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# Coping with asymmetry: How infants and adults walk with one elongated leg

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ABSTRACT

The stability of a system affects how it will handle a perturbation: The system may compensate for the perturbation or not. This study examined how 14-month-old infants—notoriously unstable walkers—and adults cope with a perturbation to walking. We attached a platform to one of participants' shoes, forcing them to walk with one elongated leg. At first, the platform shoe caused both age groups to slow down and limp, and caused infants to misstep and fall. But after a few trials, infants altered their gait to compensate for the platform shoe whereas adults did not; infants recovered symmetrical gait whereas adults continued to limp. Apparently, adult walking was stable enough to cope with the perturbation, but infants risked falling if they did not compensate. Compensation depends on the interplay of multiple factors: The availability of a compensatory response, the cost of compensation, and the stability of the system being perturbed.



## 1. Introduction

In this study, we examined how the stability of a system affects accommodation to a novel perturbation: We compared infant walkers—whose balance is notoriously unstable and whose gait is variable under the best of conditions—with adult walkers, whose balance and gait are highly stable. The perturbation was a sudden change in leg length introduced with a platform shoe on one foot. We indexed accommodation to the potential upset by observing the frequency of gait disruptions and falls, and the asymmetry and variability of gait.

### 1.1. Symmetry in walking

Walking is a highly symmetrical activity. Each leg's movement roughly mirrors the other, shifted in time: Weight shifts off of one foot as it shifts onto the other, and each foot touches down about halfway through the opposite leg's stride. Walking is automatized and rhythmical. But what if the symmetry in walking were broken so that the rhythm is perturbed? With a heavy bag over one shoulder or a cast on one leg, the forces acting on the body become asymmetrical. Uncorrected, walkers limp—their gait becomes uneven and halting because the distance and timing of each step is no longer the same for each foot. To return to normal gait, walkers must compensate for the asymmetrical forces. In many situations (such as a painful blister

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on one foot or a broken high heeled shoe), limping is the typical response. In other situations (carrying a heavy shoulder bag), walkers actively redress asymmetrical forces (by leaning) to return gait to greater symmetry.

Walkers can either compensate for the induced perturbation (i.e., correct for the perturbation to restore the symmetry of gait) or not. Whether to compensate depends on the interplay between the stability of the walking system, the size of the perturbation, and the cost and availability of compensation. A stable system can absorb a perturbation without compensation; an unstable one cannot. Skilled adult walkers are stable. Although capable of compensating, adults may not need to; coping with the effects of a slight perturbation may be preferable to a costly correction. Novice walkers, in contrast, are unstable. Their gait is variable and poorly controlled and new walkers may be less able to accommodate unusual forces, and simultaneously less equipped to compensate for them. Indeed, novice walking may be so intrinsically variable that the effects of the perturbation go unnoticed. Breaking the natural symmetry of walking provides an ideal test case for understanding how stable and unstable systems handle perturbations; well-coordinated walking is naturally symmetrical, but symmetry is not obligatory at any level of walking stability.

### *1.2. Breaking symmetry in walking*

One way to break the symmetry of walking is to add weight to one side of the body. Adults immediately compensate for a heavy weight attached to one side of the torso. The load pulls the body to one side; in response, adults immediately lean away from the weight, pulling the center of mass back over the base of support (Fowler, Rodacki, & Rodacki, 2006; Goh, Thambyah, & Bose, 1998; P. E. Martin & Nelson, 1986). Fourteen-month-old infants do not compensate for a load on one side of the torso (e.g., lead-weighted shoulder-pack). Instead of leaning away from the weight like adults, infants lean *into* the load by tipping their bodies in the direction of the weight (Garciaguirre, Adolph, & Shrout, 2007). As a consequence, infants take quicker steps on the side with the weight and slower steps on the unweighted leg, and they incur more frequent gait disruptions such as trips, double-steps, and falls. Thus, stable adult walkers cope with a perturbation induced by an asymmetrical load with compensatory postural strategies. Novice walkers do not, but lack of compensation could be a result of the additional weight.

A split-belt treadmill is another classic method for inducing gait asymmetry. One treadmill belt runs at a higher speed, initially forcing walkers to limp by taking longer, quicker steps with the leg on the fast-belt side while maintaining alternating steps. Even when the fast-moving belt moves at four times the speed of the slow-moving belt, adults require only 10–20 strides to alter the timing and size of their steps to compensate for the asymmetry induced by the treadmill (Dietz, Zijlstra, & Duysens, 1994; Prokop, Berger, Zijlstra, & Dietz, 1995; Reisman, Block, & Bastian, 2005). Less stable walkers—8 to 36-month old infants, 4- to 11-year old children, and adult clinical populations—show less robust compensation. Adaptation in infants and children is slower (Musselman, Patrick, Vasudevan, Bastian, & Yang, 2011) and more variable (Zijlstra, Prokop, & Berger, 1996), and they do not display the full suite of compensatory mechanisms used by typical adults (Choi, Vining, Reisman, & Bastian, 2009; Morton & Bastian, 2006; Musselman et al., 2011; Vasudevan, Torres-Oviedo, Morton, Yang, & Bastian, 2011). Compensation can be reflected in a host of different measures, but always includes changes in step length at every age. Moreover, infants are unpredictable: Although some infants eventually correct for asymmetry, some infants never do, and others show no initial asymmetry to correct (Musselman et al., 2011; Thelen, Ulrich, & Niles, 1987).

Neither paradigm is ideal for studying the effects of an asymmetrical perturbation in infant walkers. Load carriage—even a symmetrical load—disrupts infant walking because of the additional weight (Garciaguirre et al., 2007; Vereijken, Pedersen, & Storksen, 2009). An asymmetrical load breaks the symmetry of infants' bodies, but it compounds the already substantial problem of load carriage. Thus, we cannot know whether the lack of adult-like compensation in infants results from carrying the load, from the asymmetrical nature of the perturbation, or both. The split-belt paradigm is also not ideal because participants are forced to compensate for the perturbation: Walkers who do not compensate for the faster moving belt will find themselves abruptly without a limb beneath them. What's needed is a perturbation that breaks the symmetry of walking while leaving participants free to compensate or not. Walking with uneven leg lengths is such a perturbation.

Without compensation, when forced to walk on legs of different lengths (either experimentally induced or naturally occurring) the longer leg takes larger, slower steps and the shorter leg takes smaller, quicker steps—causing asymmetry in step length and timing. Accordingly, a large lift (>3 cm) in one shoe causes significant gait asymmetries in otherwise healthy adults, indicating that they failed to compensate for the perturbation (Brand & Yack, 1996); however, smaller lifts do not create gait asymmetry (Goel, Loudon, Nazare, Rondinelli, & Hassanein, 1997). In cases of naturally occurring leg length discrepancies, some adults show gait asymmetries even after years of practice (Kaufman, Miller, & Sutherland, 1996; Liu & Fabry, 1998; Seeley, Umberger, Clasey, & Shapiro, 2010); but others maintain symmetry inside the normal range (Kaufman et al., 1996; Liu & Fabry, 1998; Siffert, 1987), indicating that they compensate for the asymmetry induced by their uneven legs.

### *1.3. Current study*

In the current study, we assessed effects of stability on walkers' responses to a perturbation by comparing changes in gait patterns in infants and adults. We studied 14-month-olds to allow comparisons with previous work (Garciaguirre et al., 2007) and because at that age, infants are novice walkers and their gait is variable and precarious compared with adults' (Adolph, Vereijken, & Shrout, 2003). We broke the natural symmetry of walking by elongating one of walkers' legs with a large platform attached to the sole of their shoe. We chose this manipulation because the induced asymmetry is not confounded with hauling additional mass (as with asymmetrical loads) and does not force walkers to compensate (as on a split-belt treadmill). To observe the course of compensation, we assessed gait asymmetry at several time points: Before inducing leg length asymmetry with the platform; immediately after inducing asymmetry with the platform, after 15 min of practice walking with an elongated leg, and after removing the platform.

The primary outcome measure was asymmetry in step length. We focused on this measure for several reasons. It is a simple, easy to obtain, and robust functional measure of walking asymmetry. In adult walkers, step length is proportional to leg length; thus, a large disruption in the symmetry of adults' legs should cause robust changes in step length (Gurney, 2002). Although infants' step length is unrelated to their leg length (Cole, Lingeman, & Adolph, 2012; Garciaguirre et al., 2007), step length depends on walking age (time elapsed since walking onset) and balance control (Adolph et al., 2003; Bril & Ledebt, 1998), making it an important index of improvements in walking skill. We also observed gait disruptions (trips, falls, etc.) to examine the functional cost of the perturbation, and we measured participants' walking speed and the coefficient of variation (CV) of participants' step lengths to see if participants slowed down or became more variable in response to the perturbation.

Based on previous work (Brand & Yack, 1996; Garciaguirre et al., 2007; Goel et al., 1997; Gurney, 2002; Seeley et al., 2010), we expected the discrepancy in leg lengths to induce asymmetry in walking. Our primary question was whether infants and adults would compensate for the induced asymmetry. Results from load carriage and split-belt treadmill studies suggest that adults should readily compensate (Fowler et al., 2006; Goh et al., 1998). However, findings from experimental manipulations of adults' leg lengths suggest that they might not (Seeley et al., 2010). What about infants? Infants might fail to compensate and limp (similar to asymmetrical loading). They might compensate for the perturbation to maintain symmetrical step lengths (as on the split-belt treadmill). Or, infants might simply be too unskilled to respond to the asymmetry in any coherent way.

## 2. Method

### 2.1. Participants

Sixteen infants (9 boys, 7 girls) and 16 adults (5 men, 11 women) participated. Infants were tested within one week of their 14-month birthday ($M$ = 14.0 months) and were healthy, born at term, and predominantly white and middle class. Families were recruited from the New York metropolitan area and given small souvenirs in return for participation. Parents reported infants' walking age (the time elapsed between the first day that infants walked approximately 3 m independently and the test day) in a structured interview (Adolph, 2002; Adolph et al., 2003). On average, infants had 64.2 days of walking experience, confirming their status as novice walkers (range 13–124 days). All infants had experience walking in shoes.

Adult volunteers were 21.0–47.8 years of age ($M$ = 25.9) and were recruited by word of mouth. None reported current injuries that would impair their gait and none had clinically significant body asymmetries. Data from one additional adult were excluded due to equipment malfunction.

### 2.2. Platform shoes and gait carpet

To induce a leg length discrepancy, we attached a thick platform to the bottom of one of participants' shoes (illustrated in Fig. 1). We constructed 15 pairs of shoes with adjustable soles from commercially available infant (Gerber hiking boots) and adult shoes (Converse sneakers). To accommodate differences in foot size, the modified shoes included half sizes from 3½ to 6 for infants and whole (men's) sizes from 4 to 12 for adults. For both infant and adult shoes, the top of each removable sole was covered in Velcro to facilitate quick attachment and removal between conditions.

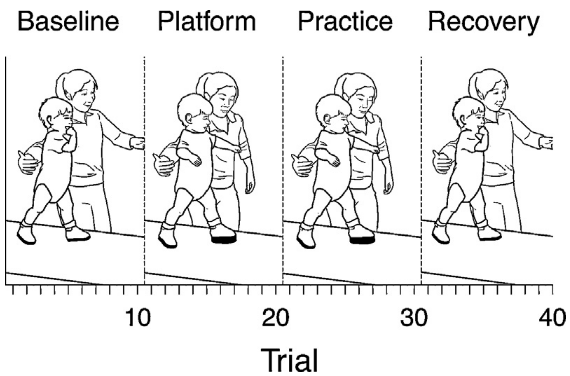


**Fig. 1.** Line drawing of apparatus illustrating the four conditions: Baseline (two thin soles), platform (one elongated leg), practice (after 15 min walking with the platform shoe), and recovery (two thin soles). Infants walked over a pressure-sensitive carpet on a raised walkway 10 times in each condition for a total of 40 trials.

We designed the height of the platform to be large enough to induce asymmetry in adult gait and small enough that infants were still able to walk. For the infant shoes, we removed the original soles and replaced them with Velcro. Then, we constructed 12 thin soles (0.7 cm) and 12 thick platform soles (2.6 cm), one for each foot. All were cut from lightweight crepe foam, a material used by shoemakers, and fitted precisely to each shoe size. Thus, the difference between a platform on one foot and a thin sole on the other was 1.9 cm. The thin sole was the same thickness as the original sole and weighed 10.3–12.4 g for the size 3½–6 shoes, respectively. Because of the additional material, the platform sole was necessarily thicker and stiffer than the original and weighed 28.1–30.7 g across the range of shoe sizes. For the adult shoes, we lined the soles of each sneaker with Velcro. Thin soles were cut from a 0.3-cm thick, pliable rubber material and precisely fit to each shoe size. In combination with the existing sole, the total thickness of the thin sole was 1.2 cm. Platform soles were cut from 4.4-cm thick, lightweight crepe foam and were as stiff as the infant platforms. The resulting difference between thin and platform soles was 3.2 cm. The thin sole weighed 70.7–126.2 g for the size 4–12 shoes, respectively, and each platform weighed 133.1–184.2 g across the range of shoe sizes.

A pressure-sensitive gait carpet (GaitRite Inc.) recorded the location of each step (3.66 m by .89 m for the infants, 5.73 m by .92 m for the adults). The entire session was recorded from both front and side views for later video coding.

### 2.3. Design/procedure

Each session lasted 60–90 min. Infants wore a t-shirt and diaper and adults wore comfortable street clothes. The correct shoe size was selected for each participant based on self report (adults) and parental report (infants) and adjusted as needed. For infants, the gait carpet was placed on a raised walkway (97 cm wide × 488 cm long × 58 cm high) to prevent infants from veering off the carpet. An experimenter followed alongside infants to ensure their safety. Caregivers stood at the end of the walkway and encouraged infants to walk toward them. Infants received four warm-up trials in the thin shoes to acclimate them to walking on the raised walkway.

For adults, the gait carpet was placed on the floor. At the end of each trial, adults circled back to the starting position. This equated the number of steps infants and adults accumulated while wearing the platform, as infants' shorter steps required approximately twice as many steps per trip to walk over the carpet ($M = 9.7$ steps) compared to adults ($M = 4.4$ steps).

All participants were tested in four conditions with ten trials each (Fig. 1). First, in the *baseline* condition, participants walked ten times at a self-selected comfortable pace in two thin-soled shoes to establish their normal walking patterns. Next, we assessed reactions to an abrupt asymmetrical perturbation in the *platform* condition. Platform side (left or right) was counterbalanced. Infants were held while one thin sole was replaced with a platform sole, then carried to the start of the walkway. Adults sat in a chair during the switch, then stood up and walked. In this way, we were able to observe participants' immediate responses to the platform shoe and any learning that occurred during the subsequent trials of experience walking with the new asymmetry. After 15 min of additional practice walking in the platform shoe, we assessed participants' walking patterns with another ten trials in the *practice* condition. Caregivers and experimenters encouraged infants to walk and run in the platform shoe using chase games, hide-and-seek, ball play, and so on. Adults were simply instructed to walk around, followed by an experimenter who timed their walking and ensured that they remained in motion. Finally, the platform was removed and participants were asked to walk again for another ten trials with two thin soles. This *recovery* condition constituted another rapid shift in walking conditions and allowed us to observe any after effects.

At the end of the session, an experimenter collected measures of participants' weight, height, and leg length. Infants were weighed nude, $M = 9.9$ kg (range = 8.0–12.6), and adults were weighed clothed, $M = 62.9$ kg (range = 49.2–81.6). Infants' recumbent height from crown to heel was $M = 76.4$ cm (range = 72.7–81.9) and adults' standing height was 169.8 cm (range = 156.4–188.1). Infants' leg length (from hip to ankle) was $M = 32.6$ cm (range = 30.5–35.8) and adults' leg length was $M = 88.4$ cm (range = 79.6–96.8).

### 2.4. Data processing and analysis

Disruptions of alternating gait were identified using the video-coding software Datavyu (www.datavyu.org). We counted the frequency of four types of gait irregularities: falls (body fell to the ground), trips (foot did not clear the ground as it swung forward), double steps (two consecutive steps with the same foot), and cross steps (the swinging leg crossing over the standing leg, making the lateral distance between feet < 0). A secondary coder scored 25% of each participant's data to ensure interrater reliability. Percent exact agreement ranged from 87.3% to 100% (all $\kappa$s significant, $ps < .001$). Because only two gait disruptions (both trips) occurred in the entire adult sample, we report gait disruption data only for infants.

Footfall measures were only calculated for trials that included several steps of uninterrupted walking, as is typical (Bril & Breniere, 1989). Portions of trials including gait disruptions were therefore removed; trials with fewer than four consecutive steps remaining were excluded from analyses of gait parameters. Forty-one of infants' trials were removed for this reason, leaving 599 trials available for analysis of footfall measures ($M = 37.4$ trials per infant). There was no relation between walking experience and the number of useable trials infants contributed. Six trials from the adults could not be used due to participants stepping outside the active region of the carpet, leaving 634 trials available. For accepted trials we calculated walking speed (total distance covered divided by the time between first and last steps) and step length (distance along the line of progression from the heel of the current step to the heel of the opposite leg's step). Step length data were used to compute measures of asymmetry and variability. Step lengths were averaged over each trial for each leg separately. To directly compare step length asymmetry in infants and adults, we computed an asymmetry index as in previous work (Musselman et al., 2011): (platform step length – thin step length)/(platform step length + thin step length). The asymmetry index represents the difference between the two step lengths as a proportion of one step from each side of the body, thereby accounting for the fact that adults take longer steps than infants. We computed the coefficient of variation (standard deviation/mean) separately for each leg because we expected the platform manipulation to affect step length differently for each leg. This conservative approach kept the step-to-step variability measure from being artificially inflated by any observed increase in step length asymmetry.

Because we were interested in trial-to-trial changes in participants' gait patterns, data were analyzed using Generalized Estimating Equation (GEE) models composed of factors for age group, condition, trial, and the interactions between them. The GEE on gait disruptions used a Poisson link function because gait disruption data were not normally distributed; all other analyses used a normal distribution. The GEE method accounts for repeated measures while also permitting analysis of linear changes over the course of repeated trials within each condition. Significant interactions between age group and condition were followed by Sidak-corrected pairwise comparisons of conditions within each age group. The GEE method also builds a regression model; tests on the coefficients of this model allowed us to look at effects in more detail (for example, describing effects in the first trial of each condition and linear changes from trial to trial within conditions—essentially providing follow-up tests on interactions that included the trial factor).

## 3. Results

### 3.1. Gait disruptions

As shown in Fig. 2, infants' gait was disrupted (trips, falls, etc.) when they first walked with the platform and when we removed the platform at the start of the last condition. During normal walking (*baseline* condition), infants averaged only 2.4 gait disruptions over the 10 trials (range from 0 to 6 disruptions). Walking with one platform shoe (*platform* condition) increased the average number of gait disruptions to 4.1, and one infant showed 14 disruptions (Fig. 2A). The spike in gait disruptions was particularly pronounced at the start of the condition (Fig. 2B); in the first three trials of the platform condition, 75% of the infants displayed gait disruptions, whereas only 50% showed disruptions on all subsequent trials combined. After extended practice walking with the platform (*practice* condition), disruptions dropped to baseline levels ($M$ = 2.9 disruptions, range 0–11). Unlike the spike at the start of the platform condition, the spike at the end of the practice condition (Fig. 2B) is driven by only two infants with 6–8 disruptions in trial nine: After excluding these two outliers, infants averaged only .43 disruptions in this trial. However, after we removed the platform (*recovery* condition), gait disruptions jumped up to $M$ = 4.9, and one infant showed a whopping total of 17 disruptions.

The GEE confirmed a main effect of condition, see row 1 of Table 1. Follow-up pairwise comparisons indicated more disruptions in the recovery condition than in the baseline condition, $p$ = .005. The platform and practice conditions were not statistically different from baseline, $ps$ > .05. However, the main effect of condition was modified by an interaction between condition and trial number, row 1 of Table 1. Tests on the coefficients of the regression

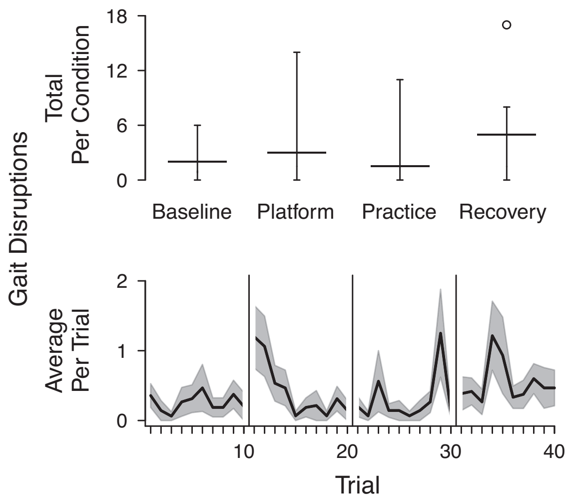


**Fig. 2.** (A) Total gait disruptions per condition. The solid line represents the median and the whiskers mark the minimum and maximum values. Circles represent outliers (values more than 1.5 times the interquartile range). (B) Average gait disruptions per trial. Shaded areas represent ± one standard error.

**Table 1**
Wald $X^2$ values for all GEE model effects.

| Variable | Age group | Condition | Trial | Age × condition | Condition × trial | Age × trial | Age × condition × trial |
|---|---|---|---|---|---|---|---|
| Gait disruptions | – | 34.99*** | 1.29 | – | 14.61** | – | – |
| Asymmetry index | .04 | 47.99*** | .67 | 5.71 | 9.59* | 1.35 | 16.74** |
| Step variability | 137.03*** | 20.32*** | 7.38** | 13.46** | 12.54** | 3.01 | 9.23* |
| Walking speed | 124.14*** | 25.19*** | 6.68* | 13.88** | 19.51*** | 3.43 | 8.17* |

* $p$ < .05.
** $p$ < .01.
*** $p$ < .001.

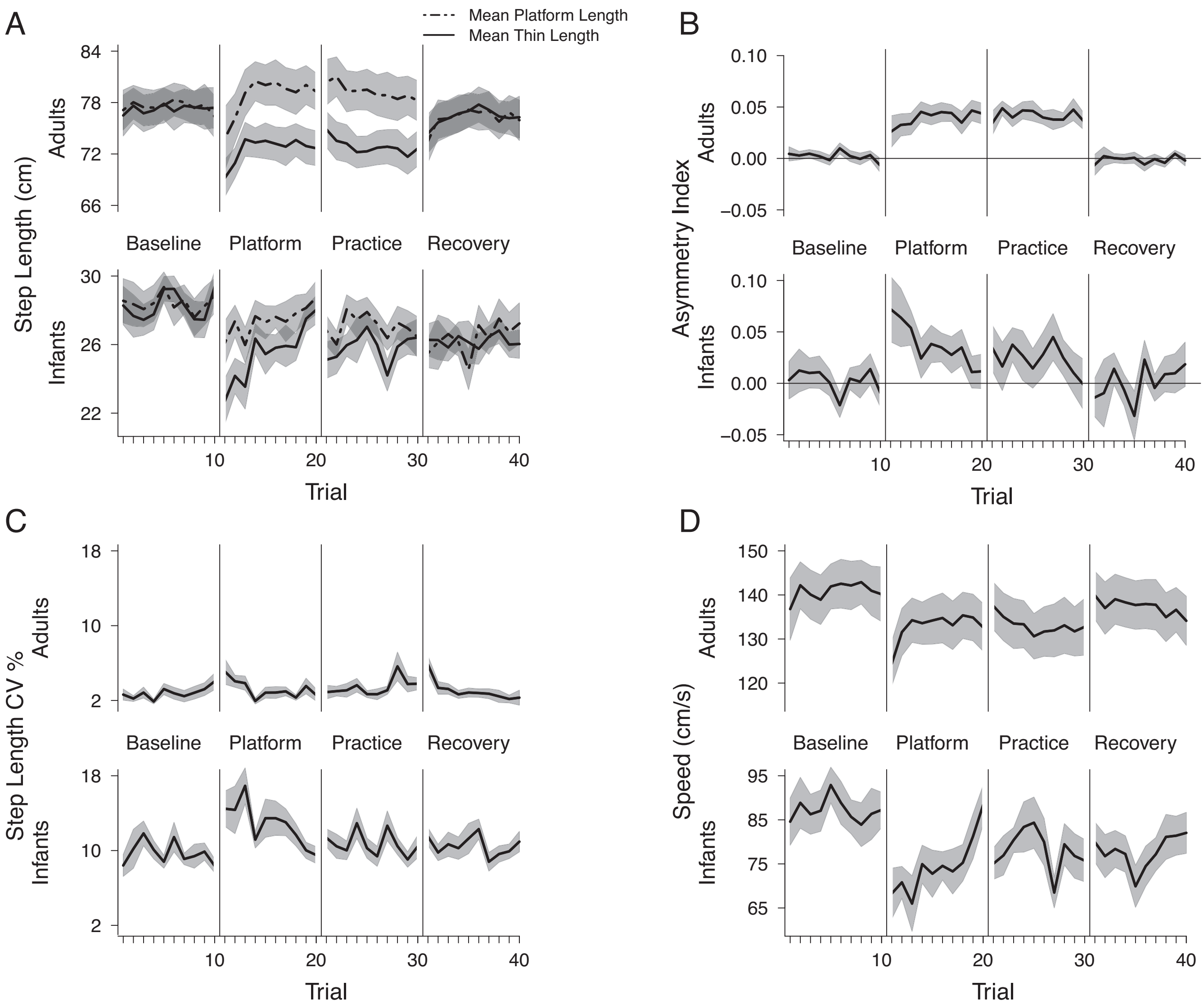


**Fig. 3.** Average gait parameters over trials for infants and adults. (A) Step length in cm in the leg wearing the platform sole (solid line) and the leg wearing the thin sole (dashed line). (B) Asymmetry index (platform step length − thin step length/platform step length + thin step length); note, the asymmetry index normalized step length across infants and adults. (C) Coefficient of variation of step lengths (standard deviation/mean). (D) Walking speed (distance/time). Shaded areas represent ± one standard error.

model confirmed an increase in gait disruptions in the first trial of the platform condition relative to baseline, *Wald* $X^2(1, N = 16) = 6.3$, $p = .01$, Fig. 2B. Over subsequent trials, gait disruptions decreased, as indicated by the significant slope coefficient during the platform condition, *Wald* $X^2(1, N = 16) = 4.3$, $p = .04$. Analyses revealed no other trial-to-trial changes in gait disruptions in any condition.

### 3.2. Step length and speed

#### 3.2.1. Baseline walking

The baseline condition accurately measured participants' normal walking. Inter-trial consistency was high in both age groups, as evidenced by correlations between gait parameters measured in different trials and high Cronbach's alphas: In infants, average $rs > .54$, Cronbach's alphas > .90; in adults, average $rs > .93$, Cronbach's alphas > .99. The average asymmetry in step lengths during the baseline condition was .2 cm in the infants and .3 cm in the adults; these asymmetries were transient and did not consistently favor the left or right side in any participant.

#### 3.2.2. Asymmetry

With the platform attached to one leg, adults' step lengths became asymmetrical and stayed that way: Adults took longer steps with the platform leg and shorter steps with the thin-soled leg, resulting in a $M = 6.2$ cm difference between step lengths in the platform condition (Fig. 3A). This asymmetry was unchanged with additional experience walking with the platform ($M = 6.4$ cm difference between step lengths in the practice condition). After the platform was removed, adults immediately reverted to normal, symmetrical walking ($M = -0.2$ cm difference between step lengths) with no signs of over-compensation or after effects.

Infants, however, showed a very different pattern (Fig. 3A). Like adults, adding the platform to one leg immediately led to asymmetrical step lengths: Infants took longer steps with the platform leg and shorter steps with the thin-soled leg, resulting in an average step length discrepancy of 1.9 cm during the platform condition. Unlike adults however, asymmetry in infants' gait sharply decreased on subsequent trials. During the first three trials of the platform condition infants' step lengths were asymmetrical by an average of 2.72 cm, but by the last three trials, the difference between the step lengths for the two legs decreased to $M = 0.7$ cm. After 15 min of additional practice walking with the platform, step lengths were asymmetrical by 1.2 cm, and after the platform was removed, asymmetry averaged 0.2 cm across the recovery condition. Thus, although both groups initially experienced asymmetrical step lengths due to the platform, adults maintained this asymmetry but infants did not.

To formally assess asymmetry, we conducted a GEE analysis on the asymmetry index (Fig. 3B). The GEE revealed several main effects and interactions, and most importantly a 3-way interaction between age group, condition, and trial (row 2 of Table 1). Adults walked asymmetrically in both the platform and the practice conditions compared to baseline, $ps < .001$. Infants also experienced an increase in asymmetry in the platform condition, $p = .009$, but asymmetry decreased over subsequent trials as indicated by a significant slope coefficient from the regression model, *Wald* $X^2(1, N = 32) = 12.0$, $p = .001$. This compensation meant that by the practice condition, infants' walking was no longer different from baseline, $p = .6$. Asymmetry in both infants and adults was not different from baseline during the recovery condition, $p = .9$ and $p = 1.0$, respectively.

### 3.2.3. Variability

A preliminary GEE analysis comparing the coefficient of variation in the platform and thin-sole legs showed no main effect for leg. Averaged across the trials in each condition, differences between legs in the COV for adults ranged from $M = .005$ in the baseline, platform, and return conditions to $M = .006$ in the practice condition; for infants, differences in COV between legs ranged from $M = .002$ in the baseline condition to $M = .03$ in the platform condition.

In further analyses, we report the average COV of the two legs. As shown in Fig. 3C, adults were consistently less variable than infants, row 3 of Table 1. Adult variability was relatively unaffected by the platform manipulation; average coefficient of variation of step length was 3% in all four conditions and follow-up comparisons indicated no differences between conditions, $ps > .05$. Despite this, visual inspection of Fig. 3C shows a brief increase in variability in the first trials of both the platform and recovery conditions. Tests of the regression coefficients confirmed these increases in variability in the first trial of each condition, *Wald* $X^2(1, N = 32) = 9.7$, $p = .02$ and *Wald* $X^2(1, N = 32) = 26.0$, $p < .001$ respectively. In both cases, variability dropped back to baseline so rapidly that the condition mean showed no effect. Thereafter, variability in adults remained unchanged from trial to trial across the entire experiment.

However, the GEE did indicate a significant main effect of condition and a significant interaction between age group and condition, row 3 of Table 1; these effects were driven by infants' responses to the platform. Infants' average step length CV was 10% during the baseline condition, but increased to 13% during the platform condition. Follow-up pairwise comparisons confirmed that infants' step lengths were significantly more variable during the platform condition compared to the baseline condition, $p < .002$. As can be seen in Fig. 3C, this initial increase in variability was substantially larger than that seen in adults, an impression confirmed by the coefficient from the regression model, *Wald* $X^2(1, N = 32) = 4.6$, $p = .03$. The GEE also revealed a 3-way interaction of age group, condition, and trial: After the large spike in variability at the start of the platform condition, infants' variability dropped off over the course of the platform condition, Fig. 3C. During the practice and recovery conditions, infants' step length variability remained at baseline levels, $M = 10\%$ for both conditions, $ps > .05$ compared to baseline.

### 3.2.4. Speed

As expected, adults walked faster than infants, row 4 of Table 1. Walking speed was also affected by the platform manipulation (row 4 of Table 1) but again a 3-way interaction of age group, condition, and trial indicated that infants' and adults' responses unfolded differently, row 4 of Table 1. Adults walked at an average speed of 141.3 cm/s during the baseline condition. The addition of the platform caused walking speed to drop to $M = 133.4$ cm/s during the platform condition and $M = 133.2$ cm/s during the practice condition, $p = .001$ and $p = .03$, respectively. Significant slope coefficients from the regression model indicated that adults' walking speed slowed further during the practice and recovery conditions; *Wald* $X^2(1, N = 32) = 11.7$, $p = .001$ and *Wald* $X^2(1, N = 32) = 6.2$, $p = .01$, respectively. However, this gradual decrease in speed was small—about 1 cm/s per trial—and only a minor adjustment on top of the 8 cm/s drop in speed present the entire time adults wore the platform. After the platform was removed, adults' walking speed rebounded to $M = 137.7$ cm/s in the recovery condition and was not different from baseline, $p = .47$.

Infants—with their shorter legs and lower levels of walking skill—walked more slowly, at an average of 87.1 cm/s during the baseline condition. During the platform condition, infants slowed to $M = 74.5$ cm/s; follow-up comparisons confirmed this as significantly slower than baseline, $p < .001$. Visual examination of Fig. 3D shows that the decrease in speed was particularly pronounced during early platform trials; the test on the regression coefficient confirmed that this initial drop in speed was larger than that seen in adults, *Wald* $X^2(1, N = 32) = 4.8$, $p = .03$. Over the course of the platform condition, infants' speed recovered from trial to trial, as indicated by a significant slope coefficient from the regression model, *Wald* $X^2(1, N = 32) = 5.0$, $p = .03$. Despite this increase, infants' walking speed remained below baseline levels during the practice condition ($M = 78.2$ cm/s, $p = .004$ compared to baseline). Similarly, the regression model indicated that infants' walking speed increased over the course of the recovery conditions, *Wald* $X^2(1, N = 32) = 6.2$, $p = .01$, but infants never returned to baseline levels of walking speed. During the recovery condition, walking speed averaged 77.1 cm/s and pairwise comparisons confirmed this as significantly slower than baseline, $p < .001$.

## 4. Discussion

### 4.1. Breaking body symmetry perturbs walking

Walking with uneven legs perturbed gait in both adults and infants. From adults' first steps in a platform shoe, they slowed down and limped. The asymmetry in step length was substantial; to put it in context, the average asymmetry of 6.2 cm represents 8% of adults' normal step length, and is larger than the 3.2 cm leg length difference that caused it. Moreover, adults—whose gait is typically stable and consistent—briefly displayed increased variability when the platform was added and removed. Walking asymmetries in adults' response to the platform manipulation are consistent with previous studies documenting altered gait patterns in response to uneven leg lengths (see Gurney, 2002 for review).

Infants were more severely affected by the platform perturbation. Their average step length asymmetry was smaller in absolute terms—about 2 cm difference between the two legs—but still represented 7% of their normal step length, about the same proportion seen in adults. Infants also showed a larger spike in variability and a larger drop in speed. Whereas variability in adults quickly returned to baseline levels, variability in infants remained high throughout the platform condition. Likewise, infants' speed never returned to baseline levels—not even after we removed the platform in the recovery condition. Moreover, infants showed a temporary increase in gait disruptions (trips, falls, etc.) when we added the platform and again when we removed it—166 in total across the platform, practice, and recovery conditions. Adults experienced only two disruptions in total. Possibly, infants were more severely disrupted by uneven leg lengths because the platform constituted a slightly larger perturbation for them (2.4% of their body height compared with 1.9% for adults).

### 4.2. Infants compensate but adults do not

Given that the platform perturbed walking in both age groups, how did infants and adults cope with the challenge? One might reasonably expect that someone who can compensate for a perturbation would do so. After all, why tolerate a perturbation—by definition, something that upsets the natural balance of things—when it's in your power to correct for it? Take the example of load carriage. Adults immediately compensate by leaning away from the direction of a heavy load (Fowler et al., 2006; Goh et al., 1998). It is awkward and inefficient to totter along while pulled in the direction of the load. Yet infants appear incapable of doing anything else (Garciaguirre et al., 2007). So, is capacity the final word? If you have the capacity to compensate, do you?

As in previous work on leg length asymmetry (Brand & Yack, 1996), adults did not compensate for uneven leg length. But infants did. Unlike adults, infants' step length asymmetry rapidly decreased to baseline levels by the end of the platform condition. One possibility—that infants' walking is so noisy and variable that they could not maintain consistent asymmetry—can be discarded. This would have manifested as an increase in step length variability. Instead, infants showed the opposite. After an initial spike in variability when the platform was added, infants' variability decreased over the course of the platform condition at the same time that asymmetry was decreasing, Fig. 3B and C. Thus, the decrease in walking asymmetry seen in the platform condition cannot be due to increased variability and motor noise masking underlying asymmetries. Instead, it appears to be active compensation on the part of the infants. Such a feat is not trivial. To compensate in this way, infants must have noticed the perturbation to their walking, felt what the platform was doing, and somehow discovered a means of counteracting it.

### 4.3. Why do infants compensate?

Why would infants make the effort to correct for asymmetry, when adult walkers did not? One possibility is that walking is so stable and consistent in adults that they are essentially locked into a routine. Adult walking is heavily automatized; our adult participants may have been unwilling or unable to break out of that well-practiced pattern within the timescale of our experiment. Of course, adults are capable of compensation when new walking patterns are forced on them—as in the split-belt paradigm—but when allowed to respond freely, adults may be biased to stick with their familiar, habitual walking patterns. Consistent with this idea, adults fail to show compensation when walking with experimentally induced uneven leg lengths over short periods (Brand & Yack, 1996; Goel et al., 1997) and when wearing a weight on one ankle (Haddad, van Emmerik, Whittlesey, & Hamill, 2006; Smith & Martin, 2007). In contrast, infants' walking is less automatized and less practiced and the developing nervous systems of infants are more plastic than those of adults. Infants and children spontaneously display a wider variety of gait patterns than adults (jumping, skipping, spinning, etc.), so infants may be more likely than adults to generate new coordination patterns.

A second possibility is that adults' greater stability affords them the option to compensate or not, depending on the situation. Clearly, adults were sufficiently stable to cope with the perturbation without risk of falling; asymmetrical walking incurred no gait disruptions. Moreover, adults frequently encounter fleeting changes to functional leg length—walking with one foot on the curb, walking with one shoe on—and therefore have extensive experience coping with asymmetry without altering their movements to compensate. Adults are aware that some perturbations may eventually require compensation (such as a lifetime of uneven leg lengths), but other perturbations do not: There's no need to actively compensate for every curb encountered and every instance of walking in only one shoe. Novice walkers, in contrast, risk falling even when unperturbed. If they cannot cope with the perturbation, compensation is mandatory, not optional. The results for gait disruptions support such a view. Infants displayed a large increase in disruptions when the platform was first added, but the rate of disruptions decreased as asymmetry decreased. This suggests that asymmetry incurred a functional cost in infants that was not present in adults: Having to vault over one long leg likely taxed infants' balance, perhaps enough to motivate them to correct for the induced asymmetry.

It is important to note that automatization and stability are not mutually exclusive. Adults are more practiced and automatized, but also have no pressure to abandon their habitual way of doing things. Infants are perhaps less locked into a particular way of moving, but simultaneously have a greater need for flexibility to avoid falling. Likely, compensation depends on the interplay between the stability of the walking system, the size of the perturbation, and the cost and availability of compensation. This possibility could be explored in future work with an older sample of infants with more walking experience.

### 4.4. No after effects

How participants handled the return to even leg lengths in the recovery condition has important implications for learning. Did participants immediately, with a sigh of relief, return to normal walking? Or did the abrupt return to even leg lengths represent another rapid, destabilizing change? Or did participants continue using the compensatory mechanism they had used to correct for the induced asymmetry, resulting in temporary over-correction errors, that is, after effects?

This last possibility deserves special attention because it has particular meaning in studies of motor learning, such as the split-belt treadmill paradigm. When returned to a tied-belt treadmill condition after extended time on the split-belt treadmill, adults do not immediately return to symmetrical walking; instead, they overcompensate in the opposite direction of the original perturbation. Adult walkers need time to unlearn their compensatory mechanisms. After effects are considered evidence of learning and are therefore the hallmark of adaptation; walkers who counteract induced asymmetry on the split-belt treadmill but do not show after effects when the perturbation is removed are not considered to have adapted (T. A. Martin, Keating, Goodkin, Bastian, & Thach, 1996; Musselman et al., 2011; Vasudevan et al., 2011). By this definition, our participants did not adapt to the platform perturbation. Neither age group showed clear after effects—including infants who successfully decreased the asymmetry of their gait while wearing the platform. Thus, although we can say that infants *compensated* for the asymmetrical perturbation, we cannot say that they *adapted* to the perturbation.

At the same time, neither group reverted immediately and perfectly back to baseline walking. Adults' walking during the recovery condition looked similar to baseline walking, but they experienced a brief spike in variability when the platform was first removed—just as they had shown when the platform was first added. This would seem to indicate that the return to even leg lengths is briefly destabilizing, despite it being a return to the status quo. Interestingly, several participants spontaneously reported feeling as though they were overcompensating at the start of the recovery condition—despite no evidence of any such overcompensation in gait measures. Similar perceptual after effects have been reported in studies using the split-belt paradigm: After being returned to normal walking, participants sometimes report feeling asymmetry in measures where no such asymmetry is present (Reisman et al., 2005).

Infants also showed evidence that the return to even leg lengths posed a challenge, in the form of increased gait disruptions. One possibility is that infants, like the adults, were upset by the abrupt change in the recovery condition. However, it is interesting to note that during the same trials midway through the recovery condition where we see a spike in gait disruptions, infants also slowed down and became asymmetrical in the opposite direction of our original perturbation (see Fig. 3A, B and D). These concurrent changes make it tempting to propose a second possibility: That infants experienced delayed after effects that caused them to overcompensate and misstep. However, given the high variability of infants' walking (and the final possibility that they were simply tired by the last condition) we cannot conclude with certainty that the increase in gait disruptions was due to overgeneralizing the compensatory mechanism learned in the previous conditions.

### *4.5. Conclusions: stability in a developmental context*

The stability of a system affects how it copes with a perturbation: More stable systems are more robust in the face of a challenge. Development affects the stability of a system: More mature systems are more stable. In the current study, we found a somewhat unexpected result: Skilled adult walkers failed to compensate for an asymmetrical perturbation to their walking, but novice infant walkers did compensate. Neither group showed strong evidence of after effects, meaning that they did not need time to unlearn a compensatory strategy. When we consider the perturbation in a developmental context in terms of the stability of participants' walking systems, short-lived compensation in infants makes sense. Infants' walking was sufficiently mature to detect the perturbation and to muster a compensatory response, but too fragile to tolerate the induced asymmetry. Thus, infants needed to compensate or risk falling. In contrast, adults could cope with the asymmetry without risking upset.

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