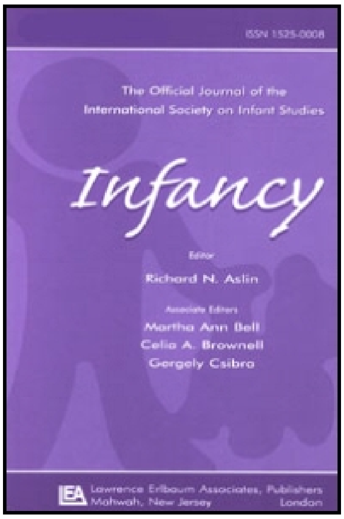

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Evidence of Early Strategies in Learning to Walk

Winona Snapp-Childs [a]; Daniela Corbetta [b]
[a] Integrative Neuroscience Program, Department of Health & Kinesiology, Purdue University, [b] Department of Psychology, University of Tennessee, Knoxville

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Evidence of Early Strategies in Learning to Walk

Winona Snapp-Childs
Integrative Neuroscience Program, Department of Health & Kinesiology
Purdue University

Daniela Corbetta
Department of Psychology
University of Tennessee, Knoxville

Learning to walk is a dynamic process requiring the fine coordination, assembly, and balancing of many body segments at once. For the young walker, coordinating all these behavioral levels may be quite daunting. In this study, we examine the whole-body strategies to which infants resort to produce their first independent steps and progress over the first months of walking experience. Six infants were followed weekly from the onset of independent upright locomotion for 8 weeks, and then every other week until 4 months of walking experience. The walking kinematics from the infants' earliest steps were cluster-analyzed and the infants were classified into 3 groups. Follow-up comparisons with kinematics recordings were used to quantify the infants' strategies more precisely and track how these early forms of walking evolved over time. Results revealed that in the first weeks of independent walking, 3 infants used a stepping strategy, 1 used a twisting strategy, and 2 used a falling strategy to move their body forward and perform their first unsupported steps. As the infants gained walking experience, their walking patterns became more similar. These findings indicate that infants discover different solutions to use their body and control their balance when beginning to walk. With time, infants adopt a more efficient solution that incorporates and integrates elements of the different strategies.

The emergence of independent upright locomotion in infancy is an important and memorable event. Walking provides a novel means to move around, it allows the

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Correspondence should be addressed to Daniela Corbetta, Department of Psychology, The University of Tennessee, Austin Peay Building, Knoxville, TN 37996. E-mail: dcorbett@utk.edu

child to interact with the environment in new ways, and it has been shown to influence and reorganize a myriad of other behaviors such as spatial understanding (Benson & Uzgiris, 1985; Clearfield, 2004), perception of affordances (Gibson et al., 1987), interactions between infant and caregiver (Biringen, Emde, Campos, & Appelbaum, 1995), and even other seemingly unrelated motor behaviors like reaching (Corbetta & Bojczyk, 2002).

For the young child, however, learning to walk is not an easy feat. Clark, Truly, and Phillips (1993) indicated that before beginning to walk, infants go through a period of "stiff leg" posture in which they seem "stuck" in a free upright standing position for extended periods of time. To walk, infants need to break this initially rigid posture. They need to figure out how to coordinate a large number of joints throughout their body while mastering the dynamic forces associated with stepping forward and maintaining equilibrium at the same time. This is a difficult and complex behavior that requires effort, time, and practice to be mastered. How do infants achieve such an exploit?

Previous research has shown that infants begin to walk by adopting temporary strategies to counteract their balance instabilities and step forward. For example, researchers have shown that novice walkers tend to adopt a wide base of support (Bril & Brenière, 1992), rotate their feet asymmetrically (Ledebt, van Wieringen, & Savelsbergh, 2004), and raise their arms to maintain balance (Ledebt, 2000). At the same time, to generate forward mobility and progress out of the stiff standing posture, infants raise their arms to help shift balance, create disequilibrium (Bril & Brenière, 1992; Ledebt, 2000), and produce trunk rotation and translation (Kubo & Ulrich, 2006a).

Learning to walk also involves the mastery of the dynamic interplay created between the successive destabilization and restabilization of the body while new steps are formed. This involves the integration of many behavioral levels beyond the arm motion, trunk rotation, and step width mentioned earlier. To walk and maintain balance, infants also need to figure out how to control the lateral and vertical forces associated with forward motion (Brenière & Bril, 1998), they need to develop functional coordination between legs and within leg segments (Clark & Phillips, 1993; Clark, Whitall, & Phillips, 1987) to maintain a regular gait cadence (Bril & Brenière, 1992).

Despite these difficult challenges in whole-body coordination and balance, infants make dramatic progress over time. Research has shown that within a few months, infants regularize their patterns of coordination between legs and within leg (Clark & Phillips, 1993; Clark et al., 1987), lower their arms (Corbetta & Bojczyk, 2002; Ledebt, 2000), and narrow the base of support (Bril & Brenière, 1992). Most of these changes occur within the first 4 to 5 months of walking experience. This is a period that Bril and Brenière (1992) called the *integration phase,* because this period is marked by a rapid postural integration of the multiple behavioral levels just described. This phase is followed by a second, more protracted *tun-*

ing phase during which infants fine tune their cadence and postural control of forces during walking over a 5-year period (Brenière & Bril, 1998).

The research reported here concentrates on the changes occurring in infant walking during the initial postural integration phase. Our overall goal is to gain insights into the kinds of strategies that infants adopt to move out of their "stiff leg" posture and generate their first steps. We ask how young walkers use their body to generate imbalance to move forward and at the same time control balance and not fall. We also ask how they progress over time. As already described, learning to walk is a complex, dynamic process, involving the coordination, assembly, and precise balancing of many body segments at once. Integrating all these behavioral levels at once can be a daunting task for inexperienced walkers; thus, they may initially resort to much simpler, less effective, transient motor solutions that allow them to step forward.

An example of the kind of strategies that young walkers might adopt during their first walking attempts was suggested by McCollum, Holroyd, and Castelfranco (1995). By means of mathematical modeling, these authors proposed three forms of early walking attempts in infants. In one form, *twisting,* infants generate torque or angular momentum from twisting their trunk sideways to produce steps. The back-and-forth lateral twisting of the trunk against a wide base of support allows the child to swing forward one leg at a time. This is a very stable form of walking because it generates little destabilizing forward momentum. In a second form, *stepping,* infants use a conservative strategy of taking small, discrete steps from a relatively stable base of support. These small steps are generated mainly by knee flexions and minimize trunk sway. As a result, this is also a fairly stable and balanced strategy that generates little forward momentum. In a third form, *falling,* infants use an energy exchange strategy to generate steps. Fallers create potential energy by leaning their body forward (as if falling) and launching themselves across the room. This is the most unstable strategy as it requires using the legs mainly to break the body's forward momentum and avoid falling. McCollum et al. (1995) contended that although mature and smooth walking requires a blend of all three strategies, infants are much more limited in the number of solutions they can use and may restrict their first attempts to walk to one of these strategies. With time and practice, however, infants will integrate twisting, stepping, and falling into their movement repertoires.

One goal of this study is to validate McCollum et al.'s (1995) stepping, twisting, or falling strategies during the earliest weeks of walking by analyzing the actual behavior of novice walkers by means of kinematics analyses. Do infants use one of these forms of walking to get out of their stiff standing posture and attempt their first steps? A second goal is to examine how these early forms of walking change over time. Are infants switching between forms as they gain walking experience or do they gradually incorporate elements of all three strategies into their walking patterns? To address these goals, we recorded kinematic data of the walking patterns of 6 infants who we followed longitudinally at close time intervals from the onset of independent locomotion until 4 months of walking experience. These recordings allowed us to replicate general findings from previous research on infant walking but also, and most important, identify the different whole-body strategies that infants use to begin to walk independently.

METHODS

Participants

Six infants (3 girls, 3 boys) participated in this experiment. All were recruited using the birth announcements published in the local newspaper. Parents were first sent a letter informing them about the study and a week later were called by phone to solicit their participation. These infants were part of a larger longitudinal study that began when they were 7 to 8 months old. Infants were followed every other week until they were able to stand alone and then every week until they were able to take three independent steps. From that time, we followed them for another 8 weeks, and then, every other week until they had 14 to 16 weeks of walking experience.

A seventh infant was also recruited, but dropped from the study after 3 weeks of independent walking because of reasons unrelated to the study. That infant's data are not included. One of the 6 infants included in the study (SB) has data for only the first 8 weeks of walking; she was too fussy to continue afterward. The other remaining infants completed the study but have occasional missing data due to illness or equipment problems. During the sessions, parents were present at all times. All infants were full term and White. They had no known motor impairments, birth difficulties, or inappropriate birth weights for gestational age. This study was approved by the Institutional Review Board at Purdue University.

Apparatus

Movement kinematics were collected at a sampling frequency of 60 Hz using two Northern Digital OPTOTRAK sensors. The sensors were placed on each side of the walking path at a 4 m distance from the path, providing a lateral view of each side of the infant during walking. Before data collection, the OPTOTRAK sensors were aligned to each other with a measurement error < 0.5 mm. A Sony Video 8 Handycam was placed about 4 m from the right side of the infant's starting position, providing a complementary lateral view of walking.

Infrared emitting diodes (IREDs) were placed bilaterally onto the participants' fifth metatarsal, lateral malleolus, knee joint, greater trochanter, wrist, elbow joint, and shoulder joint. Two IREDs were also attached to an infant headband that was placed on the infants' head to provide head position. These IREDs were positioned slightly above the ears.

Procedure

When the participants arrived at the laboratory, their clothing was removed and the IREDs were taped to the skin on the aforementioned anatomical landmarks using soft cloth hypoallergenic tape. The headbands were placed on the infant's heads and the infants were carried to the starting position at one end of the walking path by the parents. The parent, an experimenter, an attractive toy, or a combination thereof were placed 2.5 m away at the other end of the walking path to entice the child to walk about 10 times per session. After the walking trials, we collected anthropometric data including leg length, head circumference, foot length, and total height. In the first week of walking, ponderal index (1,000 * mass$^{1/3}$/ height) was calculated using height and body weight as measured from a force plate during a quiet standing trial before the walking trials.

Data Analysis

Gaps of missing data in the kinematics profiles smaller than one third of the sampling frequency (20 frames or 0.33 sec) were interpolated using a line-spline. Then, the kinematics data were filtered at 8 Hz using a double-pass, zero lag, second-order Butterworth filter. Only a portion of the trials or steps were usable for analysis; gait initiation and termination steps were excluded, as were the steps taken when falling. During the first week, we had an average of 32 steps (four usable trials) per infant but by the third week we had an average of 52 steps (seven usable trials) per infant and roughly maintained this number for the duration of the experiment. Finally, a custom-made computer program written in MATLAB was used to find the heel contacts of each foot from the ankle markers (lateral malleolus) and the following dependent variables were computed: step width (distance between the feet), knee flexion (maximum degree of flexion that occurred between two successive heel contacts), shoulder rotation (amplitude difference of the angle of the line connecting the shoulders between successive steps), and gait velocity (the distance covered divided by the time between two successive heel contacts).

These variables were chosen based on McCollum et al.'s (1995) descriptions of the dominant characteristics for each strategy. Recall that according to McCollum et al., to create steps, twisters twist the trunk, which allows them to swing the contralateral leg forward while steppers remain balanced and take discrete steps and fallers use gravity to launch themselves across the floor. Thus, if infants are stepping, then large degrees of knee flexion, narrow steps, and little shoulder rotation should be observed in their first attempts to walk. Large degrees of shoulder

TABLE 1
Body Dimensions for the First Week of Independent Walking

Infant	*Leg Length (cm)*	*Height (cm)*	*Weight (kg)*	*Ponderal Index (kg/cm^3)*	*Head Circumference (cm)*
SB	25.0	69.0	7.7	28.6	41.5
NE	28.0	74.0	10.5	29.6	49.0
EH	28.0	75.5	10.2	28.7	49.0
MW	29.0	78.5	14.1	30.8	47.0
LG	29.5	72.0	8.0	27.8	45.0
MH	32.5	77.0	11.2	29.1	47.5

rotation, low gait velocity, and broad step width providing a stable base of support should be observed in the twisters' first attempts to walk. Likewise, gait speed should be the highest in the fallers, with low levels of shoulder rotation and knee flexion.

A *k* means cluster analysis was performed in SPSS. In this analysis, individuals are classified into a specific number of groups (*k*) based on their characteristics. The characteristics entered in the analysis were the infants' standardized (*z* scores) step width, gait speed, shoulder rotation, and knee flexion averages for the first week of independent walking.[1] The number of clusters (*k*) was set at 3 based on the number of strategies outlined by McCollum et al. (1995).

Due to small sample size and nonnormal distributions, we assessed changes in walking strategy over time with nonparametric Kruskal–Wallis analyses of variance by ranks performed on all of the dependent measures. These tests were performed in blocks during the first month (Weeks 1–4), second month (Weeks 5–8), and 3rd month of independent walking (after 8 weeks).

RESULTS

Body Dimensions

Table 1 displays the body characteristics for each infant. Chubbiness is indicated by the Ponderal Index. Table 1 shows that our sample was within normal range.

Cluster Analysis

Table 2 displays the cluster membership and distance from cluster center for each infant and Figure 1 depicts the movement variables profiles of each cluster (a *z*

[1]For infant LG, we used data from the second week of walking because LG only produced three usable steps during the first week.

TABLE 2
Cluster Membership, Distance From Cluster Center and Classification

Infant	*Cluster No.*	*Distance*	*Classification*
EH	1	0.48	Stepper
LG	1	0.62	Stepper
NE	1	0.28	Stepper
MW	2	0.00	Twister
SB	3	1.26	Faller
MH	3	1.26	Faller

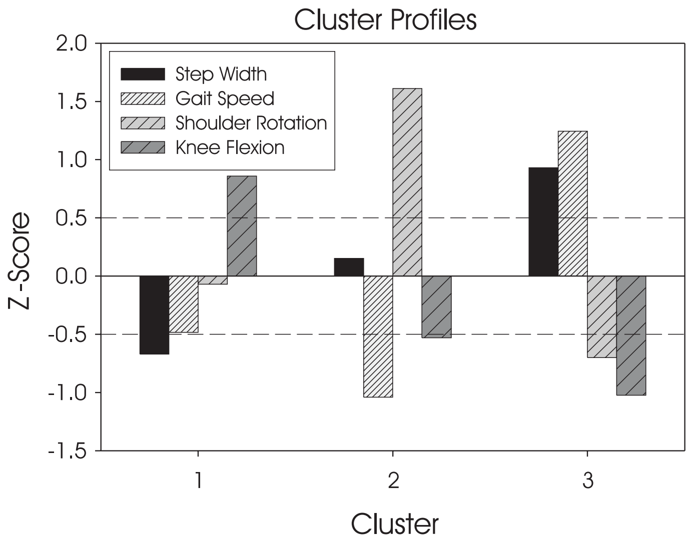

FIGURE 1 Cluster profiles for the first week of independent walking.

score < –0.5 indicates that cluster members have low scores for a variable; a *z* score > 0.5 indicates that cluster members have high scores for a variable). Infants EH, LG, and NE were grouped together (Cluster 1) with a variable profile of narrow steps with high knee flexion; this profile is consistent with the stepping strategy outlined by McCollum et al. (1995). Infant MW was in his own group (Cluster 2) and had a profile of slow steps with high shoulder rotation and little knee flexion; this profile is consistent with McCollum et al.'s twisting strategy. Infants SB and MH were grouped together (Cluster 3) and shared the profile of wide, fast steps with little shoulder rotation or knee flexion; this profile is consistent with McCollum et al.'s falling strategy.

Changes in Knee Flexion

Figure 2a depicts the average maximum knee flexion for the steppers, twister, and fallers by week and Figure 2b shows the same data for each individual infant. As evidenced by the cluster analysis, the steppers displayed great knee flexion on Week 1, whereas the twister and fallers had low knee flexion. The statistical analyses performed over the first month (first 4 weeks) of independent walking revealed significant differences among the steppers, twister, and fallers, $\chi^2 = 7.8520$, $p = .0197$; the steppers continued to produce the greatest knee flexion over the subsequent weeks, followed by the fallers and the twister. However, by the second month (second 4 weeks) of independent walking, differences among groups disappeared: second month, $\chi^2 = 0.3430$, $p = .8424$; third month, $\chi^2 = 1.6898$, $p = .4296$). By then, the fallers and the twister had increased knee flexion to a level comparable to the steppers.

Changes in Step Width

Step width averaged by groups (steppers, twister, or fallers) and by week is shown in Figure 3a, and Figure 3b depicts the same data for each individual infant. According to the cluster analysis performed in the first week of independent walking, the steppers had narrow step width, whereas the fallers had wide step width. The statistical analyses over the first month of independent walking revealed a significant difference between groups, $\chi^2 = 6.1324$, $p = .0466$; the twister had the widest steps, followed by the fallers and the steppers. This pattern of results was roughly maintained throughout the duration of the study: second month, $\chi^2 = 5.9420$, $p = .0513$; third month, $\chi^2 = 6.3720$, $p = .0413$, with the twister maintaining the widest steps, even though all infants decreased step width over time: regression analysis, $F(1, 57) = 57.74$, $p < .0001$; step width = 20.50 cm – 0.48 cm * walking week).

Changes in Shoulder Rotation

Figure 4a depicts the maximum shoulder rotation by group and by week and Figure 4b shows the same data for each individual. According to the cluster analysis performed for the first week of independent walking, shoulder rotation was high for the twister and low for the fallers. Statistical analyses reveal that during the first month of independent walking the twister had the highest levels of shoulder rotation, but this result was not significant at any time during the study: first month, $\chi^2 = 2.9429$, $p = .2296$; second month, $\chi^2 = 2.6577$, $p = .2648$; third month, $\chi^2 = 2.3981$, $p = .3015$. Overall, shoulder rotation tended to decrease over time: regression analysis, $F(1, 57) = 4.89$, $p = .0310$; shoulder rotation = 16.61° –0.27° * walking week, with the most dramatic decrease occurring from Week 1 to Week 2 of independent walking in the twister.

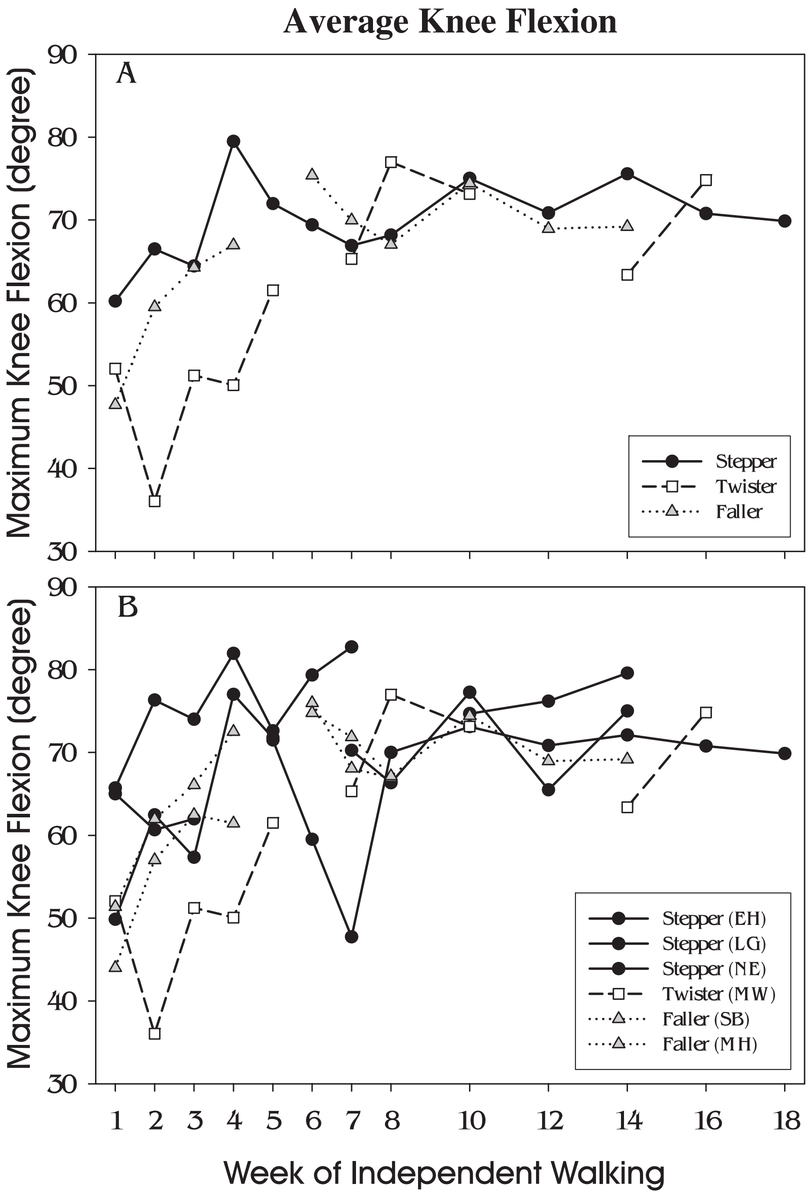

FIGURE 2 (a) Average maximum knee flexion by groups and by weeks. (b) Average maximum knee flexion by infants and by weeks.

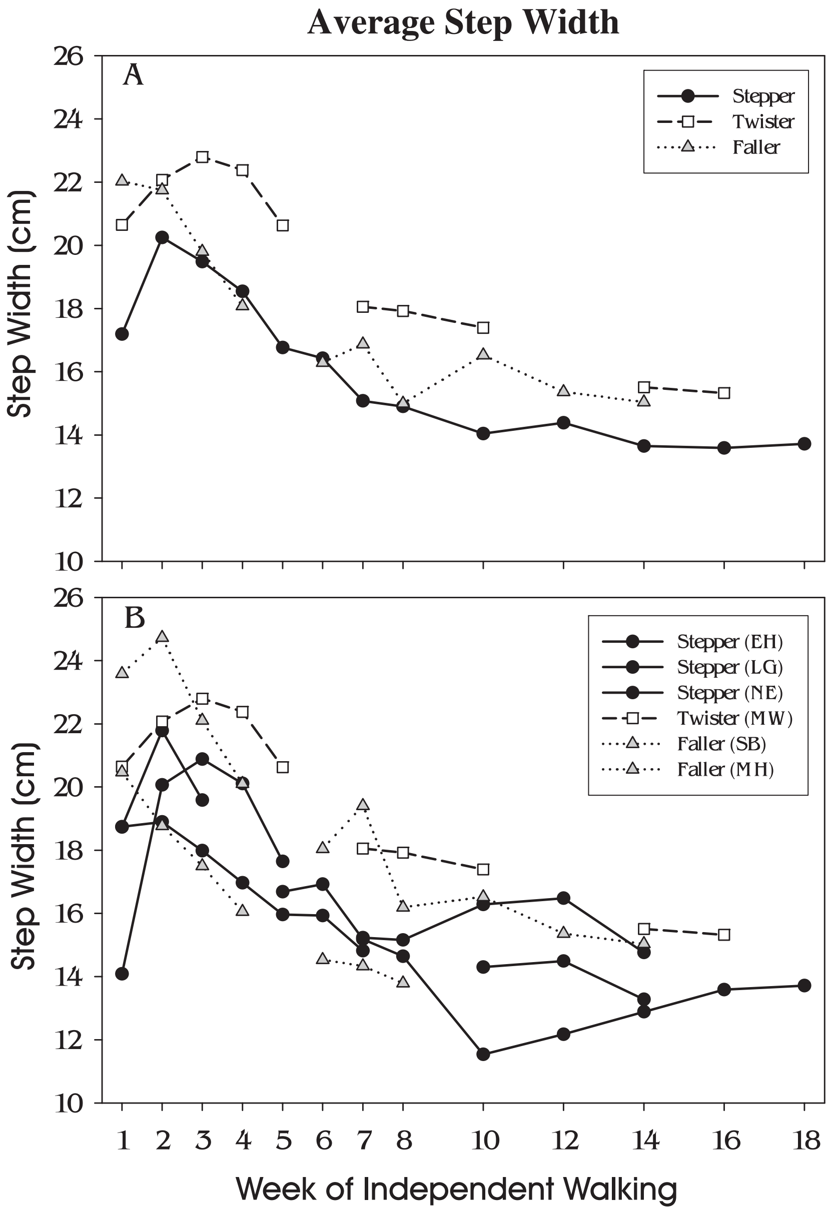

FIGURE 3 (a) Average step width by groups and by weeks. (b) Average step width by infants and by weeks.

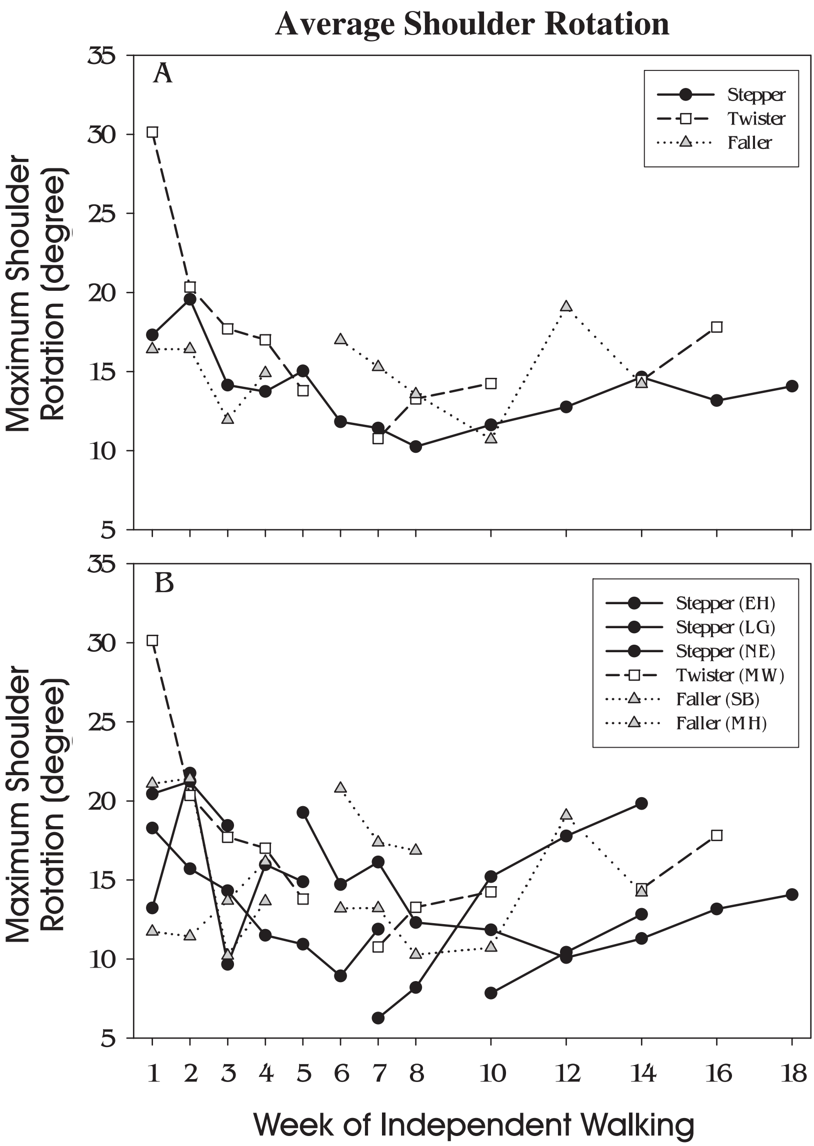

FIGURE 4 (a) Average maximum shoulder rotation by groups and by weeks. (b) Average maximum shoulder rotation by infants and by weeks.

Changes in Gait Speed

Figure 5a depicts the average gait speed by groups and Figure 5b presents the same data by individual. According to the cluster analysis performed for the first week of independent walking, gait speed was high for the fallers and low for the twister. Statistical analyses performed in the first month of independent walking revealed significant group differences in gait speed, $\chi^2 = 10.8387$, $p = .0044$; the fallers had the fastest steps, followed by the steppers and the twister. However, during the second month of independent walking, differences between groups began to disappear: second month, $\chi^2 = 5.9212$, $p = .0518$; third month, $\chi^2 = 3.5960$, $p = .1656$. Over time, gait speed increased significantly in all infants: regression analysis, $F(1, 57) = 115.11$, $p < .0001$; gait speed = 0.25 m/sec + 0.03 m/sec * walking week).

DISCUSSION

These results are consistent with the forms of walking proposed by McCollum et al. (1995). Stepping, twisting, and falling are patterns of walking that infants use to generate their first independent steps. Specifically, our data revealed that in their first week of independent walking, the steppers produced on average the greatest knee flexions and the narrowest steps, but they also maintained low shoulder rotation and took slower steps to control balance. The twister created ample shoulder rotation to shift the contralateral leg forward, but did this while adopting a wide base of support to maintain balance. Because steps were generated from winding the trunk sideways, twisting also produced low knee flexion and slow steps. The fallers, finally, took the quickest steps in their forward motion, but performed them with low shoulder rotation, low knee flexion, and a wide base of support.

All three forms appear to represent some type of compromise between the processes of generating steps and maintaining balance at the same time. As framed earlier, learning to walk is a complex and difficult dynamic process involving the coordination, assembly, and precise balancing of many body segments at once. Controlling all those levels at once is a daunting task for the inexperienced walker. Our data reveal that each of the whole-body strategies described reflects a simple, transient motor solution that infants can use to move out of their initially rigid standing posture and step forward, even though they might not be the most efficient. As observed, some forms of walking simplified the task of stepping by limiting knee flexion and shoulder rotation, others compensated body destabilization in gait speed and shoulder rotation by increasing the base of support, and if infants adopted a narrow base of support and flexed knees, they controlled balance by reducing shoulder rotation and gait speed. We limited our work to the forms outlined

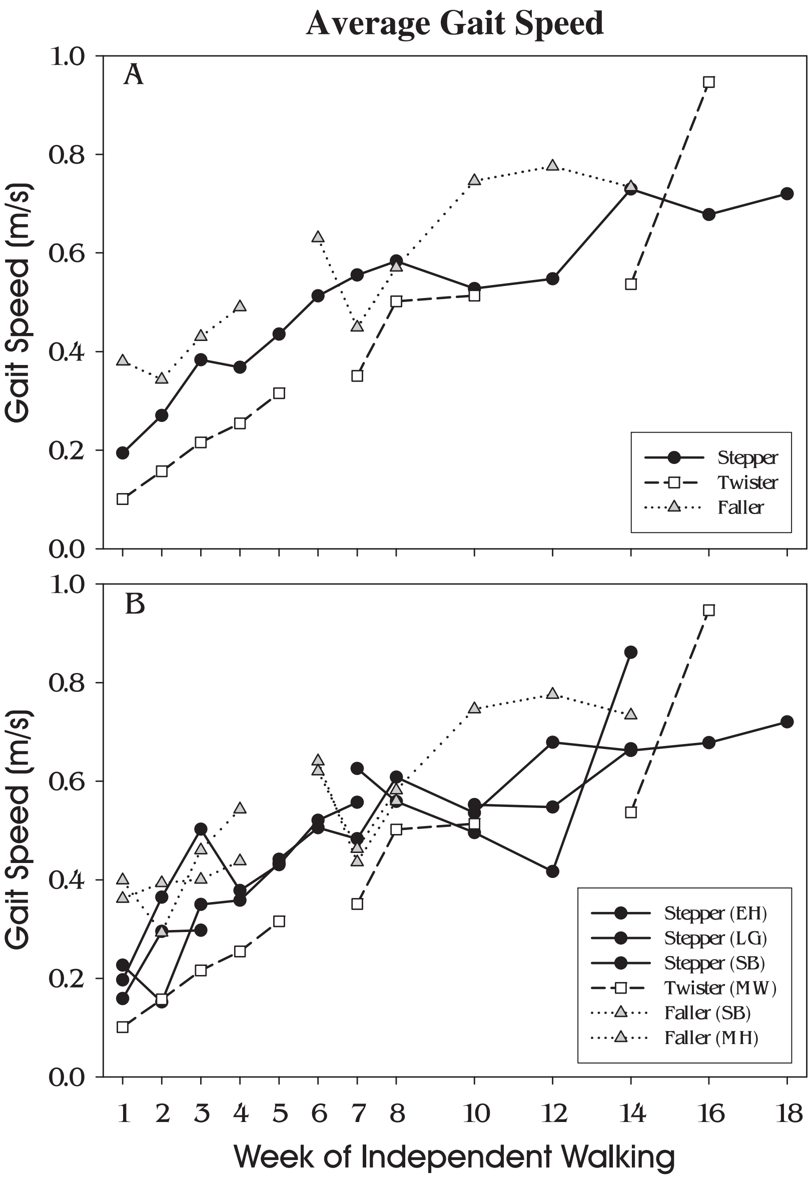

FIGURE 5 (a) Average gait speed by groups and by weeks. (b) Average gait speed by infants and by weeks.

by McCollum et al. (1995), primarily because of our small sample, but study of a larger sample might reveal other, mixed forms of early walking.

The developmental changes that occurred in the following weeks provided further evidence of the postural integration process described by Bril and Brenière (1992) and McCollum et al. (1995). Our data showed that group differences on the kinematics variables disappeared within the first month of independent walking as infants integrated and modulated their movement components into their walking pattern. The twister and fallers, for example, who were more likely to maintain their legs extended at first, increased knee flexion in the following weeks. Similarly, the twister reduced shoulder rotation after the first session and progressively narrowed the base of support. Our data clearly showed that all kinematics variables converged toward similar values for all infants before the end of the study. These findings support the idea that, within the integration phase, infants incorporate the multiple behavioral elements (Bril & Brenière, 1992) and mechanical strategies (McCollum et al., 1995) necessary for more efficient walking (see also Clark & Phillips, 1993; Clark et al., 1987). These changes also reflect the fact that infants likely become more effective at using the pendulum properties of body segments to generate steps and control balance at the same time (Kubo & Ulrich, 2006b).

From this work it is not clear why infants adopted one strategy over another. At this point, we can only speculate about the reasons that might have led to those choices. From a dynamic systems perspective, behavioral patterns emerge because of tensions between an infant's own constraints, motor history, energy level, and the demands of the task at hand (Corbetta, Thelen, & Johnson, 2000; Thelen et al., 1993; Thelen & Smith, 1994). It is possible that body characteristics at walking onset play a role. Chubbier infants, like MW, for instance, might have more difficulty bending their knees and lifting their legs against gravity. Thus, these infants may be more likely to adopt twisting or falling strategies rather than a stepping strategy. It is also possible that infants, who are relatively inexperienced at balancing their body upright before the onset of walking, are more likely to adopt a falling strategy because this strategy does not require much lateral control. Alternately, infants who bring good upright balance control into the task when beginning to walk may more readily adopt a stepping strategy. Future studies examining the control of upright posture prior to the onset of independent upright locomotion would shed some light on this question.

It is also possible that other, nonmotor factors play a role in the infants' strategy preferences. For example, in the development of reaching, it has been shown that infants' intrinsic levels of energy and activity readily affected the speed properties and joint organization of the arms when aiming for a toy (Thelen et al., 1993; Thelen, Corbetta, & Spencer, 1996). Likewise, temperaments and personalities could influence the infants' initial forms of walking. In this study, the 2 infants who adopted the falling strategy were also the infants with the most excitable and extraverted personalities. The calmer and more introverted infants adopted the stepping and twisting strategies.

In sum, this study revealed that infants begin to perform their first steps using different types of strategies involving distinct whole-body organizations. These strategies may reflect a best initial compromise between the balance requirements of the task, the coordination complexity of the behavior, and the infants' own body constraints. Within just a few weeks of walking, however, infants converge onto a set of common movement parameters and begin to use their bodies more skillfully.

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