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Baby Carriage: Infants Walking With Loads

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Maintaining balance is a central problem for new walkers. To examine how infants cope with the additional balance control problems induced by load carriage, 14-month-olds were loaded with 15% of their body weight in shoulder-packs. Both symmetrical and asymmetrical loads disrupted alternating gait patterns and caused less mature footfall patterns. Walking was most severely compromised by back loads. Infants with less walking experience, lower levels of walking proficiency, and chubbier body proportions were more adversely affected. In addition, infants displayed a unique postural response to asymmetrical loads. In contrast to older children and adults, infants leaned with loads rather than in the opposite direction to the loads. Findings are discussed in terms of development from accommodation to compensatory strategies.

Nearly as soon as infants can stand and walk, they complicate the problem of maintaining balance by carrying loads. They carry objects in their hands, hold them under their arms, and lift them overhead. In a standing posture, balance is easiest to control when the body's center of mass is maintained squarely over the base of support (Winter, 1995). In walking, the body's center of mass moves outside the base of support. Balance is dynamic: The challenge is to prevent falling by achieving balance from step to step as the moving leg swings forward (Bril & Breniere, 1993; Li, Hong, & Robinson, 2003; Wang, Pascoe, & Weimer, 2001; Winter, 1995). Carrying a load alters the biomechanical constraints on balance by displacing the location of infants' center of mass (Legg, 1985; Martin & Nelson, 1986). Given that load carriage makes balance control considerably more difficult, how might infants, whose balance is already precarious, cope with carrying loads?

How Older Children and Adults Cope With Loads

Research on load carriage in school-age children and adults has focused on routines and occupations that involve walking while carrying heavy loads, especially on the back (see Knapik, Harman, & Reynold, 1996 for a review). For example, more than 40,000,000 grade-school and college students carry backpacks filled with heavy schoolbooks (Pascoe & Pascoe, 1999). Children's typical backpack load is 20–30% of their body weight (Goodgold, Mohr, Samant, Parke, & Gardner, 2002; Negrini, Carabalona, & Sibilla, 1999). Adult campers and soldiers carry loads up to 35% of their body weight in backpacks (Goh, Thambyah, & Bose, 1998; Vacheron, Poumarat, Chandezon, & Vanneuville, 1999b). Mail carriers walk with heavy loads (20% of body weight) over one shoulder (DeVita, Hong, & Hamill, 1991). Women in some African tribes carry tremendous loads (25–70% of body weight) on their heads (Charteris, Scott, & Nottrodt, 1989; Heglund, Willems, Penta, & Cavagna, 1995; Taylor, 1995) and caregivers in many cultures carry their children in slings or packs on their backs (Bril & Sabatier, 1986).

Strategies for coping with load carriage depend on the size of the load and whether it is distributed asymmetrically or symmetrically over the body. The most common response to a heavy asymmetrical load (>15% body weight) is postural: Walkers lean their bodies away from the direction of the load, inclining their trunks forward to offset loads on their backs and sideways to offset loads on the opposite shoulder (e.g., Bloom & Woodhull-McNeal, 1987; Goh et al., 1998; Vacheron et al., 1999b). Such postural adjustments make balance control easier by returning the center of mass over the moving base of support (Gordon, Goslin, Graham, & Hoare, 1983; Hong & Cheung, 2003; Pascoe, Pascoe, Wang, Shim, & Kim, 1997; Wang et al., 2001). Postural compen-

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sations are typically immediate (Li et al., 2003) and calibrated to the size of the load (Hong & Cheung, 2003; Knapik et al., 1996; Lamar & Yu, 2000; Li et al., 2003; Martin & Nelson, 1986). That is, heavier loads result in larger angles of trunk inclination. In fact, exaggerated postural compensations are so prevalent that the American Academy of Pediatrics, American Academy of Orthopedic Surgeons, and most academic researchers have recommended that school-age children carry loads <15% of body weight in their backpacks to prevent back pain, stress injuries, and spine abnormalities resulting from chronic trunk inclination while standing and walking (e.g., Hong & Cheung, 2003; Siambanes, Martinez, Butler, & Haider, 2004; Vacheron, Poumarat, Chandezon, & Vanneuville, 1999a).

Postural compensations may be accompanied by footfall modifications (Chow et al., 2005; LaFiandra, Wagenaar, Holt, & Obusek, 2003; Pascoe et al., 1997). In response to heavy asymmetrical loads, school-age children and adults spontaneously decrease their walking speed and step length, and increase double support periods (the time during each walking cycle when both feet are on the floor). However, when velocity is controlled (by asking participants to walk to the beat of a metronome, walk at a predetermined speed, or to keep pace on a treadmill), adults can maintain their normal footfall patterns (Goh et al., 1998; Hong & Cheung, 2003; Wang et al., 2001). For extremely heavy back loads, (20% of body weight for children and 35–40% of body weight for adults), walkers can only maintain their normal velocity at the cost of taking shorter, more frequent steps, and longer double support periods when both feet are on the floor (Hong & Brueggemann, 2000; Martin & Nelson, 1986).

Postural compensations are not reported in response to symmetrical loads. With the load distributed evenly across the front and back of the body, across the two shoulders, or carried on the head, walkers hold their trunks at the same angles, on average, as in unloaded conditions (Lloyd & Cookie, 2000). Walkers may decrease body sway by keeping their backs more stiffly upright, however, to minimize the risk of being pulled off balance by the additional weight (Li et al., 2003). For example, African women with head loads and soldiers wearing double-packs (front- and backpacks) maintained an upright posture and their normal velocity and walking patterns with symmetrical loads between 10% and 20% of their body weight (Charteris et al., 1989; Lloyd & Cookie, 2000). However, when symmetrical head loads were extremely heavy (25–55% of body weight), African women only could maintain an upright posture and their normal velocity at the expense of shorter, faster steps (Charteris et al., 1989).

How Infants Cope With Loads

In contrast to the large literature on load carriage in school-age children and adults, little research has examined infants' ability to carry loads. However, a few lines of evidence suggest that infants might have the wherewithal to exhibit adult-like strategies in response to loads. Certainly, infants are sensitive to loads added to their bodies. For example, 6-week olds adjusted their rate of kicking in response to 185 g weights attached to their legs (Thelen, Skala, & Kelso, 1987), 5- to 8-month-olds varied their reaches for objects in accordance with small weights attached to their wrists (Corbetta & Thelen, 1992a, 1992b), and 6-month-olds were less likely to lean forward to reach with 200 g weights attached to their wrists than when they were not loaded with weights (Rochat, Goubet, & Senders, 1999).

Moreover, infants demonstrate the capacity for deliberate postural responses and footfall modifications. Eight- to 12-month-old infants adjusted their degree of forward trunk inclination to reach for distant objects while sitting (McKenzie, Skouteris, Day, Hartman, & Yonas, 1993) and 13- to 14-month-olds leaned in response to variations in the friction and rigidity of the ground surface (Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997). Fourteen- to 16-month-olds modified their footfall patterns by decreasing overall velocity and step length in accordance with gradual changes in the slant of the ground surface (Adolph & Avolio, 2000; Gill-Alverez & Adolph, 2005) and small variations in the width of bridges (Berger & Adolph, 2003; Berger, Adolph, & Lobo, 2005).

Several factors, however, suggest that infants' ability to cope with load carriage may be hampered compared with older children and adults. First, infants' body proportions are ill suited for upright balance (Adolph, 1997; Adolph, Vereijken, & Shrout, 2003; McGraw, 1945; Shirley, 1931; Thelen, 1984). Their exaggeratedly large heads and long torsos make their bodies disproportionately top-heavy compared with adults (Palmer, 1944; Shirley, 1931; Snyder, Spencer, Owings, & Schneider, 1975). In addition, infants' higher ratio of fat tissue to muscle mass means that they have less strength to keep their bodies within the moving base of support (Thelen, Fisher, Ridley-Johnson, & Griffin, 1982; Thelen, Fisher, & Ridley-Johnson, 1984).

Poor walking skill may also hamper infants' ability to carry loads. Since the 1930s, researchers have considered the characteristic deficiencies in infants' footfall patterns—slow walking speeds, small step lengths, high step frequency, long periods with both feet on the floor, and short periods with one foot on the ground—to be emblematic of poor balance control (Clark & Phillips, 1987; Ledebt, Bril, & Breniere, 1998; McGraw, 1945; Shirley, 1931). In other words, infants' walking patterns—without loads—under the best of circumstances resemble adults' footfall modifications in response to extremely heavy loads.

Finally, infants have limited experiences dealing with loads compared with older children and adults. Although infants spontaneously carry toys and other lightweight objects in their hands and arms, they are not likely to have many experiences carrying heavy loads or loads strapped to their torsos. In particular, most children are not likely to have experience carrying loads on their backs before they enter preschool or Kindergarten and begin wearing backpacks.

Existing work is inconclusive about infants' ability to exhibit adult-like strategies in response to load carriage. With a large load (25% of body weight) distributed symmetrically across infants' torsos in packs attached at the breastbone and scapulae, 14-month-olds showed nearly identical walking patterns in terms of the length and width of their steps in load versus no-load conditions (Adolph & Avolio, 2000). Although infants appeared to keep their bodies stiffly upright while loaded, their trunk inclination was not measured directly. Furthermore, infants' footfall patterns were measured at the end of a lengthy session during which they had extensive practice walking with and without the loads. Thus, the study cannot inform on infants' immediate adaptation to loads.

In contrast, two studies examined infants' footfall patterns immediately after the addition of a load. With a small weight attached asymmetrically to one ankle, 14-month-old infants maintained the same walking velocity in the load and no-load conditions by decreasing their step length and increasing step frequency with the loads (Schmuckler, 1993). Longitudinal observations showed that infants in their first weeks of walking decreased velocity and step length in response to symmetrically distributed loads (15% of body weight) on their shoulders, hips, or ankles. However, after a few weeks of walking experience, infants maintained normal walking patterns (Vereijken, Pedersen, & Størksen, 1999). Together, the existing data suggest that experienced infant walkers, like adults and older children, may cope with symmetrical loads with minimal disturbance, but that they modify their walking patterns in response to asymmetrical loads.

Present Study

The primary aim of the current study was to describe infants' immediate postural responses and footfall modifications while walking with loads. Toward this end, we systematically tested infants' load-carrying abilities with the loads distributed in various symmetrical and asymmetrical combinations along the front, back, and sides of infants' torsos. In each load condition, infants carried 15% of their body weight—the same-size loads that elicited immediate postural strategies and footfall modifications in school-age children and adults.

We assessed the effects of the loads using video recordings synchronized with footfall measures. The video data revealed whether the loads disrupted an alternating stepping pattern and whether infants displayed a postural response to the loads. The footfall recordings provided a description of the distance and timing of infants' steps: overall walking velocity, step length, and the relative durations that both feet were on the floor and that one foot was swinging through the air. Given the difficulty of limiting infants to particular walking speeds, we controlled velocity statistically rather than experimentally to determine whether infants could maintain normal walking patterns when velocity was controlled.

Of special interest were infants' responses to symmetrical versus asymmetrical loads. Based on previous work, we expected that infants would show larger, more frequent postural responses and footfall modifications in the asymmetrical load conditions. In particular, would infants display the adult-like strategy of leaning away from the direction of an asymmetrical load?

We considered the back-load condition to be the most revealing about infants' ability to use a ''lean-away'' strategy. On the one hand, back loading might be quite easy for infants because older children and adults show a preference for carrying heavy loads on their backs. Presumably, children and adults prefer back loads because they can easily lean forward, away from the load. But, on the other hand, back loading might prove to be most challenging for infants if they do not implement the adult-like strategy of leaning away from the direction of the load. The body has a more limited range of movement for leaning backward from the hips or the ankles compared with leaning forward and sideways. Without a lean-away strategy, infants would be more likely to fall.

A second aim was to examine developmental factors that might underlie differences in infants' ability to cope with loads. As in previous work, we used an age-matched control design (e.g., Adolph, 1995; Campos et al., 2000; Wohlwill, 1970), where we held the age at testing constant (at 14 months) and examined the effects of natural variations in infants' body proportions, walking proficiency, and walking experience on their responses to the various load distributions. If load carriage exacerbates the effects of a naturally disproportionate body, then chubbier infants should display less mature footfall patterns compared with more slender infants. In addition, we investigated whether infants' walking proficiency and experience influenced their ability to cope with load carriage. We expected less proficient and experienced infants to exhibit more gait disruptions, less effective postural responses, and less mature footfalls due to their already precarious balance. Previous work showed a wide range in body proportions, walking proficiency, and walking experience at 14 months of age (Adolph & Avolio, 2000; Adolph, Eppler, & Gibson, 1993; Adolph et al., 2003). Moreover, Adolph and Avolio (2000) and Schmuckler (1993) tested 14-month-olds in their studies of load carriage, allowing for a replication of the earlier work.

Method

Participants

Participants were recruited from purchased mailing lists and brochures disseminated in pediatricians' offices and infant–mother classes. Twenty-seven 14-month-olds ($\pm$ 1 week) completed testing (14 boys, 13 girls). All infants were born at term. Infants were White ($n = 24$), African American ($n = 1$), and Other/Unidentified ($n = 2$); their parents' mean Socioeconomic Status score was 79.12 (Nakao & Treas, 1992). All infants could walk 3.66 m (the length of the testing walkway) independently on consecutive trials. In the context of a structured interview (Adolph, 2002), parents reported the date that their infants could first walk a distance approximately the length of the testing walkway. As shown in Figure 1a, infants' walking experience ranged from 10 to 129 days ($M = 62.1$ days). Only 1 infant had experience walking while carrying a backpack and 2 while carrying a purse. Data from 4 additional infants were not analyzed because they became fussy and refused to walk with the loaded vest; 3 of these infants began testing with the back-load condition. Families received diplomas and framed photographs of their infants as souvenirs of their participation.

Footfall and Video Recordings

We analyzed infants' response to the various load conditions with a combination of footfall and video recordings. A mechanized gait carpet (3.66 m long $\times$ 0.89 m wide) recorded the time and distance of each footfall (Gaitrite Inc., Clifton, New Jersey, http://www.gaitrite.com). Temporal resolution was 80 Hz and spatial resolution was 0.64 cm. The Gaitrite resident software program calculated temporal measures from the times of infants' first and last foot contacts and spatial measures based on the x–y coordinates of the center of infants' foot pressure.

Trials were videotaped with three camera views mixed onto a single video frame. One camera recorded infants from a side view, with an experimenter panning the camera. This view provided information about infants' forward/backward leaning and about disruptions to their walking gait. A second camera recorded infants from the back. This view provided information about left/right leaning. A third camera recorded a trigger-light emitted from the gait carpet to synchronize footfall and video data.

Velcro Vest and Load Conditions

We altered the symmetry of infants' bodies by loading them with various combinations of loads around their chests and backs (Figure 2). Infants wore an adjustable nylon vest with canvas packs attached below the collarbone and across the shoulder blades. The two front packs were triangular shaped to allow room for infants' chins (7.5 cm wide $\times$ 12.0 cm long $\times$ 3.5 cm thick) and the two backpacks were square shaped (8.0 cm wide $\times$ 9.0 cm long $\times$ 3.5 cm thick) to fit more comfortably across infants' backs. The vest had Velcro straps at front, sides, and back to ensure a snug fit around infants' torsos. A strap between infants' legs prevented the vest from pulling up. To facilitate quick removal and attachment, the packs were sewn into two pairs of saddlebags that could be slung over infants' shoulders and firmly attached with Velcro at the shoulders, chest, and back. The arrangement of the packs—attaching the loads high (in the thoracic rather than the lumbar region of the torso) and close to the body (minimizing destabilizing forces from movement of the load)—was designed to be most

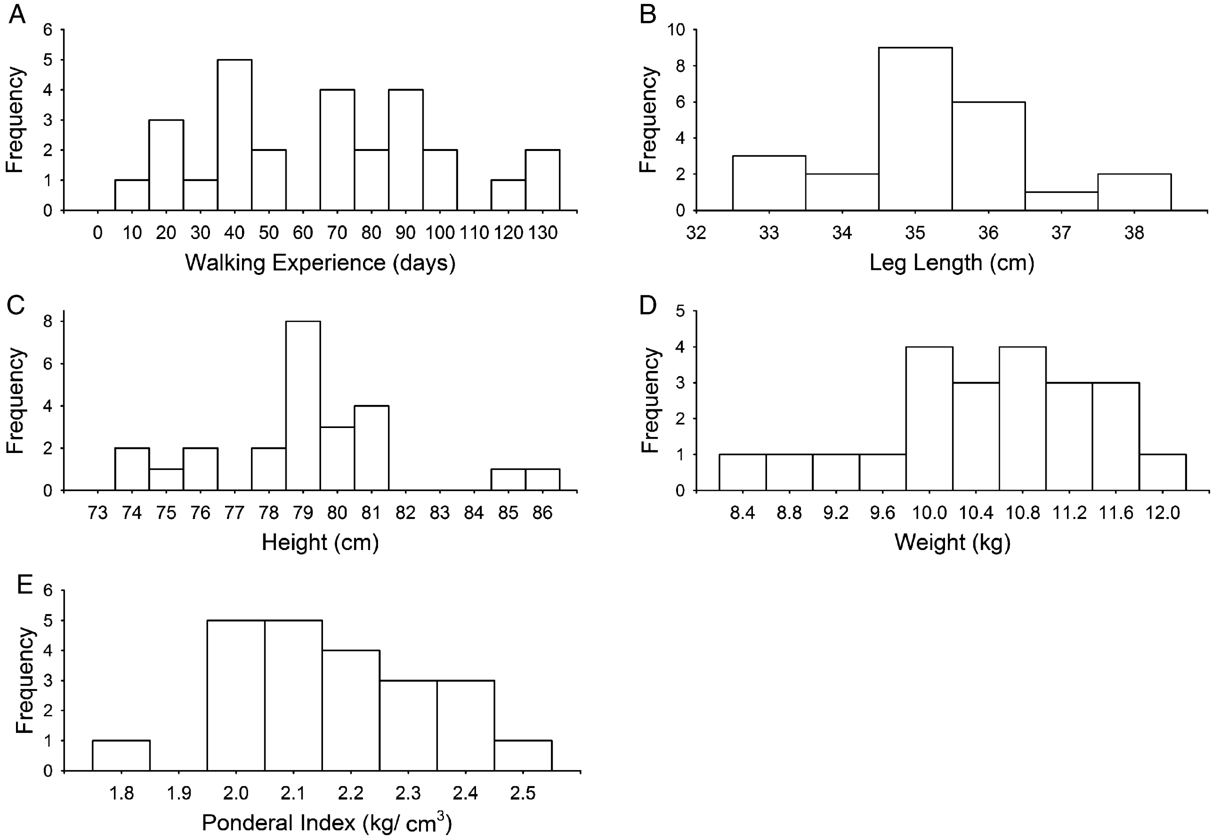

Figure 1. Frequency distributions of infants' (A) walking experience, (B) leg length, (C) height, (D) weight, and (E) Ponderal Index.

energy efficient and least physically demanding as suggested by previous physiological and biomechanical analyses (Dutta & Taboun, 1989; Legg, 1985; Mackie, Legg, Beadle, & Hedderley, 2003; Stuempfle, Drury, & Wilson, 2004).

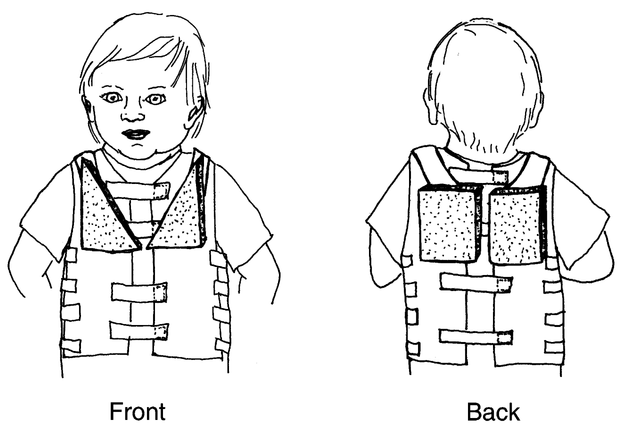

Figure 2. Front and back views of adjustable nylon vest loaded with lead or Polyfil packs. Velcro tabs allowed removable canvas saddlebags to be fastened at infants' shoulders, chests, and backs. A strap under infants' crotch held the vest firmly in place.

All four packs could be filled with Polyfil stuffing (packs and Polyfil totaled 120 g), making infants larger around their upper torso but with a negligible increase in weight. Alternatively, the packs could be filled with densely packed lead filings totaling 15% of infants' body weight (loads ranged from 1,200 to 1,800 g, increasing in 100-g increments). Pilot testing indicated that 15% was the maximum load infants could manage to walk with in the asymmetrical conditions without fussing. Moreover, 15% of body weight is the cutoff for recommended loads for children's school backpacks (Goodgold et al., 2002; Hong & Brueggemann, 2000; Hong & Cheung, 2003; Pascoe et al., 1997) and the minimum load that induces leaning strategies in grade-school children and adults (Cottalorda et al., 2003; Hong & Brueggemann, 2000; Li et al., 2003; Malhotra & Sen Gupta, 1965).

The packs were arranged in six load conditions: *no-load baseline* (Polyfil in all four packs), *symmetrical* (3.75% body weight in each of the four packs), *front* (7.5% body weight in each front pack and Polyfil in the two back packs), *back* (7.5% body weight in each back pack and Polyfil in the two front packs), *right*

(7.5% body weight in each pack in the right saddlebag and Polyfil in the two left packs), and *left* (7.5% body weight in each pack in the left saddlebag and Polyfil in the two right packs).

Procedure

Infants were tested in one 60- to 90-min session. First, an experimenter removed infants' shoes and clothes and fitted them in the nylon vest over their diapers. Then, the experimenter weighed infants on a pediatric balance scale to determine 15% of their body weight for loading the packs. Next, infants were tested while walking in the various load conditions. At the beginning of each trial, the experimenter placed infants in a standing position at one end of an elevated walkway (101 cm wide $\times$ 366 cm long $\times$ 116 cm high). The walkway was elevated to facilitate video recording and to make it easier for the experimenter to "spot" infants if they lost their balance. Parents and an assistant stood at the other end of the walkway and encouraged infants to walk toward them.

Infants wore Polyfil and lead load packs in the various combinations for two trials in each of the six load conditions for a total of 12 test trials. Between each load condition, the assistant rearranged the loads in the spare pair of saddlebags in preparation for the next condition. Meanwhile, infants walked with the Polyfil packs to give them time to recover from the loads and to keep them motivated and engaged in the game of walking over the walkway to their parents. The condition changes lasted <60 s, so that infants typically walked once or twice over the raised walkway between load conditions.

All infants began with the no-load baseline condition. Only these first two trials were used for analyses of the no-load baseline condition. Infants were assigned to one of five condition orders for the remaining combinations of packs: symmetrical, front, back, right, left; front, back, right, left, symmetrical; back, right, left, symmetrical, front; right, left, symmetrical, front, back; and left, symmetrical, front, back, right. Gender and walking experience were counterbalanced across condition orders.

At the end of the session, an experimenter measured infants' leg length (from anterior, superior iliac spine to medial malleolus) and recumbent height (from crown of head to heel) and reweighed infants on the pediatric scale with all of their clothes and diaper removed. Measurements were performed twice and then averaged. Every infant weighed slightly less nude than clothed, providing a crude assurance of the reliability of our assessments for loading the packs in the test conditions. Owing to fussiness, we were unable to measure leg length, height, and nude weight from 4, 3, and 5 infants, respectively. Figure 1b–e shows the range in infants' leg length, height, weight, and Ponderal Index (weight in kg divided by height cubed in cm), a standard measure of infants' chubbiness (Shirley, 1931). Larger values of the Ponderal Index reflect chubbier infants. All three measures of body dimensions were intercorrelated, all $ps < .05$. Walking experience was not correlated with body dimensions (all $ps > .10$) or Ponderal Index ($p = .06$).

Video Coding and Calculation of Footfall Measures

Only the two test trials in each of the six load conditions were used for analyses. We scored videotapes of infants' walking trials using a computerized video coding system, MacSHAPA (Sanderson et al., 1994), which links video frame numbers with events of interest. First, a primary coder scored each trial for frequency of *gait disruptions*: falls (fell to hands and knees on walkway or required rescue by the experimenter), trips (swinging foot failed to clear the ground), double steps (two consecutive steps with the same foot), and cross/back steps (swinging foot crossed over standing foot while moving forward or swinging foot moved backward instead of forward). In principle, infants could exhibit all four types of gait disruptions in a single trial and infants could display each type of disruption multiple times.

Next, the coder scored infants' postural responses. Given the difficulty of coding the precise angle of infants' bodies reliably from the videotapes, we treated body position as an ordinal variable. In separate passes with only the target camera view revealed, the coder characterized the angle of infants' torsos in a forward/backward direction (1 = *leaning forward*, 0 = *upright*, and -1 = *leaning backward*) and in a left/right direction (1 = *leaning to the right*, 0 = *upright*, and -1 = *leaning to the left*). Because infants may have been initially pulled off balance by the load and then compensated after several steps, the coder scored leaning strategies at two time points: at the beginning (first video frame when the experimenter stood infants on the walkway until the end of infants' third step) and the end of each trial (from infants' fourth to last steps).

Finally, the coder screened trials for *useable walking sequences* for analyzing footfall measures. To calculate measures of distance and timing accurately, the Gaitrite resident software required infants to take at least four consecutive walking steps without gait disruptions or other irregularities. Thus, the coder identified sequences of at least four consecutive steps that did not include any gait disruptions, episodes in which infants stopped walking, episodes in which infants stepped with one or both feet outside the active sensor region of the gait carpet, infants' first three steps (when they were ramping up their walking speed), and infants' last two steps (when they were slowing down to come to a stop). Each useable footfall sequence included 4–33 consecutive steps ($M = 9.31$ steps).

A second coder scored 25% of the trials from each infant. Coders agreed on 90–99% of trials for each type of gait disruption (κ values ranged from .78 to .94, all $ps < .001$), 90–97.4% of trials for leaning in forward, upright, backward, right, middle, and left directions (κ values ranged from .87 to .91), and 93% of useable walking sequences ($\kappa = .91$). Discrepancies were resolved by discussion.

The Gaitrite resident software program calculated standard distance and timing measures: step length (front-to-back distance that each leg traveled along the floor), velocity (distance/time over the whole walking sequence), swing time (length of time that each leg traveled through the air), and double support time (length of time that both feet were on the ground) based on the $x-y$ coordinates and first and last sensors activated with each footstep. Figure 3 illustrates the calculation of step length from the center of foot pressure. To examine lateral asymmetries in footfall patterns, the Gaitrite software calculated step length and swing time separately for the right and left feet over each trial. Because swing and double support times depend on walking velocity, the software calculated each value as a percentage of the gait cycle for each foot (Hong & Cheung, 2003).

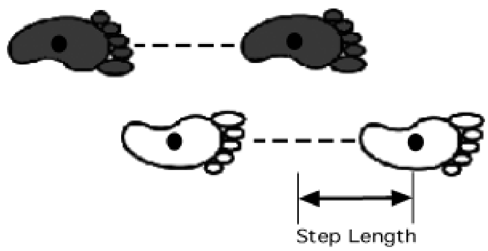

Figure 3. Step length (distance between consecutive steps) was calculated from the $x-y$ coordinates registered by the center of foot pressure. Shaded symbols = left foot, open symbols = right foot.

Results

Available Data for Analyzing Gait Disruptions, Postural Responses, and Footfall Measures

Different numbers of infants contributed data (at least one trial) to each condition for analyses of gait disruptions, postural responses, and footfall measures (see Table 1). More data were available for analyzing gait disruptions and postural responses from video than for analyzing footfall measures because the gait disruptions and other irregularities sometimes prevented infants from taking enough steps for footfall analyses. All 27 infants contributed video data to the no-load baseline condition and 25 infants also contributed video data to all of the load conditions. One infant became fussy and refused to walk in the symmetrical load condition and another refused to walk in the left load condition. Five of the 25 infants contributed only 1 trial to one of the conditions. Thus, in total, only 317 out of the expected 324 trials were available for analyses of gait disruptions and postural responses.

Owing to equipment failure, gait carpet data in the no-load baseline condition were lost for two infants, leaving 25 infants in that condition. In total, only 16 infants contributed gait carpet data to every condition because 9 infants stopped, stepped outside the active area of the gait carpet, or experienced gait disruptions serious enough to preclude calculation of footfall measures in one, two, or three of the load conditions. The back-load condition suffered most severely from missing data.

The contrasts among the conditions were all within subject, but because many infants did not have complete data over all conditions, a standard repeated measures analysis of variance would be inefficient. The standard analysis would include

Table 1
Number of Infants Contributing Data to Each Condition

	Video data		Gait carpet
	Gait disruptions	Leaning	Footfall measures
Base	27	27	25
Symmetric	26	26	23
Right	27	27	24
Left	26	26	24
Front	27	27	23
Back	27	27	20
All 6	25	25	16

only those subjects with complete data ($n = 25$ and $n = 16$ for video and footfall measures, respectively). We overcame this problem by using a version of a generalized linear model that makes use of all available trials, while taking into account the fact that trials were repeated within subject (Diggle, Heagerty, Liang, & Seger, 2002). The correlation among repeated measures within subject was taken into account through a generalized estimating equation (GEE) approach to the data, as implemented in the GENMOD procedure of the SAS system (SAS, 2006). This statistical approach also allowed us to examine whether the conditions had the same effects for the various outcome measures when we statistically adjusted for the effects of velocity and walking experience.

A somewhat different analytic approach was used in the analysis of infants' postural responses. Two features made the postural response data different from the gait disruption and footfall data: The ratings were ordinal (e.g., forward, upright vs. backward) and it was possible to obtain two ratings of leaning per trial; one initial and one final. We used statistical methods for ordinal random effects (Hedecker & Gibbions, 1994), which are a special case of hierarchical linear models (e.g., Raudenbush & Bryk, 2002), and are often called ordinal mixed models. This approach specifies a level 1 model, which fits the trials within infant as a function of condition, and a level 2 model, which allows individual differences in the infants to be considered. In the level 2 model, any tendency for participants to lean in a certain direction was taken into account by specifying the level 1 intercept to be a random effect. To account for the ordinal nature of leaning data, a constrained logistic model was used, as implemented by the GLIMMIX procedure of the SAS system (SAS, 2006). Like the GEE analysis for gait disruptions and footfalls, the hierarchical linear models that include random effects for each participant allow the dependence among repeated measures to be taken into account for the postural response data.

Gait Disruptions

Gait disruptions (trips, double-steps, cross/back-steps, and falls) reflected infants' difficulty maintaining alternating stepping patterns in the various load conditions. Overall, we observed 348 gait disruptions across 143 trials. Table 2A shows the number of trials in each condition that involved a gait disruption. As shown in the left-most column of the table, more than half of the trials in the data set (174 trials) involved no gait disruptions; the highest frequency of disruption-free trials (47) occurred in the no-load baseline condition. The second two columns in the table show the number of trials with one or more gait disruptions; most of these occurred in the back-load condition.

Table 2A
Number of Trials with Gait Disruptions in Each Condition

	Numerals of trials			
	None	1	GE 2	Total
Base	47	6	1	54
Symmetric	33	14	4	51
Right	30	20	3	53
Left	28	19	5	52
Front	26	21	6	53
Back	10	28	16	54
Total	174	108	35	317

Table 2B shows the average frequency per trial of each type of gait disruption in each condition. Although the total number of gait disruptions per trial averaged only 1.10 across conditions, the maximum number of disruptions was 9. Cross/back steps were the most frequent type of gait disruption ($M = 0.86$ per trial) and these were most prevalent in the back-load condition. The trial with 9 gait disruptions, for example, involved 9 cross/back steps in the back-load condition. Trips were the least frequent type of gait disruption ($M = 0.01$ per trial).

A GEE omnibus test confirmed that the total frequency of gait disruptions varied across the six load conditions $\chi^2(5,\ N = 27) = 14.03,\ p = .02$. Post hoc tests revealed differences between the no-load

Table 2B
Average Frequency Per Trial of Each Type of Gait Disruption in Each Condition

	Type of disruption				Total disruptions
	Trip	Fall	Cross/back	Double	
Base	.00	.00	0.11	.04	0.15
	—	—	(0.21)	(.13)	(0.27)
Symmetric	.02	.10	0.65	.00	0.77
	(.10)	(.20)	(1.08)	—	(1.13)
Right	.00	.04	0.87	.07	0.98
	—	(.13)	(1.40)	(.23)	(1.54)
Left	.02	.10	0.79	.08	0.98
	(.10)	(.20)	(1.34)	(.23)	(1.47)
Front	.00	.24	0.78	.00	1.02
	—	(.32)	(1.03)	—	(1.14)
Back	.04	.41	1.94	.30	2.69
	(.13)	(.61)	(1.19)	(.52)	(1.68)

baseline condition and the other five conditions and between the back-load condition and the other five conditions (all ps $< .05$). As shown in the rightmost column of Table 2B, infants displayed fewer total gait disruptions in the no-load condition compared with the load conditions. Gait disruptions were more prevalent in the back-load condition than in the symmetrical, front, and side load conditions.

Overall, infants with more walking experience showed fewer gait disruptions in the load conditions. The correlation between walking experience and the total number of gait disruptions summed over trials and load conditions was $r(26) = -.43$, $p < .03$. Ponderal Index, the overall measure of infants' chubbiness, was not related to the frequency of gait disruptions.

Postural Responses

Analyses of postural responses tested infants' ability to implement an adult-like response of offsetting the loads by leaning in the opposite direction. Table 3 shows the average percentage of observations that infants leaned forward/backward and to the left/right in each of the load conditions. As evident in the top two rows of the table, in the no-load baseline and symmetrical load conditions, infants primarily kept their bodies upright (in the middle) or showed a slight tendency to lean forward. As shown in the bottom four rows of the table, in the asymmetrical load conditions, infants did not exhibit an adult-like strategy to counterbalance added forces by leaning in the direction opposite to the load. Instead, infants kept their bodies upright or leaned in the direction of the load. Of the 16 observation points over the asymmetrical-load conditions (2 observations/trial × 2 trials/condition), infants leaned with the loads on 85.4%, on average. Leaning with the loads was especially pronounced in the side conditions ($M = .96$). Six infants leaned with the loads on every trial. Only one infant leaned away from the direction of a load (he leaned forward in the back-load condition), but he leaned forward on every trial in every condition.

Table 3
Average Percentage of Observations that Infants Leaned With the Load in Each Condition

	Direction of lean					
	Forward/backward			Sideways		
	Front	Middle	Back	Right	Middle	Left
Base	18.5	81.5	0.0	2.8	92.5	4.7
Symmetric	22.5	72.5	4.9	20.8	70.3	8.9
Right	23.6	54.7	21.7	96.2	3.8	0.0
Left	27.9	67.3	4.8	0.0	3.9	96.1
Front	74.5	25.5	0.0	12.4	81.0	6.7
Back	0.8	17.6	76.9	11.4	79.0	9.5

We used ordinal mixed models to test the effects of the six load conditions on infants' leaning strategies in the forward/backward and left/right direction. In both directions, the placement of the loads was related to the distribution of rated leaning scores; the omnibus tests were significant in the forward/backward directions $F(5, 601; N = 27) = 52.95$, $p < .001$ and in the left/right directions $F(5, 593; N = 27) = 44.23$, $p < .001$. Walking experience and Ponderal Index were not related to the percentage of observations on which infants leaned into the loads in the asymmetrical load conditions ps $> .10$, and were therefore not included in the final models.

In addition to the omnibus tests, the ordinal mixed model provides planned contrasts between each of the five load conditions and the no-load baseline conditions. For the front/back direction, these contrasts revealed that participants were more likely to lean forward in the front-load condition than when they were not loaded, logistic coefficient $b = -2.77$; $z = -8.01$, $p < .001$. Similarly, participants were more likely to lean backward when they were in the back-load condition compared with the no-load baseline condition, $b = 4.41$; $z = 11.46$, $p < .001$. In contrast, relative to the no-load baseline condition, infants were unlikely to lean forward or backward in the symmetrical or left-load conditions, symmetrical $b = 0.12$; $z = 0.37$, *ns*; left $b = -0.19$; $z = -0.59$, *ns*. We found a small tendency for infants to lean backward in the right-load condition, $b = 0.88$; $z = 2.66$, $p < .01$.

In the left/right direction, the ordinal mixed model also showed that infants leaned in the direction of the load. Planned contrasts confirmed that nearly all of the infants leaned toward the right in the right-load condition, $b = -6.63$; $z = -10.45$, $p < .001$, and leaned toward the left in the left-load condition, $b = 6.33$; $z = 10.10$, $p < .001$. In contrast, relative to the no-load baseline condition, we found no indication that front- or back-load conditions were related to lateral leaning compared with the control condition, front load $b = -0.47$; $z = -1.28$, *ns*; back load $b = -0.24$; $z = -0.65$, *ns*. However, we found a small tendency for participants in the symmetrical condition to lean toward the right, $b = -0.93$; $z = -2.50$, $p < .02$.

Leaning with the loads had dramatic effects on infants' ability to maintain alternating steps, especially in the back-load condition. Of the 145 gait disruptions observed in the back-load condition, infants were leaning backward on 127. Similarly, of the 54 gait disruptions observed in the front-load condition, infants were leaning forward on 53. Of the 50 gait disruptions observed in the right-load condition, infants were leaning to the right on 45. Of the 51 disruptions in the left-load condition, infants were leaning to the left on 48. Most falls in the back-, front-, and side-load conditions occurred on trials when infants were leaning with the loads.

Footfall Measures

No-load trials. The two test trials in the no-load baseline condition provided an essential comparison for assessing the effects of the loads on infants' walking patterns. Thus, consistency across the two no-load baseline trials was critical. Test–retest reliability between the first and second no-load baseline trials was generally high and comparable to values found in previous research using footfall measures (e.g., Adolph et al., 2003; Boening, 1977), suggesting that the no-load baseline trials were a reliable benchmark of infants' walking skill. Correlation coefficients were .98 for step length, .98 for velocity, .87 for double support time, and .80 for swing time, all $ps < .001$.

Infants' step length and velocity were not related to their leg length or height, all $ps > .50$. Thus, we used raw values rather than normalized values of footfall measures in further analyses. The leftmost bars in Figure 4a–d show infants' average footfall patterns in the no-load baseline condition. As is typical among infants of the same chronological age, measures of walking skill varied widely between infants; values were consistent with previous studies on infant walking (e.g., Adolph et al., 2003; Bril & Breniere, 1989, 1992, 1993; Shirley, 1931). Developmental improvements in footfall patterns follow an expected progression (e.g., Adolph et al., 2003; Bril & Breniere, 1993; Clark & Phillips, 1987; McGraw, 1935; Shirley, 1931; Stathan & Murray, 1971; Sutherland, Olshen, Biden, & Wyatt, 1988): Over the first 6 months of walking, infants take increasingly larger steps; velocity increases while both swing and double-support times decrease. Accordingly, in the current study, infants with more walking experience displayed larger step lengths $r(25) = .68$, higher velocities $r(25) = .61$, and a smaller percentage of the walking cycle in double support $r(25) = -.57$, and a larger percentage of the walking cycle in swing, $r(25) = .57$, all $ps < .005$. Walking experience predicted step length after statistically controlling for effects of velocity, partial $r(22) = .40$, $p < .05$. Chubbier infants with higher Ponderal Index scores displayed shorter step lengths $r(20) = -.50$, lower velocities $r(20) = -.47$, and relatively longer double-support periods $r(20) = .47$, all $ps < .05$.

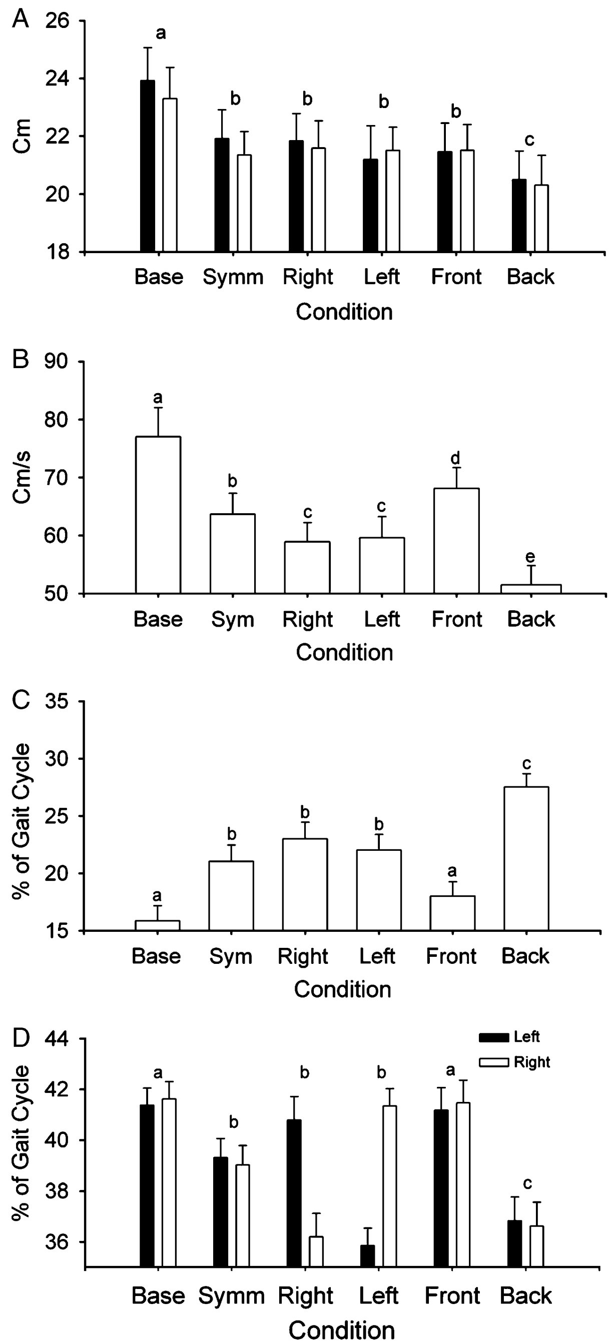

Figure 4. Footfall measures. The height of the bars represents infants' average (a) step length, (b) velocity, (c) percentage of gait cycle spent in double support, and (d) percentage of gait cycle spent in swing in each condition. For step length and swing, black bars indicate values for the left leg and white bars indicate values for the right leg. For velocity and double support, bars represent values averaged across both legs. Error bars denote standard errors. The letter notation directly above the bars indicates differences between conditions. Duplicate letters indicate no difference between conditions.

Footfall measures in the no-load baseline trials were intercorrelated such that more proficient walkers showed more mature walking patterns across measures. Infants with larger step lengths tended to walk faster $r(25) = .95$, spend a smaller percentage of the gait cycle with both feet on the floor $r(25) = -.91$, and a larger percentage with their swinging leg in the air $r(25) = .85$. Faster velocities were negatively correlated with the percentage of the walking cycle spent in double support $r(25) = -.91$ and positively correlated with the percentage of the walking cycle spent in swing $r(25) = .88$, all ps $< .001$.

No-load versus load conditions. We compared the no-load baseline condition with the five load conditions to examine whether infants showed the same sorts of gait modifications displayed by older children and adults in response to load carriage. We used the GEE approach to the data to make use of all available trials in the analysis. For each of the four footfall measures (step length, velocity, double support time, and swing time), we first carried out an omnibus test of the differences among the six conditions using a Type I error rate of $p = .05$. When this test was significant, we carried out post hoc tests of pairwise comparisons to better understand the overall effect. To examine differences between the right and left legs for step length and swing time, we entered leg as a factor in those analyses. To determine whether the results for step length and velocity reflected the same source of variation, we carried out an additional analysis of step length while statistically adjusting for velocity. We made these adjustments by entering velocity as a covariate in the GEE analysis. As in the previous model, we carried out the computations using the GENMOD procedure of the SAS software system (SAS, 2006).

Overall, walking with loads most affected the distance and timing of infants' footfall patterns in the back-load condition (compare the height of the bars relative with baseline in Figure 4). The analysis revealed a main effect for load condition on step length $\chi^2(5, N = 25) = 16.92$, $p < .005$ (see Figure 4a) but no significant differences in step length between right and left feet, and no interaction of right/left with condition. Infants took longer steps in the no-load baseline condition compared with each of the load conditions and shorter steps in the back-load condition compared with each of the other conditions, all ps $< .001$. The symmetrical-, front-, and side-load conditions differed from both no-load baseline and back-load conditions, ps $< .05$. In a second analysis, we controlled for the effect of velocity on step length, and confirmed the main effect for load condition on step length $\chi^2(5, N = 25) = 14.70$, $p = .01$. After adjusting for velocity, a similar pattern of results held: Infants took longer steps in no-load baseline than in the load conditions, shorter steps in the back-load condition compared with the other conditions, and intermediate-length steps in the symmetrical-, front-, and side-load conditions, all ps $< .05$.

Figure 4b–d shows the effect of the load conditions on timing measures. The GEE analysis confirmed main effects for condition on velocity $\chi^2(5, N = 25) = 18.56$, percentage of double-support time $\chi^2(5, N = 25) = 20.12$, and percentage of swing time $\chi^2(5, N = 25) = 18.48$, ps $< .003$. Post hoc tests revealed that velocity was the highest in the no-load baseline condition and the lowest in the back-load condition, all ps $< .001$. Velocity was higher in the front-load condition than in the symmetrical condition and velocity in both was higher than in the two-side-load conditions, ps $< .05$. Percentage of the gait cycle spent in double support was the lowest in the no-load baseline and front-load conditions and the highest in the back-load condition, all ps $< .01$. The symmetrical- and side-load conditions differed from the other conditions, ps $< .005$.

The GEE analysis on percentage of the gait cycle spent in swing revealed a unique condition by foot interaction $\chi^2(5, N = 25) = 17.02$, $p = .005$. Infants displayed smaller percentages in swing on their right foot while carrying loads on their right side and smaller percentages in swing on their left foot while carrying loads on their left side. Averaged across both legs, infants showed larger percentages in swing in the no-load baseline and front-load conditions compared with each of the other conditions and smaller percentages in swing in the back-load condition compared with each of the others, ps $< .05$. The symmetrical- and side-load conditions differed from no-load baseline, front-, and back-load conditions, ps $< .001$. A second analysis, in which we controlled for the effects of velocity on percentage of the gait cycle in double support and swing, confirmed the main effect for load condition on both double support χ^2 $(5, N = 25) = 15.00$, $p = .01$ and swing time χ^2 $(5, N = 25) = 16.25$, $p = .006$.

We examined the effects of walking experience and Ponderal Index on footfall measures in two additional GEE analyses. In the first analyses, we entered walking experience as a covariate and in the second, we entered the Ponderal Index. These analyses took into account infants' performance in the no-load baseline trials and compared it with their performance in the load trials. The first GEE showed a significant effect for walking experience on step length $\chi^2(1, N = 25) = 7.55$ and velocity

$\chi^2(1, N = 25) = 6.18$, $ps < .01$, meaning that more experienced walkers took longer, faster steps in the load conditions than less experienced walkers. In the second GEE analysis, the Ponderal Index showed effects on step length $\chi^2(1, N = 25) = 3.59$ and velocity $\chi^2(1, N = 25) = 4.59$, all $ps < .05$, indicating that chubbier infants displayed less mature footfalls in the load conditions.

Footfall measures in the no-load baseline condition predicted the size of footfall modifications in the five symmetrical- and asymmetrical-load conditions, such that more proficient walkers maintained more mature footfall patterns while carrying loads. Faster velocities, larger step lengths, shorter percentages of double support, and longer percentages of swing in the no-load condition predicted the same pattern of results in 18 of the 20 possible correlations between no-load baseline and load conditions; Pearson's *r*s ranged from .60 to .89 ($M = .74$) for the 18 significant correlations, all $ps < .005$.

Discussion

Load carriage—especially on the back—is a daily task for millions of adult workers, college students, and schoolchildren (e.g., Karkoska, Franz, & Pascoe, 1997; Pascoe & Pascoe, 1999). Although researchers have described both the immediate compensatory responses and the long-term health consequences of load carriage in adults and older children (American Academy of Orthopedic Surgeons, 2000; National Back Pain Association, 1997; U.S. Consumer Product Safety Commission, 2000), infants' adaptation to loads remains largely unexamined. How might infants who are just mastering upright balance cope with the additional problem of carrying a load?

The current study described infants' immediate, short-term responses to load carriage. We recorded gait disruptions (cross-steps, falls, etc.), postural responses (direction of torso leaning), and footfall modifications (velocity, step length, etc.) under various placements of symmetrical and asymmetrical loads (totaling 15% of body weight). We found several important similarities and intriguing differences between infants' adaptation to load carriage and older children and adults' responses to loads as reported in the literature. We discuss these similarities and differences before turning to larger developmental questions.

Infants Versus Children and Adults

Ability to carry loads. Infant walkers, like expert older walkers, can execute immediate, effective responses for symmetrical and asymmetrical load carriage. The frequent switching between load conditions required infants to detect the current constraints on balance and to respond differentially to each load distribution from trial to trial. Moreover, the loads were substantial; 15% of body weight is sufficient to induce changes in posture and walking patterns in older children and adults (Cottalorda et al., 2003; Hong & Brueggemann, 2000; Li et al., 2003; Malhotra & Sen Gupta, 1965). Thus, adaptation required considerable modification of infants' normal posture and walking patterns.

However, we found an important difference in infants' ability to carry loads compared with older walkers. Unlike older children or adults, infants misstepped and fell in the load conditions (51.7% of load trials included gait disruptions compared with 13.0% in the no-load condition). For infants, falling is commonplace rather than unusual and falls are not limited to situations involving load carriage. Indeed, a video-tracking study showed that 14-month-old infants averaged 15 falls per hour in the course of free play and unrestrained walking (Garciaguirre & Adolph, 2006). Falls were seldom precipitated by carrying loads or variations in the ground surface. Most commonly, infants fell due to variability in their own motor systems—in response to small disruptions of balance as they turned their heads or bodies, changed locomotor position, or placed their swinging foot outside the base of support. Apparently, small, unexpected changes in the distribution of forces are sufficient to cause infants to misstep or fall; load carriage only exaggerates the prevalence of infants' falls.

Symmetrical versus asymmetrical loads. Based on previous research (Adolph & Avolio, 2000; Charteris et al., 1989; Lloyd & Cookie, 2000; Vereijken et al., 1999), we expected that infants, like adults, should show minimal disruptions in walking patterns while carrying symmetrical loads. However, contrary to our expectations, we found that infants showed the same frequency of gait disruptions and footfall modifications in the symmetrical condition as in the front- and side-load conditions. Possibly, practice may underlie the discrepancy with earlier work. Testing infants after a lengthy session carrying the loads (Adolph & Avolio, 2000) or after earlier sessions carrying the loads (Vereijken et al., 1999) might have ameliorated the deleterious effects of symmetrical load carriage.

Another difference between infants and older walkers concerns how they cope with asymmetrical loads. In previous work, adults' walking was less impaired with back loads than in other asymmetrical conditions (DeVita et al., 1991). In contrast, infants fared worst in the back-load condition compared with other asymmetrical conditions: Missteps and falls were the highest and footfall patterns were the most disrupted. The difference between infants and adults is likely to stem from their different postural responses to loads as described below.

Postural responses to loads. Like adults, infants modified their posture in response to asymmetrical loads by inclining their trunks. For both age groups, postural responses are immediate and persistent. Infants exhibited postural leaning in their first steps and rarely altered the direction of their trunk inclination over the course of each walking sequence. In asymmetrical trials, infants exhibited trunk inclination on 87.7% of their first three steps and the same direction of leaning on 80.3% of their last few steps. Likewise, in previous work, adults began leaning immediately after donning an asymmetrical load and trunk inclination increased over several minutes of load carriage (Hong & Cheung, 2003; Li et al., 2003).

However, the most striking difference between infants and mature walkers is the nature of their postural response to load carriage. Older children and adults *compensate* for load carriage by leaning away from the direction of the load; they lean forward while carrying a backpack, to the left while carrying a briefcase in their right hand, and so on (DeVita et al., 1991; Legg, 1985). Leaning away from the load keeps the center of mass more squarely over the base of support (Legg, 1985). Footfall modifications are not necessary during adult load carriage because the bulk of the problem is addressed by trunk inclination. In other words, adults' compensatory postural response offsets or ameliorates the effects of the loads.

In contrast, infants merely *accommodate* to load carriage, as if managing the best that they can with a difficult balance control situation. Rather than implementing a compensatory response that redistributes the forces over the moving base of support, infants leaned with the loads; they leaned forward while carrying a front load, backward while carrying a back load, and so on. As destabilizing forces increased, infants modified their footfalls to prevent themselves from falling. Infants' postural response exacerbates the immediate balance control problem and the bulk of the task of load carriage must be handled by footfall modifications.

Accommodation rather than compensation may have caused back loads to be most difficult for infants because back loads exacerbate natural asymmetries between the front and back of the body. The feet are asymmetrical from front to back; the toes extend farther than the heel. As a consequence, the base of support is asymmetrical and walkers' bodies can lean farther forward than backward. Asymmetries in muscle strength also favor forward leaning. The calf muscles on the back of the leg are stronger than the shin muscles on the front (Convertino, Doerr, Flores, Hoffler, & Buchanan, 1988; Marieb, 1995). When the body rotates around the ankles, the stronger calf muscles pull the body backward during a forward lean and the weaker shin muscles pull the body forward during a backward lean. This discrepancy in muscle strength means that the body can sway farther forward than backward. Healthy, young adults, for example, can lean 12° in the forward direction while standing but only 5° in the backward direction (McCollum & Leen, 1989).

Thus, adults and older children may prefer back loads because their compensatory "lean-away" strategy allows them to exploit the larger distance that they can incline their trunks forward. Infants may fare worst in the back-load condition for the same reason: With their accommodating "lean-with" strategy, in the back-load condition, they are forced to lean backward—in the direction where their bodies have the smallest range of motion.

Footfall modifications. A final similarity between infants and adults concerns how they modify their walking patterns. While carrying loads, infants modified their footfalls by decreasing overall velocity, shortening step lengths, decreasing the percentage of the gait cycle in swing with one foot in the air, and increasing the percentage of the gait cycle in double support with both feet on the floor. Older children and adults show similar responses to asymmetrical load carriage (Chow et al., 2005; Pascoe et al., 1997). That is, across age groups, gait modifications in response to load carriage represent the immature walking patterns that are emblematic of poor balance control in infant walkers (e.g., Adolph et al., 2003; Ledebt et al., 1998; McGraw, 1945).

An especially notable finding was that infants spent a smaller percentage of the gait cycle in swing with the foot on the same side as the load. Essentially, when carrying side loads, infants were severely limping with the ipsilateral foot. This ad hoc response to side loads might further suggest that infants are accommodating to loads instead of compensating like adults.

Another important difference between infant and mature walkers concerns the relationship between velocity and other footfall measures. For both infants and adults, walking velocity is positively correlated with step length and negatively correlated with double support and swing times during both unencumbered walking and load carriage (Bril & Breniere, 1992; Chow et al., 2005; LaFiandra et al., 2003; Pascoe et al., 1997). But, when velocity is controlled behaviorally by asking adults to walk on a motorized treadmill or to the beat of a metronome, modifications in footfall measures disappear except when carrying enormous loads (Goh et al., 1998; Wang et al., 2001).

In contrast to adults and older children, modifications in infants' footfall patterns are not fully explained by changes in velocity. With infants, it was not possible to control velocity with a behavioral manipulation. Instead, we controlled for the effects of velocity statistically. The benefit of our statistical approach was that we could observe changes in preferred walking speed while simultaneously examining changes in other footfall measures independent of velocity. Infants walked slower in every load condition. Most important, after controlling for the effects of velocity, effects of load carriage on step length, double support, and swing remained across load conditions. This result suggests that infants' footfall modifications are a response to increased balance constraints induced by the loads, rather than a simple by-product of decreased velocity.

What Develops?

The findings from the current study with infants, in combination with previous studies with older children and adults, point to two types of changes in the development of load carriage. One type of developmental change occurs after the toddler period, when older children make the dramatic switch from accommodation to compensation in their postural strategies, that is, when they lean away from rather than with the load. The second type of developmental change occurs during the toddler period as infants become more proficient at implementing their "lean-with" response.

Postural strategies. Even the most experienced infant walkers leaned with rather than away from the loads in every asymmetrical load condition. Several factors—either alone or in combination—may contribute to the acquisition of the adult-like compensatory strategy. One explanation is that the loads were simply too heavy for infants to offset by leaning away. With lighter loads, infants may have had sufficient strength to lean away from the load. On this account, what develops may be sufficient strength to implement the more mature strategy. However, the fact that none of the infants—even the most slender, proficient, or experienced—exhibited compensatory trunk inclination argues against this interpretation. Moreover, previous work with older children and adults suggests that loads $<15\%$ of body weight do not induce postural responses.

A second possibility is that infants had not yet discovered the lean-away strategy. In this case, what develops might be the realization that the gambit of leaning away from the direction of motion can be used to regain equilibrium. Given that the most experienced walkers had accumulated 3–4 months of everyday experience, such a discovery might require several additional months or years of experience with upright balance and locomotion. Prior experience carrying loads to the front and sides of the body did not prompt infants to lean away from the load.

A third possibility is that infants could not implement the lean-away strategy while simultaneously inducing sufficient disequilibrium to shift the body weight onto one foot and to produce the propulsive forces necessary to move the body forward (Ledebt et al., 1998). In this case, what develops might be sufficient balance control to execute the more mature maneuver. Such development could take years because children do not show adult-like patterns of gait initiation and control over the displacement of their center of mass until 6 years of age (Bril & Breniere, 1993).

A final speculation is that the difference between infant and adult postural responses to load carriage reflects a greater cost of modifying footfalls in mature walkers. Even under the most favorable walking conditions—traveling down a straight, flat, unobstructed path without carrying loads—infants' step-to-step variability in footfall measures is higher than that of older children and adults and infants' path of progression is winding, not straight (Adolph et al., 2003). Indeed, infants' variable footfalls and weaving path of progression may reflect an ad hoc response to the outcome of their last step (McGraw, 1935). In the case of load carriage, the cost in efficiency of modifying footfalls may not be salient for infants. In contrast, older children and adults may be loath to incur a cost in efficiency or function and thus they implement a compensatory postural response to load carriage so as to minimize the need to modify their stable walking patterns.

Ironically, despite greater efficiency in the short term, adults' more mature compensatory response incurs substantial costs in the long run. Prolonged trunk inclination to offset a load is related to muscle strain, back strain, stress fractures, spinal abnormalities, knee pain, and joint problems (Knapik et al., 1996). Possibly, infants' greater variability and apparently less efficient strategy of leaning with the loads may actually have long-term benefits by avoiding health problems due to the more mature strategy.

Footfall modifications. The second type of change in the development of load carriage is infants' ability to control their footfalls while leaning in the direction of the load. The study used an age-matched control design so as to control for age-related changes while allowing several putative developmental factors to vary. All of the infants were within 1 week of their 14-month birthday, but showed a wide range of individual differences in body proportions (characterized by Ponderal Index), level of walking proficiency (indexed by footfall measures in the no-load baseline condition), and duration of everyday walking experience (indexed by the number of days between walking onset and test dates). As in previous work (Adolph et al., 2003; e.g., Shirley, 1931), body proportions and walking experience were related to walking proficiency when infants were not carrying loads, such that infants with more slender body proportions and longer durations of walking experience displayed more mature footfall patterns in baseline.

We found that intercorrelated developmental changes in infants' body proportions, walking proficiency, and walking experience may jointly contribute to infants' changing ability to control their footfalls during load carriage. Infants with more slender body proportions, higher baseline levels of walking proficiency, and more walking experience showed more mature footfall patterns in the load conditions. Possibly, chubbier body proportions and less proficient walking patterns created larger destabilizing forces. Alternatively, infants with a higher fat to muscle ratio or lower levels of walking proficiency may have been less equipped to counteract destabilizing forces.

One interpretation of the positive finding for walking experience is that more experienced infants had more opportunities to practice carrying loads. However, all of the load conditions were relatively novel: None of the infants had extensive experience carrying substantial loads, back loads, or loads strapped to their torsos or slung over one shoulder. Thus, everyday walking experience appears to facilitate transfer to the relatively novel balance control problem posed by our load-carriage task. Similarly, in previous work, the duration of infants' everyday sitting, crawling, and walking experience predicted their ability to cope with novel tasks such as leaning over gaps and locomotion over cliffs, slopes, and bridges (Adolph, 1997, 2000; Campos et al., 2000).

Like ongoing changes in body dimensions and walking proficiency, some of the benefits of everyday walking experience may be indirect. Everyday experience might facilitate the acquisition of learning sets. With such a learning mechanism, infants identify the relevant parameters for newly acquired balance control systems and a set of procedures and strategies for calibrating the settings of those parameters online (Adolph, 2002, 2005). A learning set for upright walking could provide infants with the wherewithal to maintain balance under the novel conditions of load carriage imposed in the present study. As Harlow (1949, 1959) put it, infants might be "learning to learn."

In summary, the present work provides a systematic framework for investigating the effects of load carriage on children's locomotion. It remains to be seen whether the strategies demonstrated by toddlers are still evident when children begin to wear backpacks or carry other heavy loads.

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