Walking Infants Adapt Locomotion to Changing Body Dimensions

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Infants acquire independent mobility amidst a flux of body growth. Changes in body dimensions and variations in the ground change the physical constraints on keeping balance. The study examined whether toddlers can adapt to changes in their body dimensions and variations in the terrain by loading them with lead weights and observing how they navigated safe and risky slopes. Experiment 1 verified the reliability of a new psychophysical procedure for testing infants' responses in 2 experimental conditions. In Experiment 2, this procedure was used to compare infants' responses on slopes in feather-weight and lead-weight conditions. The lead weights impaired infants' ability to walk down slopes. Babies adapted to altered body dimensions by treating the same degree of slope as safe in the feather-weight condition but as risky in the lead-weight condition. Exploratory activity on the starting platform predicted adaptive responses on risky slopes.

Locomotion requires continual adaptation of ongoing movements. Changes in body dimensions and variations in the properties of the ground surface change the physical constraints on maintaining balance. The present research examined whether walking infants can adapt to experimental manipulation of their body dimensions to cope with locomotion over varied terrain.

Effects of Changing Body Dimensions on Infant Locomotion

Infants' body dimensions change dramatically over the first 2 years of life. Newborns are extremely top-heavy with large heads and torsos and short, weak legs. As infants grow, their body fat and muscle mass are redistributed. In contrast to newborns, toddlers' bodies have a more cylindrical shape and they have a larger ratio of muscle mass to body fat, especially in the legs (Thelen & Fisher, 1982). From birth to 2 years, babies' height nearly doubles and their weight more than quadruples (Snyder, Spencer, Owings, & Schneider, 1975). Rate of growth is accelerated in infants' lower limbs compared with their upper bodies; leg length increases by 130% from birth to 2 years, but crown-to-rump length increases by only 69% and head circumference by only 50% (Malina, 1984; Shirley, 1931; Snyder et al., 1975). As a result, infants' body dimensions become more evenly proportioned and their center of mass lowers from the bottom of the sternum to slightly above the navel (C. E. Palmer, 1944). It is as if infants' bodies are growing to fit their comparatively large heads.

Changes in infants' body dimensions are important because they affect the physical constraints on maintaining balance. A lower center of mass, for example, makes the body more stable because, like a bobo doll, less muscle force is required to stay upright as the body sways back and forth around the ankles or hips. In contrast, increased mass on top and displacement of the center of mass upward or outward from the body's vertical axis makes the body less stable, like a top-heavy bookcase or a file cabinet with too many open drawers. Both factors increase the size of destabilizing torques, and more muscle force is required to maintain the same angle of sway before falling over. Adults experience the effects of such changes in their functional body dimensions when they walk carrying a heavy backpack or when the center of mass is displaced forward during late stages of pregnancy.

The problem of keeping balance is compounded as infants venture onto novel ground surfaces. Like changes in body dimensions, variations in terrain also affect the magnitude of forces acting on the body. On a downward slope, for example, balance is especially precarious because the body has a smaller region of permissible sway before falling over. The base of support decreases and range of motion around the ankle joints is limited because the feet are at an angle. The supporting leg is flexed so that muscles must lengthen, requiring more strength to exert force. The body must be kept stiffly upright to prevent falling over. Calf and trunk muscles must work to keep the body aligned with respect to gravity, leaving less available muscle resources for rotating the body around the ankles or hips. With each step, gravity pulls the body down the slope, requiring muscle force to curb forward momentum. The total available muscle torque for generating compensatory swaying movements is limited. Thus, a lower center of
mass, without adding to overall mass, makes the body more stable on slopes by decreasing the size of destabilizing torques due to gravity and inertia. But more weight on top and a higher center of mass require more muscle torque to move the body the same angular distance, exacerbating the already difficult problem of maintaining balance.

In sum, the laws of physics suggest that infants’ body dimensions should affect their ability to resist gravity for crawling and walking (e.g., Thelen, 1984). Indeed, correlational evidence shows that body dimensions are related to the timing of locomotor milestones. Slimmer, more cylindrically shaped babies begin crawling and walking sooner than chubbier, more top-heavy infants (Adolph, 1997; Adolph, Vereijken, & Denny, 1998; Garn, 1966; Shirley, 1931). Surprisingly, several studies failed to find independent effects of infants’ body dimensions on their crawling and walking skill on flat ground (Adolph, 1997; Adolph et al., 1998), slopes (Adolph, 1995; Adolph, Eppler, & Gibson, 1993), or other variations in terrain (C. F. Palmer, 1987, 1989; Schmuckler, 1996; Ulrich, Thelen, & Niles, 1990). One possible explanation is that infants of the same age have a limited range of body dimensions but a wide range in other factors that affect locomotor skill (muscle strength, interlimb coordination, flexibility, etc.). Thus, effects of body dimensions may be masked by the influence of other factors. In addition, growth naturally co-occurs with changes in infants’ muscle strength and other dynamic factors. Previous studies have not measured the effects of body dimensions on locomotor skill with other factors held constant.

Adapting to Changing Body Dimensions and Variations in the Terrain

How might infants adapt locomotion to changes in their body dimensions and to variations in the terrain? Research with adults suggests that exploratory movements yield information about the current status of the body in relation to environmental properties. For example, Mark and colleagues (Mark, Baillet, Craver, Douglas, & Fox, 1990) altered adults’ body dimensions by fitting them with platform shoes. Participants recalibrated judgments of appropriate chair heights for sitting to their elongated legs and higher center of mass only when they were allowed to make exploratory stepping and swaying movements. Without these subtle exploratory movements, adults could not judge chair heights accurately: They underestimated chair heights by erring in the direction of their old, normal leg lengths. Similarly, adults use information gleaned from exploratory movements to detect the current status of their limbs in nonlocomotor tasks. For example, Pagano and colleagues (e.g., Pagano, Garrett, & Turvey, 1996; Pagano & Turvey, 1995) have altered adults’ body dimensions by splinting 200-g rods or masses to their arms. Blindfolded participants recalibrated judgments of the dimensions and orientations of their elongated and heavier arms after only a few seconds of wiggling their unseen limbs to explore their new inertial properties. In other words, exploratory movements, not internally represented body schemes, revealed the requisite information for on-line perception via the pattern of forces acting on body tissues.

Like adults, even very young infants are sensitive to unaccustomed changes in the forces acting on their limbs. Six-week-olds performed fewer spontaneous stepping movements while wearing weights on their legs and more stepping movements when their legs were submerged in a tank of water to lessen the pull of gravity (Thelen & Fisher, 1982). With only one leg weighted, infants maintained their normal overall kick rate across both legs by suppressing kicks in the weighted leg and executing more frequent movements in the unweighted leg (Thelen, Skala, & Kelso, 1987). Exploratory leg movements thus yielded information about the dynamic status of the moving limbs.

Exploratory movements are also required to gauge possibilities for locomotion over sloping ground. Adults judged correctly whether slopes were safe for walking based on visual information and on haptic information gleaned from exploratory touching movements with their feet (Kinsella-Shaw, Shaw, & Turvey, 1992), hands (Proffitt, Bhatta, Gossweiler, & Midgnett, 1995), and hand-held probes (Fitzpatrick, Carello, Schmidt, & Corey, 1994). Likewise, in studies of infant locomotion over slopes, 14-month-old toddlers walked down shallow slopes but slid down or avoided steep ones (Adolph, 1995; Adolph et al., 1993; Eppler, Adolph, & Weiner, 1996). Infants’ judgments of whether slopes were safe or risky were scaled to their actual ability to walk down slopes, and their exploratory movements neatly mirrored their perceptual judgments. On risky slopes, infants hesitated on the starting platform and peered over the brink. They tested their ability to maintain balance by swaying and stepping on the starting platform and by rocking back and forth over their ankles at the brink of the slope.

Infants’ ability to adapt to naturally occurring changes in their body dimensions is further complicated by the saltatorial nature of their growth. In contrast to traditional depictions of gradual, continuous growth, recent research shows that infants’ bodies grow in fits and starts (Lampi, 1983, 1993; Lampi, Veldhuis, & Johnson, 1992). Daily and weekly measures of infants’ weight and height over the first 21 months of life showed that babies grow in brief but substantial spurts. Infants literally grew overnight in increments ranging from 0.5 cm to 2.0 cm. The sudden growth spurts were separated by plateaus of stability ranging from 2 days to 2 months in which no significant growth occurred. The uneven performance typical of infants’ developing motor skills may be due to the abrupt nature of their bodies’ growth (Thelen et al., 1987). However, the plateau periods between growth episodes may provide infants with an opportunity to adjust to their changing bodies. Thus, the question remains as to whether infants can immediately detect a significant change in their body dimensions and relate it to possibilities for action or whether they need a longer period of adjustment. Like the adults in platform shoes in Mark and colleagues’ (1990) study, do infants recalibrate to their altered bodies during their first few steps and sways on awakening after a growth spurt? Or does recalibration occur only after a more extended period of time walking around and testing the new consequences for balance control?

The present research addressed the developmental question of how infants acquire locomotor skill amid the flux of body growth and encounters with novel ground surfaces. Like pregnant women, infants’ bodies change over a relatively short time course. And like adults’, infants’ everyday environment poses constant challenges for balance control—plush carpets and slippery hardwood floors, the playpen mattress and playground sandbox, household stairs and slides, and so on. In contrast to adults, however, infants learn to crawl and walk at the same time that their body dimensions change and at the same time that they encounter new properties of the ground surface.
We examined whether newly walking infants can adapt locomotion to changes in their body dimensions and to variations in the terrain by experimentally manipulating their functional body dimensions with a lead-weighted vest. The lead weights made balance more precarious by adding to infants' overall mass and by raising their center of mass. Then, we tested the babies in a novel situation in which such altered body dimensions make balance control especially difficult—walking down slopes. By comparing infants' responses on steep and shallow slopes in weighted and unweighted conditions, we could determine whether they can adapt locomotion to changing body dimensions and to variations in surface slant.

We devised a psychophysical double staircase procedure that involved frequent switching between weighted and unweighted conditions and between steep and shallow slopes. This procedure has an advantage over blocking the weighted and unweighted conditions because it is not subject to differential effects of fatigue or changes in infants' response criteria over time. Moreover, making adaptive responses would require infants to detect on-line the current status of their body dimensions relative to the degree of slope and then to plan actions accordingly. Walking with the lead weights would require infants to generate the appropriate compensatory forces to take their new body dimensions into account. In both conditions, impossibly steep slopes would necessitate alternative sliding positions or avoidance. Experiment 1 verified the reliability of the psychophysical double staircase procedure for testing infants' locomotor abilities and perceptual judgments on slopes under two identical experimental conditions. Experiment 2 used this new procedure to compare infants' walking abilities and judgments while carrying feather-weight versus lead-weight loads.

Experiment 1: Consistency Across Identical Feather-Weight Conditions

Experiment 1 was designed to establish the reliability of the psychophysical double staircase procedure for measuring infants' walking ability and perceptual judgments on slopes. Before testing the weighting manipulation, it was necessary to verify that the new procedure reliably indexes infants' abilities and judgments across two identical experimental conditions. Previously, Adolph (1995) introduced a single psychophysical staircase procedure to assess the accuracy of 14-month-old walking infants' perceptual judgments and the efficiency of their exploratory behavior on safe and risky slopes. The procedure estimated the steepest slope each infant could walk down successfully and then compared exploratory activity and perceptual judgments on safe and risky slopes relative to this "walking boundary." The present experiment introduces the above-mentioned double staircase procedure, running two independent protocols in tandem.

The new procedure involves frequent switching between two weighting conditions. To establish the reliability of the procedure, we measured infants' performance under two identical feather-weight sham conditions in which their body dimensions were modified only trivially. The procedure developed for this study required more than twice the number of slope trials used in previous research (Adolph, 1995, 1997) and required infants to participate in a physically arduous task for over 60 min. Similar psychophysical methods have been used in sound lateralization tasks with infants (e.g., Ashmead, Davis, Whalen, & Odom, 1991) and in verbal or keypress response tasks with adults (e.g., Cornsweet, 1962), but no experimenters have reported such costly motor responses from such young participants. It was therefore important to determine whether infants could maintain participation over such a long and arduous procedure.

We reasoned that if the new procedure is reliable, infants should show differences in their responses based only on degree of slope and not based on switches between sham conditions. Perceptual judgments and exploratory activity should be scaled to the relative degree of risk. Infants should walk down safe hills and slide down or avoid increasingly risky ones. But, across the two sham conditions, infants should show identical walking abilities, perceptual judgments, and levels of exploratory activity. Such results would mean that infants can maintain the same response criteria and the same level of interest across dozens of trials and frequent switching of their feather-weight shoulder packs. In addition, we collected measures of infants' walking experience and walking skill on flat ground to provide independent verification of the estimates of their walking ability on slopes derived from the staircase procedure. As in previous research, we expected that body dimensions would be poor predictors of infants' walking ability because of a narrow range of body dimensions in the cross-sectional sample.

Method

Participants

Twenty-four infants (12 girls and 12 boys) participated in Experiment 1. We recruited families from newspaper advertisements and from a booth at a "baby fair" catering to new parents. All infants were healthy term babies, and most were White and of middle-class socioeconomic status (SES). All babies were 14 months old (± 10 days) and could walk at least 12 ft (3.7 m) independently. Their nude weight ranged from 8.14 to 11.58 kg (\(M = 10.03\) kg) and height ranged from 70.50 to 86.10 cm (\(M = 80.68\) cm). Walking experience ranged from 14 to 179 days (\(M = 81.88\) days). Only 9 infants had slid down a playground slide independently, 8 had experience walking down slopes (e.g., wheelchair ramps, sloping driveways), and 10 had experience descending stairs independently. During the test session, infants wore T-shirts, diapers, rubber-soled shoes, and the laboratory vest with feather-weight saddlebags. Seven additional infants became fussy during testing, and their data were not used. Families received infant T-shirts, diplomas, and framed photographs of their children as souvenirs of their participation.

Adjustable Vest and Saddlebags

We constructed an adjustable padded vest with removable saddlebags slung over each shoulder. Velcro fastenings down the front and back and along the sides of the vest ensured a snug fit. Velcro patches over the chest, shoulders, and back of the vest allowed for quick removal and firm attachment of the saddlebag pouches to the vest. Infants wore two triangular pouches \((7.5 \times 12.0 \times 3.0\) cm\) in the front to allow free head movement and view of the floor beneath their feet. They wore two rectangular pouches \((8.0 \times 9.0 \times 3.0\) cm\) in the back. For the purpose of this control experiment, the saddlebags were unweighted in both conditions. We filled each pouch with pillow stuffing to increase infants' chest circumference with only a negligible increase in weight (total weight of feather-weight saddlebags = 120 g).

Sloping Walkway

Infants encountered safe and risky hills on a motorized walkway with adjustable slope (see Figure 1). The walkway consisted of three wooden
boards connected with piano hinges. Flat starting and landing platforms (86 × 91 cm) flanked a middle sloping section (86 × 91 cm) to form a single continuous surface (width = 86 cm, length = 273 cm). The height of the starting platform remained constant at 116 cm, but the height of the landing platform adjusted from 116 to 25 cm via a drive screw from an electric garage door opener. A push button changed the height of the landing platform to set the slope of the center board in 4° increments from 0° to 88°. A protractor on the side of the walkway indicated the slope of the center section relative to the starting platform. Plush carpeting covered the walkway during slope trials to provide traction and cushioning. Wooden posts located at the corners of the starting and landing platforms provided infants with opportunity for manual support. Volleyball nets spanning the sides of the walkway served as visual barriers and a safety precaution. A catwalk along one side of the walkway provided an experimenter with easy access to the infants to ensure their safety as they went down slopes.

Procedure

We tested each infant in a single session of 90–120 min. First, babies became comfortable with the laboratory and experimenters while parents reported infants’ locomotor experience. Then, infants were fitted in their laboratory vest without saddlebags and weighed. Next, the feather-weight saddlebags were affixed to the vest, and infants were tested on slopes using the new, psychophysical, double staircase procedure. After trials on slopes, experimenters collected footprint measures of infants’ walking skill on the flat walkway. Footprints were collected at the end rather than the beginning of the session to maximize the likelihood that infants could complete the lengthy testing on slopes. An assistant videotaped infants on the flat walkway and slopes from the side of the walkway. Finally, experimenters measured infants’ body dimensions.

Psychophysical double staircase procedure. We used a modified psychophysical double staircase procedure to estimate each infant’s walking ability and perceptual judgments on slopes. Because infants of the same age show a wide range in walking skill, it was necessary to normalize their perceptual judgments to their walking ability to assess the accuracy of their decisions about whether slopes were safe or risky for walking. In contrast to other psychophysical procedures, the staircase procedure uses a relatively small number of trials to determine a change point in behavior and most trials occur around the change point. The experimenter determines each “step size” (stimulus level) based on the outcome of the previous trial until narrowing in on the change point according to a predetermined criterion. Thus, the total number of trials is tailored to the abilities of individual participants. In general, more difficult increments follow correct or successful trials and easier increments follow incorrect or unsuccessful trials.

In a typical double staircase procedure, the experimenter presents stimuli from the same condition, running two independent protocols in tandem (Cornsweet, 1962). Because participants cannot easily track presentation order, the double staircase procedure provides more reliable estimates than two single protocols. For our purposes, the double staircase procedure allowed comparisons between two experimental conditions. We conducted two independent staircase protocols in tandem, one for each identical feather-weight condition. Both pairs of feather-weight saddlebags were arbitrarily labeled A and B. Order of protocols was counterbalanced.

Infants began each trial in a standing position on the starting platform. Parents stood at the end of the landing platform and encouraged infants to descend, using various attractive toys and Cheerios as enticements. An experimenter followed alongside infants to ensure their safety. The adults did not caution infants or provide information about how to descend. Trials began when the experimenter released infants on the starting platform and only after babies oriented their eyes and heads toward the landing platform. This ensured that infants had time for at least brief visual inspection of slopes before deciding whether or not to walk down. Trials were timed out at 60 s if infants refused to descend the slope.

All infants began with an easy baseline 4° slope. Degree of slope was increased or decreased depending on the outcome of the previous trial. The experimenter coded each trial on-line as either a success (walked down safely), failure (tried to walk but fell), or refusal to walk (slid down or avoided descent). For the purpose of estimating walking boundaries, failures and refusals were treated as equivalent, unsuccessful outcomes. In both protocols, we used a two-down, one-up staircase procedure. After each successful trial, the experimenter increased slope by 8°. After a failure or refusal, the experimenter presented infants with a shallow baseline slope of 4° to provide babies with an easy success and to maintain their motivation to continue with the experiment. Then the experimenter removed infants’ saddlebags for the current condition, attached the saddlebags for the other condition, and switched from the current staircase protocol to the other protocol. On re-entering a staircase protocol, the experimenter presented infants with a slope 4° shallower than the last unsuccessful trial for that condition. This process continued for each protocol until the experimenter identified walking boundary to a 75% criterion—the steepest slope that infants walked down successfully at least three out of four times and less than three out of four times at the next 4° and 8° increments. Occasionally, infants met the criterion for walking boundary in one protocol before the other. In these cases, the experimenter switched feather-
weight saddlebags and presented the baseline 4° hill in the completed protocol. Figure 2 illustrates typical protocols from one child in the double staircase procedure.

It is important to note that the staircase procedure provides only a conservative estimate of infants' walking abilities. If infants refused to walk on perfectly manageable hills, the trials would be coded as refusals and walking boundaries would be underestimated. However, the practice of presenting easy baseline trials after failures and refusals renewed infants' motivation to walk.

After identifying walking boundaries for both staircase protocols, the experimenter presented infants with additional trials to assess their perceptual judgments on safe and risky slopes. By definition, slopes shallower than infants' walking boundaries were safe for walking and slopes steeper than boundaries were increasingly risky for walking. Trials were aggregated into eight slope groups relative to boundary: the boundary slope (0°), slopes slightly shallower or steeper than boundary (±4°), slopes at an intermediate range (±8°–12°), slopes considerably shallower and steeper than boundary (±16°–20°), and an impossibly risky slope far steeper than boundary (40°). Each slope group is represented by its midpoint. The aim was to collect a total of four trials in each slope group for each protocol at all increments except the very steepest 40° slope. The four-trial rule provided enough data to smooth out chance irregularities, while keeping the number of trials constant across slope groups and protocols for later statistical analyses. Infants received only two trials at 40° because we expected infants to respond consistently at such an extreme increment. We included trials from the staircase protocols in all analyses of perceptual judgments and exploratory activity to minimize the additional number of trials required. The experimenter filled out each slope group, one trial at a time, from the shallowest to steepest slope group in one feather-weight condition. Then, following an easy 4° baseline trial, the experimenter changed infants' saddlebags and switched from the current feather-weight condition to the other feather-weight condition. Because of the personalized nature of the staircase protocol, children with steeper walking boundaries had more trials on slopes than children with shallower boundaries. The total number of trials per child ranged from 62 to 87 (M = 74.92).

**Footprint measures of walking proficiency on flat ground.** We used a footprint method of gait analysis (Adolph, 1995, 1997; Adolph et al., 1993) to measure infants' walking skill on flat ground. A drop leaf attached to the starting platform increased the total length of the walkway to 364 cm during footprint trials. Experimenters removed the carpeted surface from the walkway and replaced it with butcher paper. An experimenter attached inked adhesive tabs to the bottom of infants' sneakers at the toe and heel. Infants walked over the flat, extended walkway toward their parents, leaving behind a trial of footprints on the butcher paper.

**Body dimensions.** We collected measures of infants' body dimensions to assess effects of naturally occurring body growth on walking ability on flat ground and slopes. Prior to testing on slopes, the experimenter measured infants' clothed weight on a pediatric scale (babies wore a T-shirt, shoes, and the laboratory vest without saddlebags). After testing on slopes, the experimenter measured infants' bare body weight using a pediatric scale and measured various body dimensions with a calibrated tape: head circumference across the eyebrow line, leg length from the iliac crest of the hip bones to the malleolus of the ankle bones, recumbent height from the crown of the head to the soles of the feet, crown-rump length from the top of the head to the buttocks, and trunk length from the shoulders to the buttocks.

**Data Coding**

All slope data collected on-line were recorded from videotapes of the sessions. Only video-based data were used in the analyses. Primary coders

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**Figure 2.** Typical staircase protocols for sham feather-weight A and B conditions. S = successes (walked slope safely); F = failures (tried to walk but fell); R = refusals to walk (slid down or avoided going). Shaded rows indicate the infant's walking boundary in each condition (steepest slope with at least three out of four successes). Dark vertical lines indicate frequent switching of saddlebag conditions and entry into the opposite protocol.
scored each slope trial using a computerized coding system, MacSHAPA, that records frequency and durations of specified behaviors (Sanderson et al., 1994).

**Walking Boundaries on Slopes**

As described above, coders recoded trial outcome as either a success, failure, or refusal, then recalculated walking boundaries according to the 75% success criterion. Walking boundaries calculated from videotape were in exact agreement with 100% of the walking boundaries calculated online. A second coder independently scored 20% of the slope trials from each infant. Coders were in exact agreement on 97% of trials.

**Perceptual Judgments on Safe and Risky Hills**

We indexed the accuracy of infants’ perceptual judgments by calculating the ratio of infants’ attempts to walk to the total number of trials: (successes + failures)/(successes + failures + refusals to walk). The inverse no-go ratio, (refusals)/(successes + failures + refusals), yields the same information. We calculated this go ratio (Adolph, 1995, 1997) separately for each child over the four trials in each slope group in feather-weight A and B conditions. By definition, the go ratio is .75 or 1.0 at the walking boundary, but the ratio can vary from 0 to 1.0 at all other slope groups. Also by definition, the probability of successful walking is high on safe slopes shallower than infants’ walking boundaries but low on risky slopes steeper than their boundaries. Our logic was that infants would have a high go ratio on hills they perceived as safe but a low go ratio on hills they perceived as risky. Perfect perceptual judgments would be indicated by a go ratio that exactly matched the probability of success at each slope group.

For each trial, coders scored the method of locomotion that infants used to descend slopes as either walking (without holding onto the nets for support) or using an alternative strategy: walking with support (holding onto the nets), crawling (on hands and knees), sliding (headfirst prone), backing (crawling backward with feet pointed toward the landing platform), or avoiding (refusing to descend for the duration of the trial). On trials scored as refusals, these data reflected whether infants switched from walking to a less precarious position or simply avoided going. On trials coded as successes, coders scored infants’ step number and step time (from their first step on the hill to their first step on the landing platform). These data reflect whether infants adjusted their gait to cope with walking down steeper slopes. A higher step number and step time reflects shorter, slower steps. A second coder scored method of locomotion, step number, and step time on 20% of trials for each infant. The correlation coefficient for interrater agreement was 96% for method of locomotion, and correlation coefficients for step number and step time were .97 and .92, respectively.

**Exploratory Activity**

Exploratory activity included only behaviors on the starting platform before infants began going down slopes. Because the go ratio depended only on infants’ behavior after they crossed the brink of the slope, measures of exploration and perceptual judgments were independent. In principle, infants could succeed, fail, or refuse to walk regardless of whether they hesitated or touched slopes prior to descent. Trials began only after infants oriented their eyes and head toward the landing platform to ensure that babies had time for at least brief visual inspection of slopes before deciding whether or not to walk. Thus, measures of latency and touching indicate whether infants engaged in more prolonged visual and haptic exploration.

We calculated each measure as an average for each child over the four trials in each slope group.

**Latency.** Latency was the time between the start of the trial, when the experimenter released infants on the starting platform, and their attempt to descend the slope. It included the time that infants stepped and swayed on the starting platform, looked at the slope, touched the slope, or performed evasive activities such as trying to escape from the starting platform. The time required to approach the slope and get into the final descent position was subtracted out so that latency did not include the time required to perform awkward shifts in position. If infants avoided going down the slope or fussed incessantly, coders recorded latency as 60 s or until the experimenter stopped the trial, whichever occurred first. If infants started down the slope immediately, coders scored latency as 0.1 s. A second coder scored latency on 20% of each infant’s trials. The correlation coefficient for interrater reliability was .97.

**Touching.** Coders recorded whether or not infants actively touched the slope before attempting to descend. Touching included rocking or stepping movements on the brink of the slope; rubbing the bottom of a foot over the slope; and using the hands to pat, rub, or probe the slope. Coders scored touches only when infants stopped moving forward, oriented their heads toward the slope, and contacted the hill with hands or feet for at least 0.5 s. A second coder scored touching on 20% of the trials for each infant. The percentage of interrater agreement was 88%.

**Walking Skill on Flat Ground**

Footprint sequences were used to calculate measures of infants’ walking skill on flat ground. Only the middle portion of the sequences, after infants had hit their stride, were used in analyses (Breiniere, Bril, & Fontaine, 1989). Coders placed a transparent grid over the trails of footprints to obtain the x- and y-coordinates of each heel and toe mark. A computer program (Adolph, 1995; Adolph et al., 1996) transformed the coordinates into distance and angle measurements (illustrated in Figure 3). Step length is the distance between consecutive placements of opposite feet. Step width is the lateral distance between the feet. Dynamic base is the angle between three consecutive footsteps. It provides a measure of the straightness of infants’ walking and takes both step length and step width into account. Larger step lengths, smaller step widths, and dynamic base angles approaching 180° characterize the more mature gait patterns of experienced walkers (e.g., Adolph et al., 1996; Breiniere et al., 1989; McGraw & Breeze, 1941; Shirley, 1931). Sixteen children completed two sets of footprint sequences for both feather-weight conditions. Two additional children completed footprint sequences for only the feather-weight A condition, and 3 additional children completed sequences for only the feather-weight B condition. Test–retest reliability was calculated separately for each measure in each feather-weight condition. Correlation coefficients ranged from .72 to .92, comparable to reliability obtained in footprint sequences with adults (Boening, 1977).

**Results and Discussion**

We conducted analyses on infants’ behaviors normalized to the walking boundaries for each condition. Omnibus tests (analyses of
variance; ANOVAs) were performed on measures for which we could ensure that each child contributed data to each risky slope group; on other measures, we used paired t tests to maintain a critical sample size for each comparison. The critical analyses focused on differences between consecutive slope groups (linear trend analyses) and differences between conditions at each slope group (planned pairwise comparisons).

Overall, the results replicate and extend previous studies with walking infants (Adolph, 1995, 1997; Adolph et al., 1993; Eppler et al., 1996). The new psychophysical double staircase procedure yields reliable estimates of infants' walking ability, perceptual judgments, and exploratory activity on slopes and shows that infants can maintain a stable response criterion over the lengthy and physically demanding session. On every measure, infants responded differentially to degree of slope but behaved similarly in the two identical feather-weight conditions. We discuss each measure in turn below.

**Walking Boundaries on Slopes**

As shown in Figure 4A, infants displayed a wide range of walking boundaries (4°–24° and 4°–28° in feather-weight conditions A and B, respectively). Some children could walk down very steep slopes and some could manage only very shallow ones, emphasizing the importance of normalizing infants' perceptual judgments to their walking abilities. Most important, infants displayed similar walking boundaries in the A (M = 15.00°, SD = 6.49°) and B conditions (M = 15.67°, SD = 7.26°), indicating that the double staircase procedure yields reliable estimates of children’s walking ability, paired t(23) = -1.45, p > .10. Sixteen infants had identical boundaries in both feather-weight conditions. The remaining 8 infants had boundaries differing by only one slope increment (4°), distributed randomly across the conditions.

Overall, infants' success at walking down slopes decreased in accordance with degree of slant. Figure 4B shows the average ratio of successful trials to attempts to walk, (successes)/(successes + failures), at each slope group normalized to each infant’s walking boundary for each feather-weight condition. Variable numbers of children contributed data to success ratios because they often refused to walk on risky slopes. Paired t tests confirmed the similarity between walking boundaries at each risky slope group (all ps > .10). Collapsing across feather-weight A and B conditions, repeated measures ANOVA on success ratios at 0°, +4°, +10°, and +18° slope groups showed a significant effect for slope, F(3, 39) = 75.56, p < .001. Trend analyses confirmed a significant linear effect, F(1, 13) = 340.6, p < .001.

With respect to developmental correlates of walking boundaries, just as switching between the feather-weight saddles had no effect on infants’ walking boundaries on slopes, there was no difference in infants’ walking skill on flat ground due to sham conditions. Repeated measures multivariate analysis of variance (MANOVA) showed no differences in infants’ average step lengths, step widths, or dynamic base angles or in the coefficients of variation for each measure (all ps > .10). As expected, infants with more walking experience had more mature gait patterns. Correlation coefficients between infants’ walking experience and their average step length, step width, and dynamic base angles were .63, -.51, and .60, respectively (all ps < .05).

More experienced, skillfull walkers on flat ground had steeper walking boundaries on slopes, providing independent verification of the validity of estimates of walking boundaries derived from the staircase procedure. Each measure was significantly correlated with infants' average walking boundaries: walking experience (r = .59), step length (r = .54), step width (r = -.46), and dynamic base angle (r = .53; all ps < .05). As in Adolph's (1995) cross-sectional study, the range in infants’ body dimensions was small and there was no relationship between measures of children’s natural body dimensions and their walking skill on flat ground or slopes. Likewise, there was no relationship between infants' walking skill and various “chubbiness” indices reported in the literature such as Ponderal Index (weight/height³; Shirley, 1931), standing height/leg length, trunk length/leg length, or weight/standing height (Garn, 1966; Malina, 1984; Shirley, 1931).
Perceptual Judgments on Safe and Risky Hills

Infants' perceptual judgments were based only on the relative degree of risk. There were no differences between the sham feather-weight conditions. Infants scaled their perceptual judgments to their walking boundaries—they walked down safe hills and slid down or avoided risky ones (Figure 5). On safe hills, go ratios were consistently high. On risky hills, go ratios steadily decreased from .70 at the +4° slope to .10 at the +40° slope. A 2 (sham conditions) × 4 (0°, +4°, +10°, and +18° slope groups) repeated measures ANOVA on go ratios showed only a main effect for slope group, F(3, 69) = 54.9, p < .001. Trend analyses revealed a significant linear effect, F(1, 23) = 122.4, p < .001, confirming differences between consecutive slope groups. Planned comparisons showed no differences between sham conditions at each slope group (all ps > .10).

On average, infants slightly overestimated their ability to walk down slopes. Their go ratios at each slope increment were higher than their probability of success at that increment (cf. Figures 4b and 5). Like any measure of perceptual judgments, the go ratio may be affected by infants' response criteria (bias toward reckless or cautious responding). Infants' overestimation in the current study may have been due in part to aspects of the experimental procedure that were designed to ensure infants' participation over large numbers of trials. In particular, frequent presentation of easy baseline trials and hysteresis effects from presenting probe trials in ascending order may have biased infants toward more liberal response criteria (see Adolph, 1997).

On trials on which infants refused to walk, they used a variety of alternative locomotor methods: 23% backing, 45% sitting, 2% crawling, and 6% walking while holding the nets for support. Infants avoided descent on only 24% of trials. On refusal trials, most infants (n = 18) used multiple descent methods over the course of the session, showing a flexible variety of means for coping with risky slopes. There were no differences in infants' descent methods across the two feather-weight sham conditions.

On trials on which infants walked successfully, they adjusted their gait in accordance with the degree of slope. As shown in Figure 6, step number and step time increased from −10° to 0°, where they reached asymptote, meaning that infants took shorter, slower steps on steeper, more challenging slopes. Variable numbers of children contributed data on risky slopes because step number and step time were calculated only for successful walk trials. Paired t tests confirmed no effect of sham condition on slope groups between −10° and +4° (all ps > .10). Collapsing across feather-weight conditions, repeated measures ANOVAs comparing −10°, −4°, 0°, and 4° slope groups showed significant effects for slope on step number and step time, F(3, 54) = 7.55, p < .001, and F(3, 51) = 7.07, p < .001, respectively. Trend analyses confirmed significant linear effects for both measures, F(1, 18) = 10.4, p < .005, and F(1, 17) = 12.8, p < .002, respectively.

Apparently, the slope task was relatively novel for infants, and they discovered alternative descent methods and adaptive gait modifications during the course of the session. There were no differences in number of alternative descent methods between

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**Figure 5.** Mean go ratios (± SE) at each slope group in feather-weight A and B conditions. Go ratio = (successes + failures)/(successes + failures + refusals to walk). Each go-ratio curve is normalized to the walking boundary for that condition, represented by the dashed vertical line at 0. Safe slopes are represented by negative numbers on the x-axis to the left of the walking boundary, and increasingly risky slopes are represented by positive numbers to the right of the walking boundary. S = successes; F = failures; R = refusals to walk.

**Figure 6.** Modification of walking gait on successful trials at each slope group in each feather-weight condition. A: Mean number of steps (±SE). B: Mean step time (±SE). Each curve is normalized to the walking boundary in the appropriate feather-weight condition, represented by the dashed vertical line at 0.
infants with prior experience descending playground slides or stairs and infants with no prior experience on these surfaces (all ps > .10). Likewise, there were no differences based on prior experience walking down slopes for measures of step number or step time (all ps > .10).

Exploratory Activity

Latencies were brief on 4° baseline trials (M = 1.76 s). There was no relationship between latency on these easy slopes and trial number (r = -.10), indicating that babies maintained their motivation to participate over the lengthy sessions. Most latencies on test trials were also of short duration (Mdn = 3.63 s), but if infants hesitated, even for a brief moment, they were more likely to refuse to walk (61% of trials) than if they started down slopes immediately (14% of trials). On trials on which infants hesitated, they looked down the slopes, performed stepping and swaying movements on the starting platform, touched slopes, tested alternative sliding positions, and occasionally called to their parents or engaged in evasive tactics such as trying to escape from the starting platform. Touching was predominantly performed with the feet (98% of trials), and most foot touches involved rocking back and forth over the ankles right at the brink of the slope. Such rocking movements generate proprioceptive information about infants’ own stability relative to the slope (visual information from the acceleration of optic flow patterns as infants sway back and forth and haptic information from torque at the ankles and from shearing forces between the bottom of the foot and the sloping surface). After touching, infants were more likely to refuse to walk (57% of trials) than if they did not touch (28% of trials).

Overall, infants’ exploratory activity mirrored their go ratios (see Figure 7), suggesting that they used information from looking, swaying, and touching movements to judge whether slopes were safe for walking. Exploratory activity increased at the same slopes on which go ratios decreased (cf. Figures 5 and 7). Latency and touching increased with relative degree of risk, but infants behaved similarly across the feather-weight sham conditions. Both latency and touching increased on slopes slightly shallower than walking safe for walking. Exploratory activity increased at the same slopes on which go ratios decreased (cf. Figures 5 and 7). Latency and touching increased with relative degree of risk, but infants behaved similarly across the feather-weight sham conditions. Both latency and touching increased on slopes slightly shallower than walking boundaries until reaching asymptote at intermediate degrees of slope. We conducted 2 (sham conditions) × 4 (0°, 4°, 10°, and 18° slope groups) repeated measures ANOVAs on latency and touching, which revealed only a main effect for slope group, \( F(3, 69) = 9.2, p < .001 \), and \( F(3, 69) = 3.5, p < .020 \), respectively. Trend analyses confirmed a significant linear effect for slope with the latency measure, \( F(1, 23) = 12.5, p < .002 \).

The pattern of increasing exploration with increase in degree of slant replicates previous research with this age group (Adolph, 1995; Adolph et al., 1993). As in previous research, avoidance responses were not solely responsible for the high latency curve. Latency showed the same pattern across consecutive slopes when avoidance trials were removed. Thus, the finding that latency and touching increased as slopes became challenging for maintaining balance suggests that infants engaged in more prolonged exploration after a brief glance at the slope suggested to them that something was amiss (Adolph, 1995; 1997; Adolph & Eppler, 1998). The finding that exploration did not show an inverted U-shaped function suggests that babies may use information from prolonged looking and frequent touching to select alternative strategies for descent. In fact, trials were typically punctuated with alternations between bouts of looking, touching, swaying, testing alternative sliding positions, and engaging in various evasive activities.

Summary of Experiment 1

The results of Experiment 1 demonstrate the reliability of the psychophysical double staircase procedure for comparing infants’ responses across two experimental conditions. With only feather-weight stuffing in both pairs of saddlebags, infants behaved similarly in both sham conditions, displaying similar walking boundaries, perceptual judgments, and levels of exploratory activity. Such consistency is all the more remarkable given the twofold increase in trials compared with earlier research, the physically taxing procedure, the increase in chest circumference due to wearing the feather-weight saddlebags, and the annoyance of having the shoulder packs removed and reattached between trials. Moreover, the results replicated and extended previous findings with infants of the same age group (Adolph, 1995; Adolph et al., 1993). Exploratory activity on the starting platform was related to infants’ perceptual judgments, suggesting that infants used information...
gleaned from exploratory looks, sways, and touches to decide whether slopes were safe for walking.

As in previous cross-sectional studies (e.g., Adolph, 1995), there was no effect of infants' natural body dimensions or overall chubbiness on walking skill on flat ground or slopes. This null finding may have resulted from the relatively narrow range of body dimensions in infants of the same age and the relatively wide range in other developmental factors that affect the biomechanics of walking (muscle strength, coordination, etc.). Experiment 2 provided the critical test of the effects of changing body dimensions by experimentally altering infants' body dimensions while holding other developmental factors constant.

Experiment 2: Adapting to Feather-Weight and Lead-Weight Conditions

Experiment 2 used the same psychophysical double staircase procedure to examine infants' ability to adapt locomotion to experimental changes in their body dimensions. We altered their body dimensions by putting lead weights in one set of saddlebags. The weights increased infants' mass and raised their center of mass, making their bodies less stable and more top-heavy. Without a concomitant increase in muscle strength or coordination, the lead weights should make balance more precarious, especially while walking down slopes. Because infants showed no differences between conditions with identical feather-weight saddlebags in Experiment 1, we reasoned that differences in infants between feather-weight and lead-weight conditions in the current experiment could be attributed to carrying the extra load in their lead-weight saddlebags.

The experiment had three aims. First, we assessed whether systematic changes in infants' body dimensions cause corresponding changes in their ability to walk. This was done by comparing walking boundaries on slopes and footprint measures on flat ground in the feather-weight and lead-weight conditions. With heavy loads (25%–60% of their body weight), adults take smaller, faster steps to minimize the problem of maintaining balance during single leg support (Martin & Nelson, 1986). Thus, we expected infants to display shallower walking boundaries on slopes and less mature gait patterns on flat ground while wearing their lead-weight saddlebags. Second, we determined whether infants detect the changes in their functional body dimensions and are able to adapt their behavior accordingly. We compared their go ratios in the two weighting conditions. If infants gauge the relative degree of risk based on their current body dimensions in relation to the slope of the ground surface, they should show similar go ratios in both weighting conditions normalized to their walking boundary in each condition. However, if the lead weights cause infants to behave more cautiously toward the same relative degree of risk, their go ratios in the lead-weight condition would be displaced to the left of their go ratios in the feather-weight condition. If the lead weights cause infants to behave more recklessly, their go ratios in the lead-weight condition would be displaced to the right of their go ratios in the feather-weight condition. Finally, we examined the informational basis for infants' judgments by observing their exploratory behavior before starting down slopes. Differences due to the weights would indicate that infants detected the change in their functional body dimensions. More exploratory movements in the lead-weight condition would suggest that infants sought to obtain additional information about their altered abilities on slopes. Alternatively, less exploration in the lead-weight condition would suggest that exploratory movements were hampered or that infants' attention was consumed by the effort to maintain balance.

Method

Participants

Twenty infants (10 girls and 10 boys) participated in Experiment 2. Seven additional infants became fussy during testing, and their data were not used. Participants were recruited from newspaper advertisements and from a booth at a "baby fair." Most infants were White and of middle-class SES. Infants were 14 months old (± 10 days), and all could walk at least 12 ft (3.7 m) independently. Walking experience ranged from 3 to 107 days ($M = 62.55$ days). Three infants had prior experience sliding down playground slides independently, 8 had experience walking down slopes, and 9 had experience descending stairs. Other aspects were the same as in Experiment 1.

Vest With Feather-Weight and Lead-Weight Saddlebags

We modified infants' functional body dimensions with the same adjustable vest with removable saddlebags used in Experiment 1. One pair of saddlebags was filled with feather-weight stuffing and the other pair of saddlebags was filled with heavy lead weights. The feather-weight saddlebags increased infants' chest circumference by the same amount, but they also increased their body weight by 25% and raised the location of their center of mass. Pilot data showed that a 25% increase in total body weight was the maximum amount that infants could tolerate before their legs collapsed. As a point of comparison, relatively fit adult hikers can comfortably carry only 25%–33% of their body weight (Fletcher, 1974). An experimenter measured each infant's clothed weight (infants wore T-shirts, diapers, rubber-soled shoes, and the laboratory vest without saddlebags) prior to testing to determine the amount of weight to put into the lead-weight saddlebags. Infants' clothed weight ranged from 8.85 to 12.20 kg. Thus, babies carried between 2.20 and 3.00 kg in their lead-weight shoulder packs. An experimenter measured infants' bare body weight after testing. All infants were slightly heavier clothed than nude, affirming the reliability of the measure of their clothed weight.

Procedure

Infants encountered safe and risky hills on the same adjustable walkway described in Experiment 1. We used the identical experimental and data-coding procedure described in Experiment 1 to test infants in Experiment 2. We determined infants' walking boundaries and perceptual judgments on slopes in both their lead-weight and feather-weight conditions. Order of protocols was counterbalanced; half of the infants wore feather-weight saddlebags first, and half wore lead-weight saddlebags first. After the slope trials, we collected footprint measures of infants' walking skill on flat ground wearing their feather-weight and lead-weight saddlebags (two trials in each condition). As in Experiment 1, footprints were collected at the end of the session to maximize the likelihood that infants would complete testing on slopes. Finally, the experimenter measured infants' bare body dimensions.

A primary coder scored videotapes of the test sessions. A second coder independently scored 20% of the slope trials from each infant for each measure. Walking boundaries calculated from videotape were in exact agreement with 100% of the walking boundaries calculated on-line. Coders were in exact agreement on 97% of trials for success, failure, and refusal. Likewise, interrater reliability was high for measures of exploratory activ-
ity. The correlation coefficient for latency was .89, and coders were in exact agreement on 84% of trials scored for touching. Correlation coefficients for step number and step time were .97 and .99, respectively, and coders were in exact agreement on 98% of trials for method of locomotion.

Results and Discussion

Changes in Body Dimensions

According to anthropometric data reported in the literature, the center of mass in an average 14-month-old is located midway between the navel and the bottom of the rib cage at 58.7% of standing height (Snyder et al., 1975). The average height of infants in the present study was 80.29 cm, and their average clothed weight was 10.34 kg. Thus, when the babies were loaded with 25% of their body mass (M = 2.59 kg) at their shoulders (M = 78% of standing height), we raised their center of mass to 63% of their standing height, or by an average of 3.11 cm (see the Appendix).

Based on a simple physical model of postural control, the effect of the weighting manipulation was to reduce the angular distance that infants could sway forward and backward before losing balance, a region of reversibility (Riccio & Stoffregen, 1988) or angle of permissible sway (Adolph & Eppler, 1998). When infants stand perfectly upright, the torque acting on their bodies is 0. However, when their bodies are at an angle as they sway back and forth, the torque acting on their bodies is represented by a sine function. While wearing the lead weights, the sine of the angle of permissible sway, \( \theta \), was reduced by an average of 25% when infants rotated around their ankles and by an average of 35% when they rotated around their hips (see the Appendix). The already exacerbated problem of walking down slopes, as described above, was further exacerbated by the lead weights.

Walking Boundaries on Slopes

The experimental manipulation of infants' functional body dimensions affected their ability to walk down slopes. As shown in Figure 8a, infants displayed a wide range of walking boundaries in both the feather-weight (4°–24°) and lead-weight (0°–16°) conditions. Most important, infants had steeper walking boundaries in the feather-weight (\( M = 12.00^\circ \), SD = 5.35°) than the lead-weight (\( M = 7.60^\circ \), SD = 5.34°) condition, indicating that the lead weights impaired their walking skill on slopes, paired \( t(19) = 5.39, p < .001 \). Three infants had boundaries 12° steeper in the feather-weight condition, 13 infants had boundaries 4° steeper in the feather-weight condition, and 4 infants had identical boundaries in both conditions.

Figure 8b shows the average success ratio, \( \frac{\text{successes}}{\text{successes} + \text{failures}} \), at each slope group normalized to infants' walking boundary for each weighting condition. Paired \( t \) tests confirmed similar success ratios between conditions at each slope group steeper than walking boundary (all \( ps > .10 \)). This result, together with the reliable difference in infants' walking boundaries, suggests that the lead weights affected the value of the boundary slope but did not affect the psychometric function underlying infants' motor performance. As expected, success ratios decreased between consecutive slope groups from the boundary slope to 18° as shown in Figure 8b. Collapsing across feather-weight and lead-weight conditions, repeated measures ANOVA on success ratios at 0°, 4°, 10°, and 18° slope groups showed a significant effect for slope, \( F(3, 39) = 91.9, p < .001 \). Trend analyses confirmed a significant linear effect, \( F(1, 13) = 549.6, p < .001 \).

Fourteen babies completed two sets of footprint sequences for both weighting conditions. One additional child completed footprint sequences for only the feather-weight condition. Test–retest reliability was calculated separately for each measure in each feather-weight condition. Correlation coefficients ranged from .78 to .96, comparable to reliability obtained in footprint sequences with adults (Boening, 1977).

In general, infants with more walking experience were better walkers on flat ground. In the feather-weight condition, correlation coefficients between infants' walking experience and their average step length, step width, and dynamic base angles were .34 (\( p >

![Figure 8.](image-url)
boundaries (i.e., each infant contributed data in both weighting condition at the same absolute degree of slope. These data were thus, a stringent test of whether infants could adapt to the lead condition at their feather- and lead-weight walking boundaries were safer in the feather-weight condition and riskier in the lead-weight condition. Because infants’ ability to walk down slopes was impaired while wearing the lead weights, many babies weaved and staggered across the flat walkway. By the end of the session, infants’ bodies were stiffer but their gait appeared more normal.

Perceptual Judgments on Safe and Risky Hills

The important psychological question was whether infants could adapt their perceptual judgments to their altered body dimensions. Because infants’ ability to walk down slopes was impaired while loaded with the lead weights, the same slopes lying between their feather- and lead-weight walking boundaries were safer in the feather-weight condition and riskier in the lead-weight condition. Thus, a stringent test of whether infants could adapt to the lead weights is a comparison between their go ratios for each weighting condition at the same absolute degree of slope. These data were available for all infants at their feather- and lead-weight walking boundaries (i.e., each infant contributed data in both weighting conditions at both boundary slopes). As shown in Figure 9, infants were more likely to walk down the same absolute degree of slope while loaded with feather weights compared with lead, and they were more likely to walk down their shallower walking boundary than their steeper one. Repeated measures ANOVA confirmed the effects of weighting condition, F(1, 19) = 7.52, p < .013, and slope, F(1, 19) = 10.03, p < .005. Because our method involves constant switching between the feather and lead conditions, these results provide evidence that newly walking infants can adapt their perceptual judgments to altered body dimensions and degree of slope on-line at the start of each trial.

Despite these impressive results, infants did not completely recalibrate their judgments to the relative degree of risk. Given the difference in infants’ feather- and lead-weight walking boundaries, complete recalibration would be indicated by identical feather- and lead-weight go ratio curves after normalizing each curve to its respective walking boundary (i.e., the curves would be superimposed). However, if the lead weights caused infants to respond more cautiously or more recklessly, the go-ratio curve for the lead weights would be displaced, respectively, to the left or the right of the curve for the feather weights. As shown in Figure 10, go ratios for both conditions decreased on increasingly risky slopes, but ratios were higher in the lead-weight than feather-weight condition on slopes slightly steeper than infants’ walking boundaries. A 2 (feather- and lead-weight conditions) × 4 (0°, 4°, 10°, and 18° slope groups) repeated measures ANOVA on go ratios revealed main effects for condition, F(1, 19) = 8.6, p < .009, and slope group, F(3, 57) = 44.2, p < .001, and an interaction between condition and slope, F(3, 57) = 2.9, p < .044. Trend analyses confirmed a linear effect, F(1, 19) = 80.8, p < .001, indicating that go ratios decreased on increasingly risky slopes. Paired comparisons between feather- and lead-weight conditions at each risky slope group showed differences only at the 4° and 10° slopes (all ps < .024). As in Experiment 1, in both conditions, go ratios at each slope increment were slightly higher than infants’ probability
Go Ratio

Figure 10. Mean go ratios (±SE) at each slope group in feather-weight and lead-weight conditions. Go ratio = (successes + failures)/(successes + failures + refusals to walk). Each go-ratio curve is normalized to the walking boundary for that condition, represented by the dashed vertical line at 0. Safe slopes are represented by negative numbers on the x-axis to the left of the walking boundary, and increasingly risky slopes are represented by positive numbers to the right of the walking boundary. S = successes; F = failures; R = refusals to walk.

of success at that increment, indicating that they overestimated their ability to walk down slopes (cf. Figures 8b and 10).

With respect to descent method, as in Experiment 1, infants displayed a flexible variety of means for navigating risky slopes. Moreover, the lead weights did not prevent infants from using alternative sliding positions on refusal trials. On feather-weight trials on which infants refused to walk, they went down the slope in a backing position (31%), sitting position (34%), crawling (10%), sliding prone (1%), or walking while holding the nets for support (5%), or they avoided descent (17%). On refusal trials on which infants were loaded with lead weights, they descended in a backing position (29%), sitting position (35%), crawling (11%), sliding prone (1%), or walking with support (4%), or they avoided going (19%).

In contrast to infants’ flexibility in descent methods, the lead weights may have hampered infants from adjusting their gait to walk down slopes (Figure 11). On the challenging slopes around infants’ walking boundaries, they tended to adapt step number and step time more in the feather-weight than lead-weight condition (Table 1). As shown in Figure 11, in the feather-weight condition, step number and step time tended to increase on steeper, more challenging slopes. However, the lead-weight condition showed flatter curves for both measures. Paired comparisons between consecutive slope groups suggested differences only between -10° and -4° for both conditions (Table 2). Apparently, the effort of maintaining balance while loaded with lead weights impaired infants’ ability to modify their step length and step velocity.

As in Experiment 1, infants appeared to discover alternative descent methods and gait modifications for coping with slopes during the course of the testing. There were no differences in number of descent methods between infants with prior experience descending playground slides or stairs and infants with no prior experience (all ps > .10). Similarly, experience walking down slopes was not related to measures of step number or step time (all ps > .10).

Exploratory Activity

Infants’ exploratory activity on the starting platform provided clues about the informational basis for their decisions. Latencies were brief on easy baseline trials in both the feather-weight (M = 1.08 s) and lead-weight (M = 1.13 s) conditions. Baseline latencies did not change over the course of the session for either the feather-weight (r = -.04) or lead-weight (r = .01) conditions, indicating that infants maintained their motivation to participate. As in Experiment 1, most latencies on test trials were also short (Md = 2.80 s and 1.20 s for feather-weight and lead-weight trials, respectively). However, if infants hesitated even for a few seconds before starting down slopes, they were more likely to refuse to walk (66% and 62% of trials in feather- and lead-weight conditions, respectively) than if they went down immediately (11% and 6% of trials in feather- and lead-weight conditions, respectively). During the time that they hesitated, infants looked at the slopes, stepped and swayed on the starting platform, touched slopes, tested
alternative sliding positions, and occasionally appealed to their parents or the experimenter for help. Touches were executed primarily with the feet in both weighting conditions (94% of trials in both feather- and lead-weight conditions). Most foot touches were performed by rocking back and forth over the ankles at the brink of the slope. If infants touched slopes, they were more likely to refuse to walk (70% and 78% of trials in feather- and lead-weight conditions, respectively) than if they did not engage in haptic exploration (30% and 27% of trials).

Surprisingly, babies tended to explore less, not more, at slightly risky slopes in the lead-weight condition compared with the feather-weight condition (Figure 12). At boundary and slightly steeper slopes, infants displayed longer latencies and more touching while wearing their feather-weight packs. Latency increased on increasingly risky slopes until reaching asymptote at 18° in both conditions, but touching indicated a U-shaped curve in the feather-weight condition and a relatively flat function in the lead-weight condition. A 2 (feather- and lead-weight conditions) × 4 (0°, 4°, 10°, and 18° slope groups) repeated measures ANOVA on latency revealed main effects for condition, F(1, 19) = 7.0, p < .016, and slope, F(3, 57) = 8.4, p < .001. Trend analysis confirmed a significant linear effect for slope, F(1, 19) = 10.6, p < .004. Similarly, repeated measures ANOVA on touching revealed a main effect for condition, F(1, 19) = 19.1, p < .001; a nearly significant main effect for slope group, F(3, 57) = 2.5, p < .070; and an interaction between condition and slope, F(3, 57) = 3.7, p < .017. Paired comparisons showed differences between feather- and lead-weight conditions at the 10° slope group (p < .001).

The difference in exploratory movements between the two weighting conditions suggests that infants were sensitive to their altered body dimensions. However, the lead weights may have hampered infants’ ability to execute exploratory touching, rocking, and swaying movements, thus resulting in less accurate go ratios on the slopes near walking boundary where extended exploratory movements should prove most useful.

Summary of Experiment 2

Experiment 2 showed that altered body dimensions indeed affect the biomechanics of walking down slopes. The additional mass and the higher center of mass in the lead-weight condition resulted in shallower walking boundaries and less modification of ongoing gait patterns on slopes. Most important, young walking infants showed evidence of impressive adaptation to experimental manipulation of their body dimensions. Babies were more likely to walk down the same degree of slope while wearing the feather weights than the lead weights, and they were able to make these judgments on-line between frequent switching of weights and slopes. However, recalibration to the relative degree of risk was not complete. On slopes slightly steeper than infants’ walking boundaries, infants made more errors loaded with lead packs than with feather packs. These errors may have resulted from differences in infants’ exploratory activity. Infants explored less while loaded with lead weights on the same slightly risky slopes where their feather- and lead-weight go ratios were discrepant.

General Discussion

Adaptive locomotion involves detecting threats to balance caused by body constraints and variations in the ground surface. In everyday situations, adults adapt to changes in their functional body dimensions and changes in surface properties by modifying ongoing gait patterns and, when necessary, avoiding risky ground. This research examined the development of adaptive locomotion by observing how newly walking infants cope with experimental changes in their body dimensions for descent of safe and risky slopes. We devised a psychophysical double staircase procedure to compare infants’ walking boundaries on slopes under two weighting conditions. At the same time, we assessed the extent to which babies could adapt to altered body dimensions on slopes steeper and shallower than their feather- and lead-weight walking boundaries. Results indicate that altered body dimensions affect infants’ walking skill on slopes and that babies can adapt locomotor responses to their altered dimensions. We discuss each point below, beginning with the double staircase procedure for estimating walking boundaries.

Table 1
Paired t Obtained in Comparisons Between Feather-Weight and Lead-Weight Conditions at Slope Groups Normalized to Walking Boundary in Each Condition

<table>
<thead>
<tr>
<th>Measure</th>
<th>-10°</th>
<th>-4°</th>
<th>0°</th>
<th>4°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step number</td>
<td>t</td>
<td>df</td>
<td>t</td>
<td>df</td>
</tr>
<tr>
<td>Feather</td>
<td>1.19</td>
<td>10</td>
<td>1.57</td>
<td>15</td>
</tr>
<tr>
<td>Lead</td>
<td>-0.73</td>
<td>10</td>
<td>-0.04</td>
<td>15</td>
</tr>
<tr>
<td>Step time</td>
<td>-0.73</td>
<td>10</td>
<td>1.37</td>
<td>17</td>
</tr>
<tr>
<td>Feather</td>
<td>-2.44</td>
<td>10</td>
<td>0.44</td>
<td>15</td>
</tr>
<tr>
<td>Lead</td>
<td>-2.24</td>
<td>16</td>
<td>-1.10</td>
<td>17</td>
</tr>
<tr>
<td>Step time</td>
<td>-2.48</td>
<td>10</td>
<td>0.80</td>
<td>15</td>
</tr>
</tbody>
</table>

*p < .05. **p < .01.

Table 2
Paired t Obtained in Comparisons of Consecutive Slope Groups for Feather-Weight and Lead-Weight Conditions

<table>
<thead>
<tr>
<th>Measure</th>
<th>-10° vs. -4°</th>
<th>-4° vs. 0°</th>
<th>0° vs. 4°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step number</td>
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<td>df</td>
<td>t</td>
</tr>
<tr>
<td>Feather</td>
<td>-3.42**</td>
<td>16</td>
<td>-1.65</td>
</tr>
<tr>
<td>Lead</td>
<td>-2.44*</td>
<td>10</td>
<td>0.44</td>
</tr>
<tr>
<td>Step time</td>
<td>-2.24*</td>
<td>16</td>
<td>-1.10</td>
</tr>
<tr>
<td>Feather</td>
<td>-2.48*</td>
<td>10</td>
<td>0.80</td>
</tr>
</tbody>
</table>

*p < .05. **p < .01.
Effects of Changing Body Dimensions on the Biomechanics of Walking

In an earlier study, Adolph (1995) introduced a psychophysical single staircase procedure for estimating infants' walking skill on slopes. The double staircase procedure in the present study expands on previous work by introducing a way to compare two experimental conditions without blocking trials. Because the procedure involves frequent switching between conditions, any effects of fatigue and changing response criteria are distributed evenly across the conditions. In addition, the new procedure ensured a constant number of trials for each infant at each slope group to smooth out chance irregularities and to facilitate statistical comparisons.

Experiment 1 verified the reliability of the new procedure for estimating walking boundaries. When infants were loaded with feather-weight shoulder packs in two sham weighting conditions, most infants (67%) displayed identical boundaries. In contrast, when one pair of shoulder packs was loaded with lead weights in Experiment 2, most infants (80%) had shallower walking boundaries in the lead-weight than the feather-weight condition. In addition, while carrying the heavy weights, they showed less modification of ongoing gait patterns on the challenging slopes near their walking boundaries. Apparently, an increase in mass and higher center of mass impair infants' walking ability on slopes. Similarly, every measure of walking skill on flat ground showed negative effects of the lead weights as predicted. Thus, we demonstrated experimentally that infants' body dimensions affect their walking skill. Moreover, correlations with infants' walking experience and measures of walking skill on flat ground attest to the validity of the estimates of walking skill on slopes. In both experiments, more experienced and skillful walkers on flat ground had steeper boundaries on slopes.

However, despite the reliable effect for weighting condition on walking boundaries, effect sizes were surprisingly small. The lead weights only decreased walking boundaries by an average of 4.4°, and only the dynamic base measure revealed statistically significant differences for walking skill on flat ground. Similarly, with small weights attached to one leg, 14-month-old toddlers showed surprisingly little disruption of walking patterns in response to the asymmetrical perturbation. They took smaller steps, but maintained other gait parameters at normal levels (Schmuckler, 1993).

Several factors may have contributed to the small effect sizes for the weight manipulation. First, our measures of walking boundaries, gait modification on slopes, and footprints on flat ground were relatively crude measures of walking skill. Although reliable, these measures could not detect more subtle changes in muscle actions, postural adjustments, joint angles, and energy expenditure. Such subtle changes characterize the biomechanical effects of load carrying in adults. Expert adult walkers, for example, learn to carry prodigious loads over uneven terrain with minimal energy cost and gait adjustments. Women in certain East African tribes can carry up to 70% of their body weight balanced on top of their heads without a proportional increase in oxygen consumption and without changing step frequency (Heglund, Willems, Penta, & Cavagna, 1995; Maloy, Heglund, Prager, Cavagna, & Taylor, 1986; Taylor, 1995). They manage this remarkable feat by maintaining a progressively upright posture with increasing loads and by minimizing vertical movement of the load. Likewise, other subtle gait adjustments, such as bending more at the knees, mitigate threats to balance control. Adults weighted high at the shoulders increased knee flexion as they swayed to and fro to track a moving target (Bardy, Marin, Stoffregen, & Bootsma, 1999), and adult athletes such as gymnasts and Sumo wrestlers commonly bend their knees to maintain balance.

Similar to the studies of East African women, 25% of infants' body weight was clearly a prodigious load. Pilot work showed that heavier weights caused infants' legs to collapse in the very first trial. Although our recording method did not allow measures of joint angles, infants in the present study appeared to accommodate the lead weights by flexing more at the knees like adult athletes and by keeping a stiffly upright posture like the East African women. Walking with knees deeply flexed, termed a "Groucho Marx walk" by McMahon and colleagues (McMahon, Valiant, & Frederick, 1987, p. 232b), lowers the center of mass and thereby counteracts the upward displacement of the center of mass due to the weights. Bending the knees also reduces vertical movement of the load. This is especially important for infants because vertical acceleration of their center of mass is negative at foot contact, meaning that infants fall downward into each step (Breniere &

Figure 12. Exploratory activity at each slope group in feather-weight and lead-weight conditions. A: Mean latency to descend slope (±SE). B: Mean touching of slope prior to descent (±SE). Each curve is normalized to the walking boundary in the appropriate weighting condition, represented by the dashed vertical line at zero.
In adults, vertical acceleration is positive, meaning that they propel upward into each step. By reducing vertical movements of the load, infants could minimize the fall of their center of mass with each step. In addition, keeping a stiffer, straighter posture reduces forward and backward sway. Less anterior–posterior sway would decrease destabilizing torques due to gravity and inertia, minimizing effects of the lead weights on walking boundaries. However, increased knee flexion and a straighter posture might have interfered with infants’ ability to adjust their step length and step time on slopes, resulting in the differences for these measures on the slopes near infants’ walking boundaries.

A second explanation for the small effect size is that infants may have accommodated the lead load in part by changing the magnitude or timing of muscle forces. Adult walkers can carry loads of up to 20% of body weight on their back and shoulders without noticeable change in spatial and temporal gait kinematics (Gordon, Goslin, Graham, & Hoare, 1983; Kino, 1985; Martin & Nelson, 1986; Nottrodt & Manley, 1989). Adults preserved their normal step length and timing patterns as they walked over flat ground with a mailbag (20% body weight) slung over one shoulder. To accommodate the asymmetric load, they changed the moments of force acting on their hip and knee joints by exerting stronger trunk muscle actions on the unweighted side (DeVita, Hong, & Hamill, 1991). Similarly, biomechanical effects of the weights in the present study may have occurred at the muscular rather than kinematic level, especially while walking over flat ground.

Finally, in our study, footprint measures were collected at the end of the lengthy session. Although most babies appeared to stagger across the walkway during their first trial with the lead weights, their gait appeared more normal after several trials. Thus, infants had ample time to discover subtle modifications in posture and muscle forces for walking with lead weights on flat ground before we measured their footprints.

How Infants Adapt to Changing Body Dimensions for Locomotion Down Slopes

The central question of interest was whether infants’ perceptual judgments of safe and risky slopes would reflect their altered body dimensions and, if so, how recalibration occurs. The frequent switching between feather- and lead-weight saddlebags and steep and shallow slopes required infants to gauge their ability on-line in the first few moments after the experimenter released them on the starting platform. The same slopes that were safe in the feather-weight condition could be risky in the lead-weight condition, and infants could not predict their weighting condition prior to the start of the trial.

Results showed that 14-month-old walkers do adapt their perceptual judgments to changing body dimensions, but when body dimensions are unpredictable from trial to trial, recalibration to relative degree of risk is not complete. Infants were more likely to refuse to walk at the same absolute degree of slant while wearing the lead weights than the feather, indicating that go ratios did not depend solely on degree of slope. However, infants were also more likely to overestimate their ability on slightly risky slopes in the lead-weight condition compared with the feather. Go ratios in the lead-weight condition were higher at the 4° and 10° slopes, where probability of success decreased sharply.

The role of exploratory movements was considered. As with the adults perched on platform shoes in Mark and colleagues’ (1990) study or the participants with rods splinted to their forearms in Pagano and colleagues (Pagano, Garrett, & Turvey, 1996; Pagano & Turvey, 1995) experiments, recalibration to altered body dimensions may have depended on information obtained from exploratory movements in the present study. Infants executed stepping and swaying movements on the starting platform and touching movements at the brink of increasingly risky slopes, and at the same time they leaned forward to peer over the edge. Such exploratory movements generate multiple, redundant sources of information about surface properties and the current status of the critical region of permissible sway. Binocular disparity, motion parallax, and changing texture gradients provide visual information about slant and depth. Touching movements at the brink of the slope provide mechanical information about slant and friction. Most important for adapting to the lead-weight shoulder packs, swaying, stepping, and touching movements provide visual and mechanical information about infants’ own postural stability relative to surface properties. The speed and direction of optic texture elements specify the speed and direction of infants’ movements as they sway backward and forward around their ankles or hips (e.g., Bertenthal & Clifton, 1998). Stepping and rocking movements with the feet straddling the brink of the hill generate torque and shearing forces that specify the new inertial properties of infants’ bodies. Changes in input to mechano-receptors in the joints and skin are concomitant with changes in the optic array.

Results suggest that infants’ exploratory movements had functional consequences for guiding locomotion adaptively. Prolonged bouts of exploratory looking, swaying, and touching were more likely to precede adaptive judgments than failed attempts. In both experiments, as in previous research (Adolph, 1995, 1997), exploration increased at the same slopes where go ratios decreased, suggesting that infants used information gleaned from exploratory movements to decide whether slopes were safe or risky for walking. Moreover, levels of exploration were lower for the lead-weight condition at the same slightly risky slopes where infants erred, providing further evidence for a causal relationship between exploration and perceptual judgments.

Why then might infants have explored less while wearing the lead weights? It is unlikely that lower levels of exploration reflected insensitivity to the heavy weights. Previous studies of much younger, 6-week-old infants wearing much smaller weights (285 g) showed that babies are sensitive to the dynamic status of their limbs (Thelen et al., 1987). Presumably, the much older infants in the present study loaded with 10 times as much weight (approximately 2,500 g) should be able to detect the change in the forces acting on their bodies. It is also unlikely that the higher go ratios and lower levels of exploration in the lead-weight condition resulted from carry-over effects between weighting conditions. There were no differences in infants’ go ratios, latency, or touching between feather-weight conditions in Experiments 1 and 2 (all ps > .10). Furthermore, the lead weights did not render small exploratory movements more informative because of more severe consequences from weight shifts and so forth. Without the large, easily observable movements that we coded from videotape, they erred more often on risky slopes. A more likely explanation is that...
infants’ exploratory movements were hampered by the lead weights. Swaying, touching, and leaning over to peer down the slope may have been more difficult while encumbered with the lead weights because of the increased threat of losing balance. By keeping their bodies stiffly erect in the lead vest, infants may not have explored the outer regions of permissible sway, and without sufficient exploration, perceptual judgments were impaired.

**Developmental Implications**

Findings from this study inform our understanding of how infants may adapt to naturally occurring changes in their body dimensions over the course of development. Naturally occurring growth changes make infants’ bodies more stable by lowering their center of mass rather than raising it as we did. In addition, normal growth is periodic (Lampl, 1993), meaning that infants have several days to adjust to their new dimensions between growth spurts, rather than a few moments as we switched their shoulder packs between weighting conditions. Given our results showing that infants can partially adapt their judgments to sudden, adverse changes in their body dimensions, it is likely that recalibration is more complete when they have a longer period of adaptation and when growth changes are less radical and more conducive to maintaining balance. These hypotheses could be tested experimentally by blocking trials for each weighing condition and by lowering rather than raising infants’ center of mass. In fact, the adults in Mark and colleagues’ (1990) study showed steady improvement in their perceptual judgments of appropriate chair heights for sitting when trials with and without the platform shoes were blocked. If infants’ center of mass were lowered by loading them with lead weights around the hips, we would expect them to have a larger region of permissible sway and to recalibrate their judgments accordingly.

Moreover, our results suggest that adaptation occurs on many levels—behavioral, kinematic, and muscular—but that adaptation may require exploratory movements to detect the change in destabilizing forces. Even an inadvertent step or sway provides information about the current status of infants’ postural stability relative to the ground surface. Apparently, infants in the early stages of walking react to such perceptual information by adjusting their judgments of what they can and cannot do, by modifying ongoing gait patterns, and by changing the underlying muscle forces. The finding that infants deliberately engage in prolonged exploratory movements when approaching a patch of novel ground suggests the infant’s exploratory movements were hampered by the lead weights. Swaying, touching, and leaning over to peer down the slope may have been more difficult while encumbered with the lead weights because of the increased threat of losing balance. By keeping their bodies stiffly erect in the lead vest, infants may not have explored the outer regions of permissible sway, and without sufficient exploration, perceptual judgments were impaired. Instead, the natural flux of development may provide infants with the flexibility to gauge their abilities on-line as they approach each novel surface and novel task.

**References**


Appendix

Effects of Lead Weights

Effects of Lead Weights on Location of Center of Mass

We determined the location of infants' altered center of mass in the lead-weight condition (CoMlead) by adding the torque produced by their mass in the feather-weight condition (Mfeather) to the torque produced by the addition of the lead weights load (Mlead) using vector addition. Note that the gravity term, which is common to each component of the formula, is not included in Equation 1:

\[
\text{CoM}_{a} \times M_{a} = (\text{CoM}_{\text{feather}} \times M_{\text{feather}}) + (\text{CoM}_{\text{lead}} \times M_{\text{lead}}). \quad \text{(A1)}
\]

The infants in Experiment 2 had a mean mass (Mfeather) of 10.34 kg and height of 80.29 cm. Given that infants' natural center of mass was estimated as 58.7% of their height (Snyder et al., 1975), the location of CoMfeather = 47.13 cm. The lead-weight packs were 25% of infants' natural mass (Mlead = 2.59 kg) and were added to their shoulders (CoMlead = 62.65 cm). Infants' altered total mass in the lead-weight condition (Mtota) was 12.93 kg. Using Equation 1, the location of infants' raised center of mass in the lead-weight condition (CoMtota) was 50.24 cm, or 63% of their standing height.

Effects of Lead Weights on Angle of Permissible Sway

We estimated the reduced angular distance of infants' permissible sway in the lead-weight condition by setting their available muscle torque in the feather-weight condition (Tfeather) equal to their available muscle torque in the lead-weight condition (Tlead). Presumably, infants' muscle strength and their ability to counteract the effects of destabilizing torques was constant throughout the session. Thus, the maximum torque infants could counteract while wearing the lead weights was equal to the maximum torque they could counteract while wearing the feather weights (Equation 2):

\[
T_{\text{feather}} = T_{\text{lead}} \quad \text{(A2)}
\]

and, equivalently,

\[
M_{\text{feather}} \times g \times \sin \theta_{\text{feather}} \times \text{CoM}_{\text{feather}} = M_{\text{lead}} \times g \times \sin \theta_{\text{lead}} \times \text{CoM}_{\text{lead}} \quad \text{(A3)}
\]

The maximum angle that infants could sway in the feather-weight and lead-weight conditions is denoted \( \theta_{\text{feather}} \) and \( \theta_{\text{lead}} \) respectively. The sine of these angles, \( \theta \), is used in Equation 3 to measure the component of their weight perpendicular to the body while swaying. Substituting infants' mass and the location of their center of mass in each condition into Equation 3, the ratio of \( \sin \theta_{\text{lead}} / \sin \theta_{\text{feather}} = .75 \) when infants swayed around their ankles, thus reducing the angle of permissible sway by 25%. Infants' average hip height was 33.65 cm. When recalculating the distance of infants' center of mass in each condition from their hips, the ratio of \( \sin \theta_{\text{lead}} / \sin \theta_{\text{feather}} = .65 \), thus reducing the angle of permissible sway by 35%.

Received September 15, 1998
Revision received May 17, 1999
Accepted June 25, 1999