normal" body proportions, dwarves learn about the specific constraints and propensities of their own bodies in the course of practicing mobility. When walkers’ legs are elongated experimentally without the opportunity to practice walking, step length does not reflect the new, elongated leg length. In the case of an achondroplasic 10-year-old undergoing a surgical intervention that elongated the shanks of both legs by 22 cm and adults wearing stilts that comparably elongated their legs, participants continued to walk as if on their original, shorter legs (Dominici et al., 2008).

Practice with prosthetics yields a different story. Fitted with lower limbs that simulate the articulations of real legs and feet or that present the high-tech curves of a carbon-fiber spring, both single and double-leg amputees can walk, run, leap, and compete in a variety of athletic contexts. American sprinter and single amputee, Marlon Shirley, runs the 100-m dash in less than 11 seconds. South African double amputee, Oscar Pis-
torius, runs 200 m in less than 22 seconds. Such
tiations, and those of thousands of others benefit-
ting from prosthetic limbs, are not the result of devices
that generate species-typical walking, but of physical
training and learning how to best exploit the capabili-
ties of an alternative anatomy.

Future Directions

Research on the development of locomotion has a
rich history and a promising future. Compared with
other aspects of motor development (eye and face
movements, manual actions), locomotion is especially
amenable to observation because the movements and
muscles involved in transporting the whole body from
one place to another are relatively large. As a
consequence, empirical problems and conceptual issues
are addressed directly with behavioral data. Much
has been accomplished, but there is still work to do.
Research based on the road behind is necessary and
important, but progress is likely to be incremental.
Research that forges new directions for the road ahead
entails more risk, but may present more opportunities
for truly new insights into development.

The Road Behind

Despite more than 100 years of work on the develop-
ment of locomotion by some of developmental psycho-
ology’s most illustrious academy, many fundamental
challenges and puzzles remain. Researchers have not
going to exhaust the array of interesting questions in
understanding basic developmental processes such as
how infants accomplish their first crawling and walk-
ing steps, how they learn to guide locomotion adaptive-
ly, which experiences are critical to foster learning, and
how mobility affects other domains of development.
As has been the case over the last century of work,
continued progress will likely be spurred by technolo-
gical and procedural innovations.

Technological advances for recording, scoring, and
analyzing movements continually open up new possi-
bilities for studying the earliest vestiges of locomotion,
precursory forms, and improvements in locomotor skill.
New recording devices offer increasingly high
temporal and spatial resolution, allowing researchers
to describe movements and forces with great precision.
Techniques that require putting markers or sensors on
the body are increasingly unintrusive; devices are
small, light-weight, and wireless. In particular, wire-
less, head-mounted eye-tracking has recently become
available, allowing researchers to study visual guidance
of locomotion in freely moving, un tethered infants and
children under natural conditions or in laboratory ex-
periments (Franchak & Adolph, 2010; Franchak et al., in
press). New, widely available computerized video cod-
ing technologies (e.g., OpenSHAPA.org) provide the
means for scoring vast amounts of behavioral data
quickly, reliably, and efficiently, and for linking video
data with motion tracking and physiological data. New
data visualization techniques and time-series analyses
provide the means for exploring how movements un-
fold in real time.

Creative innovations in test paradigms, procedures,
apparatuses, and experimental designs are especially
important for assessing changes in flexibility and
exploratory activity and for charting the sequelae of
 locomotor development in other domains of
development. For example, techniques borrowed from
psychophysics allow precise estimation of children’s
abilities and perceived propensities. Age-matched
control designs allow researchers to compare
 locomotor responses and downstream effects of
 locomotion based on infants’ locomotor status and
experience. As new technological and conceptual tools
become available and widely adopted, we expect to see
continued incremental progress in understanding basic
problems in motor development.

The Road Ahead

The pivotal role of experience in motor
development suggests that much remains to be learned
about the flexibility and diversity of human locomotor
development. Many of the examples provided in this
chapter—cultural practices that give children vastly
different sorts of motor experiences, insights from
studies with animals, development in humans with
altered anatomies, endpoints hitherto unimagined—are
not widely appreciated in the field of motor
development. Few studies have examined locomotor
development in the context of other motor actions such
as carrying, visual search, social interaction, and sport
activities. Relatively little work has focused on skill
acquisition after the infancy period and, as a
consequence, surprisingly little is known about the
acquisition of specialized forms of locomotion such as
bicycling, swimming, brachiating (locomotion with the
arms), skiing, and climbing. Locomotion writ large is
tightly untapped by developmental research. As
researchers discover such potentially useful sources of
information, we expect to see more interdisciplinary,
cross-cultural, comparative, and lifespan approaches.

The Road Less Traveled

As illustrated throughout this chapter, motor de-
velopment is one of the few areas in developmental psy-
chology where many of the conceptual issues raised by
the early pioneers and much of their descriptive empir-
ical work retain their relevance, side-by-side with state-
of-the-art ideas and findings. Perhaps one reason for
the unusual longevity of research on the development
of locomotion is that motor behavior presents a fascinating range of variability, contextual effects, quirky developmental changes, and contingencies that continue to generate challenging questions for researchers.

A second, more theoretically compelling reason for the long-standing relevance of so much early work is that the early pioneers in motor development explicitly framed the phenomena in terms of general developmental questions concerning the origins of new forms, patterns of change, the role of experience in engendering change, system-wide influences, and so on. Gesell and McGraw were especially influential in treating motor development as a model system for extracting general principles of development. This gambit of thinking about developmental processes at two levels—the particulars of the behavior and the general principles illustrated by the behavior—continues with modern theorists such as Thelen and Gibson. But it is a road less traveled by many developmental researchers.

Learning to walk is more than the detailed muscle actions and kinematics provided by new technologies and more than the surprising abilities of fetal rats and African women load-carriers provided by comparative and cross-cultural work. It is a behavior that involves patterned neural activity, perception, cognition, and social interaction and that has reverberations throughout these domains of development. Moreover, the development of locomotion presents an opportunity to discover general principles and mechanisms that can inform our understanding of developmental change.

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