Early Stage of Walking: Development of Control in Mediolateral and Anteroposterior Directions

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ABSTRACT. The authors examined the changes in bipedal gait of toddlers in the anteroposterior (AP) and mediolateral (ML) directions, as a set, at the onset of independent gait and 1 month after onset. Two groups with distinctly different dynamic resources were studied: 8 toddlers with typical development (TD) and 8 toddlers with Down syndrome (DS). Three-dimensional kinematic data were collected, and gait parameters, such as walking speed, stride length, and stride frequency, as well as the ratio of exchange between potential energy and kinetic energy of the center of mass (COM), were calculated. Displacement of the COM in the AP and ML directions were also analyzed. For some gait variables, toddlers with DS seemed to show more mature values at walking onset than their peers with TD. Those group differences reversed and increased by Visit 2. When the authors considered the motion of the COM of the system, it became clear that the qualitative differences between those groups were characterized primarily by constraints in the ML direction. The authors propose that establishment of coupling between AP and ML oscillations is a key component for the emergence of independent bipedal walking for both populations.

Key words: dynamic strategies, mediolateral control, stability constraints, walking onset

When walking overground at their preferred speed, preadolescents with typical development (TD) and those with Down syndrome (DS) do not significantly differ from each other in gait parameters such as speed, stride frequency, and stride length after researchers have normalized those parameters to the participants' body size (Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). Overground walking is a well-practiced activity by the age of 8–10 years, and therefore experiences and adaptation may minimize inherent differences between those two groups.

In fact, Ulrich et al. (2004) also showed that when those groups are challenged with additional constraints (e.g., walking on treadmill vs. overground), significant differences emerge. For example, preadolescents with DS

showed significantly shorter step length and higher stride frequency than did their TD peers, even after those variables were normalized to their body size.

Although the groups showed similar performances during overground walking, there were clear differences in terms of their chronological age at onset of walking. Toddlers with TD typically walk around 12 months of age, whereas toddlers with DS require approximately another year (Henderson, 1986). Why do toddlers with DS require another year? How do they move at the onset of independent walking, and does their manner of walking reflect different control strategies?

One hypothesis is that bipedal walking is a universal skill composed of intrinsic neural organizations and supported by the development of sufficient strength and balance control so that functional behavior can be generated. Therefore, both groups would have the same intrinsic neural mechanisms that require the development and support of muscle strength and balance. The walking patterns that emerge should be organized quite similarly at the onset of bipedal gait. In that sense, independent gait in toddlers with DS may be regarded as a delayed but not uniquely different version of that generated by toddlers with TD. Alternatively, even in a skill so universal, pattern generation may emerge in unique ways, with overlapping or identical constraints but with unique contributions of each. Each group may achieve the same goal, bipedal locomotion, while using their different dynamic resources. They therefore would produce qualitatively different walking patterns, even at the onset of that demanding behavior.

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There is a clue that toddlers with TD may use a different strategy to walk than toddlers with DS at the onset of walking, because a few significant differences persist even after years of practice. By age 8–10, gait parameters of those populations in the anteroposterior (AP) direction, such as walking speed and stride length, are not significantly different, but the normalized step width of preadolescents with DS, a gait parameter in the mediolateral (ML) direction, is significantly wider than that of their TD peers (Ulrich et al., 2004). In a simulation study of passive walkers and in subsequent *in vivo* studies, scientists have argued that control requires more active control in the ML than in the AP direction (Bauby & Kuo, 2000; Kuo, 1999). In developmental studies of gait, improvements in ML stability in toddlers with TD coincide with the emergence of independent walking (Assaiante, Thomachot, & Aurenty, 1993; Ledebt, Bril, & Wiener-Vacher, 1995; Yaguramaki & Kimura, 2002).

Although many aspects of gait continue to develop over several years, there is some indication that the very early organization of bipedal locomotion is qualitatively different from that produced even a few weeks or months later. Bril and Brenière (1992) observed gait parameters for 2 years after the onset of independent walking. All gait variables in their study showed nonlinear but yet monotonic change over time, with two exceptions. Step frequency was low for the first month, showed an abrupt increase in the 2nd month, and was followed by a monotonic decrease thereafter. Lateral acceleration of the center of mass (COM) was constant in the first 2 months and decreased monotonically thereafter. Step width changed as a function of walking speed only in the first 2 months. Those findings seem to indicate the emergence of transition in that special period of gait development.

Our goal in this study was to investigate the very early control of independent walking, immediately after walking onset and 1 month later. We analyzed kinetic and kinematic changes in both the AP and ML directions, as well as the coupling between oscillations in those two directions. We compared the onset and developmental paths of two populations with distinct dynamic resources, that is, toddlers with TD and those with DS. By examining the solutions discovered by those toddlers, we expected to gain insight into the constraints affecting human bipedal gait patterns.

Method

Participants

Eight toddlers with TD and 8 toddlers with DS participated in the study. They visited the Motor Development Laboratory in the Division of Kinesiology at the University of Michigan when their parents reported that they had become able to perform three to six consecutive independent steps (i.e., first visit). We identified families in advance of that point and maintained phone contact as walk onset approached. We confirmed parents' reports when the families arrived at the laboratory. The second visit occurred

approximately 1 month later. All toddlers were part of a larger longitudinal study in which participants were tested several additional times at later dates. The Institutional Review Board of the University of Michigan approved this study; parents or guardians reviewed and signed informed consent forms before their child participated in the study.

Procedure

On arrival at the laboratory, toddlers were given time to acclimate by playing with toys and the research team members. We subsequently removed all clothing except diapers and attached 2-cm-diameter reflective markers bilaterally to the following body landmarks: temporomandibular joints, shoulders, elbows, greater trochanters, knees, midshanks, heels, and third metacarpophalangeal joints. Toddlers then walked over the carpeted floor to parents, repeating trials until we had a minimum of four passes in which they were able to remain upright and forward facing to produce at least 3–6 steps per pass (Visit 1) and 10–15 steps per pass (Visit 2). Toddlers walked through a calibrated viewing volume ($2.90 \times 1.40 \times 1.55$ m) established with a six-camera Peak Motus real-time system (Peak Performance Technologies, Centennial, CO) with which we collected three-dimensional positions of markers at 60 Hz. We set the acceptable summed measurement error of the calibration at $< .008$ m for each test session. The *x*-, *y*-, and *z*-axes of the floor-fixed coordinate system coincided, respectively, with the AP direction, the ML direction of the walkway, and the direction perpendicular to the floor. At the end of each test session, we took a series of anthropometric measurements, including total body height and weight; arm, forearm, thigh, shank, and foot lengths; foot width; and thigh and shank circumferences. Mean numbers of total strides extracted for each participant were 11.9 and 29.3 for Visit 1 and Visit 2, respectively.

Data Reduction and Analysis

We identified initial contact of the foot (touchdown) on the basis of the acceleration profile of the heel marker, using an algorithm developed by Hreljac and Marshall (2000). We obtained stride length and stride frequency from distance and duration between two consecutive heel contacts of the ipsilateral foot. We obtained step width as the distance between a line connecting two consecutive heel contacts of the ipsilateral foot and a heel contact of the contralateral foot.

We calculated the COM of the whole body on the basis of the 16-segment model given by the regression equation of Sun and Jensen (1994), with the following modifications. We assumed that the COM of the neck segment was the midpoint between the shoulder markers. We set the mass of the hands to zero; we operationalized the mass of the forearm so that it was located at the elbow joint. In addition, we calculated mean walking speed as the mean displacement of the COM per corresponding walking period.

To minimize the effect of anthropometric differences between the groups, we converted gait variables into dimensionless values, as follows:

$$\left. \begin{aligned} \hat{v} &= \frac{v}{\sqrt{gl_o}} \\ \hat{l}_{\text{STRIDE}} &= \frac{l_{\text{STRIDE}}}{l_o} \\ \hat{f}_{\text{STRIDE}} &= f_{\text{STRIDE}} / \sqrt{gl_o} \\ \hat{w}_{\text{STEP}} &= w_{\text{STEP}} / w_{\text{HIPS}} \end{aligned} \right\}, \quad (1)$$

where $\hat{v}$, $\hat{l}_{\text{STRIDE}}$, $\hat{f}_{\text{STRIDE}}$, and $\hat{w}_{\text{STEP}}$ are converted values for speed (v), stride length (l_{STRIDE}), stride frequency (f_{STRIDE}), and step width (w_{STEP}); l_o is leg length; and w_{HIPS} is the distance between the two hip markers.

During bipedal walking in adults, the behavior of the COM in the sagittal plane is similar to that of an inverted pendulum, and one can therefore assume that a significant amount of energy is conserved between potential energy of the COM (EP) and kinetic energy (EK_{TOT}), as is given in the following equations:

$$\left. \begin{aligned} EP &= Mgh_{\text{COM}} \\ EK_{\text{TOT}} &= \frac{1}{2}M(V_x^2 + V_y^2 + V_z^2) \end{aligned} \right\}, \quad (2)$$

where M is mass of the whole body, g is the gravity constant, h_{COM} is height of the COM from the floor, and $v_{i=x,y,z}$ is the velocity of the COM in each direction (Cavagna, Heglund, & Taylor, 1977). In developmental studies of gait, the degree to which individuals use the inverted pendulum mechanism has been identified as an indicator of gait maturation (Halleman, Aerts, Otten, De Deyn & De Clercq, 2004; Ivanenko, Dominici, Cappellini, Dan, Cheron, & Lacquaniti, 2004). One indicator of how well that mechanism is used during walking is the recovery value (R_1), which is given by the following equation (Halleman et al.):

$$R_1 = \frac{\Delta^+ EP + \Delta^+ EK_{\text{TOT}} - \Delta^+ E_{\text{TOT}}}{\Delta^+ EP + \Delta^+ EK_{\text{TOT}}}, \quad (3)$$

where E_{TOT} is the sum of EP and EK_{TOT} , and Δ^+ indicates the positive increment (or gain) of each type of energy: kinetic and potential. In addition, to capture specifically the conservation from potential energy to forward kinetic energy, we calculated another recovery value (R_2), given by the following equation (Ivanenko et al., 2004) for this study:

$$R_2 = \frac{\Delta^+ EP + \Delta^+ EK_x - \Delta^+ E'_{\text{TOT}}}{\Delta^+ EP + \Delta^+ EK_x}, \quad (4)$$

where $EK_{i=x,y,z}$ is $(1/2)MV_i^2$ and E'_{TOT} is a sum of EP and EK_x . In addition, we calculated the mean ratio of kinetic energy in each direction (i.e., EK_x , EK_y , and EK_z) with respect to total kinetic energy (EK_{TOT}) and expressed them as rEK_x , rEK_y , and rEK_z , respectively.

To capture the kinematic change in trajectory of the COM across the toddlers' two visits, we calculated a ratio

of the displacement of COM ($r\text{COM}_{\text{AMP}}$) in the AP direction (COM_x) relative to that in the ML direction (COM_y) in each stride. We selected the midpoint of both hip markers to represent the pelvis; ML displacement of that point is presented herein as PELVIS_y . Displacement of the COM and pelvis were also converted into dimensionless values, as follows:

$$\left. \begin{aligned} n\text{COM}_i &= \frac{\text{COM}_i}{l_o} \\ n\text{PELVIS}_i &= \frac{\text{PELVIS}_i}{l_o} \end{aligned} \right\}_{i=x,y,z}. \quad (5)$$

Because of the mechanical coupling, the frequency of the body's oscillation in the ML direction must coincide with that in the AP direction during bipedal walking. One may model the mechanism of oscillation in the ML direction as a compound inverted pendulum (e.g., Donelan, Kram, & Kuo, 2001), and we hypothesized that the frequency of ML oscillation (and therefore that of AP oscillation) is mainly a function of the amplitude of ML oscillation. We performed multiple regression analysis with R^2 selection (one predictor in the model), with stride frequency as a criterion variable, and with amplitude of the COM, pelvis displacement, as well as step width as predictors.

Statistics

For age, height, and weight comparisons between the groups at Visit 1, we used a one-way analysis of variance (ANOVA). For most other dependent variables, we used a 2 (Group) $\times$ 2 (Visit) ANOVA with repeated measures on visit. When the Group $\times$ Visit interaction was significant, we tested the effect of group within each level of visits as well as the effect of visits within each level of group (i.e., simple effect) as a post hoc, least squares means analysis of cell differences. We set the level of significance at .05.

Results

Anthropometric Measurement

As expected, new walkers with DS were significantly different from those with TD in age and anthropometric measurements (Table 1). At Visit 1, toddlers with DS were older (117 ± 29.0 weeks) than those with TD (59.3 ± 9.5 weeks), $F(1, 14) = 28.7$, $p < .001$. Toddlers with DS were significantly taller, $F(1, 14) = 11.4$, $p = .0045$, and the main effect of visit was significant, $F(1, 14) = 30.8$, $p < .0001$. Also, toddlers with DS were significantly heavier than those with TD, $F(1, 14) = 7.10$, $p = .0185$, and the main effect of visit was significant, $F(1, 14) = 9.48$, $p = .0082$. The Group $\times$ Visit interaction effects were not significant for either height or weight.

Gait Variables

With respect to normalized walking speed, the main effect of visit and the Group $\times$ Visit interaction effect were signifi-

cant, $F(1, 14) = 41.25$, $p < .0001$, and $F(1, 14) = 7.64$, $p = .0152$, respectively. The group main effect was not significant. Although normalized speed in Visit 1 between the two groups was not significantly different, children with TD walked significantly faster than those with DS in Visit 2, $F(1, 14) = 6.20$, $p = .0260$. Increases in normalized walking speed between the two visits were significant for both groups, $F(1, 14) = 42.20$, $p < .0001$, and $F(1, 14) = 6.69$, $p = .0215$, respectively, for toddlers with TD and those with DS.

Normalized stride length by group and visit, plotted as a function of normalized speed, is shown in Figure 1A. The main effect of visit and the Group $\times$ Visit interaction effect were significant, $F(1, 14) = 37.87$, $p < .0001$, and $F(1, 14) = 5.58$, $p = .0332$, respectively. The group effect was not significant. Although the difference between the two groups in Visit 1 was not significant, toddlers with TD showed significantly longer stride length than those with DS in Visit 2, $F(1, 14) = 8.78$, $p = .0103$. The increases in normalized stride length between the two visits were significant for both toddlers with TD and those with DS, $F(1, 14) = 36.26$, $p < .0001$, and $F(1, 14) = 7.19$, $p = .0179$, respectively.

In Figure 1B, we illustrate normalized stride frequency by group and visit, plotted as a function of normalized speed. Both the main effects and the interaction effect were significant, $F(1, 14) = 23.59$, 11.40 , and 4.94 , $ps = .0003$, $.045$, and $.0433$, respectively, for visit, group, and the Group $\times$ Visit interaction. The difference between groups was significant only in Visit 1, $F(1, 14) = 17.88$, $p = .0008$; toddlers with DS had a higher stride frequency. Toddlers with TD showed a significant increase in normalized stride frequency between the two visits, $F(1, 14) = 33.89$, $p < .0001$; toddlers with DS did not.

TABLE 1. Anthropometric Data and Normalized Walking Speed (Mean $\pm$ Standard Deviation)

Group	Visit			
	1		2	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
<i>Height (m)</i>				
TD	0.72	0.03	0.74	0.04
DS	0.80	0.05	0.82	0.05
<i>Weight (kg)</i>				
TD	9.8	0.7	10.2	0.7
DS	11.4	1.5	11.5	1.5
<i>Normalized walking speed</i>				
TD	0.13	0.06	0.37	0.07
DS	0.18	0.08	0.28	0.12

Note. TD = toddlers with typical development; DS = toddlers with Down syndrome.

With respect to normalized step width ($\hat{w}_{STEP}$), the main effect of visit was not significant. The main effect of group approached statistical significance, $F(1, 14) = 4.50$, $p < .0521$. The interaction effect was not significant (Figure 1C).

Recovery Values (1 and 2) and Energy Ratio

Our results suggested that Recovery Value 2 (R_2), which reflected the conversion of EP to forward EK , could differentiate between the groups more effectively than Recovery Value 1 (R_1), which includes EP dissipated among the x , y , and z directions. For R_1 , only the main effect of visit was significant, $F(1, 14) = 4.78$, $p = .0462$ (Figure 2A). With respect to R_2 , the main effect of visit and the interaction effects were significant, $F(1, 14) = 15.07$, $p = .0017$, and $F(1, 14) = 8.13$, $p = .0128$, for visit and Group $\times$ Visit, respectively. The increase in R_2 value was significant only in toddlers with TD, $F(1, 14) = 22.67$, $p = .0003$, and was significantly higher in Visit 2 for toddlers with TD than for those with DS, $F(1, 14) = 5.89$, $p = .0293$ (Figure 2B).

The changes in the ratio of the two components of kinetic energy (rEK_X and rEK_Y) over the two visits are shown in Figure 2C. For rEK_X , both the main effect of visit and the interaction effect were significant, $F(1, 14) = 37.80$, $p < .0001$, and $F(1, 14) = 10.74$, $p = .00455$, respectively. Post hoc analyses revealed that toddlers with DS showed significantly higher rEK_X than TD peers in Visit 1, $F(1, 14) = 5.96$, $p = .0286$, but that relationship was reversed in Visit 2, $F(1, 14) = 4.82$, $p = .0456$. The increase within group over visits for toddlers with TD was significant, $F(1, 14) = 44.42$, $p < .0001$, but toddlers with DS did not show a significant increase.

With respect to rEK_Y , the main effect of visit and the Group $\times$ Visit interaction were significant, $F(1, 14) = 32.39$, $p < .0001$, and $F(1, 14) = 9.10$, $p = .0092$, respectively. The main effect of group was not significant. The groups were significantly different in Visit 1, $F(1, 14) = 5.87$, $p = .0295$, but not in Visit 2. Toddlers with TD showed a significant decrease by Visit 2, $F(1, 14) = 37.91$, $p < .0001$, but toddlers with DS did not change significantly. During initial walking, toddlers with TD showed rEK_Y values as high as or greater than 30% of EK_{TOT} (Figure 2C).

For rEK_Z , the main effect of visit and the Visit $\times$ Group interaction effect were significant, $F(1, 14) = 24.75$, $p = .0002$, and $F(1, 14) = 4.96$, $p = .0429$, respectively. The main effect of group was not significant. The difference between the two groups reached significance only in Visit 2, $F(1, 14) = 11.82$, $p = .0040$. A significant decrease in rEK_Z was observed in toddlers with TD, $F(1, 14) = 25.93$, $p = .0002$, but not in toddlers with DS. The mean value of rEK_Z was small throughout, remaining less than 5% across visits and groups, and was therefore not included in Figure 2C.

Kinematic Changes in COM

Both the main effect of visit and the interaction effect, Visit $\times$ Group, were significant for $rCOM_{AMP}$, $F(1, 14) = 35.96$, $p < .0001$, and $F(1, 14) = 14.63$, $p = .0019$, respec-

FIGURE 1. Changes in gait parameters of typically developing toddlers (TD) and those with Down syndrome (DS) over two visits. Vertical error bars indicate 1 standard deviation (SD). Horizontal error bars indicate SD of normalized walking speed. (A) Normalized stride length, (B) normalized stride frequency, and (C) normalized step width.

FIGURE 2. Changes in energy use of typically developing toddlers (TD) and toddlers with Down syndrome (DS) over two visits. **A.** Recovery Value 1 indicates the ratio of exchange between potential energy and a sum of kinetic energy in three directions ($E_{K_{TOT}}$) of the center of mass (COM). **B.** Recovery Value 2 indicates the ratio of exchange between potential energy and the forward kinetic energy of the COM. **C.** Changes in the ratio of the anteroposterior component of kinetic energy (rEK_X) and the mediolateral component of kinetic energy (rEK_Y) with respect to E_{TOT} .

tively. The main effect of group was not significant. In Visit 1, toddlers with DS showed a significantly lower $rCOM_{AMP}$ value than toddlers with TD, $F(1, 14) = 12.70$, $p = .0079$, but that difference became nonsignificant by Visit 2. The decreases in $rCOM_{AMP}$ observed between those two visits were significant only for toddlers with TD, $F(1, 14) = 12.70$, $p < .0001$, but not for toddlers with DS (Figure 3A).

The main effect of visit and the interaction effect, Visit $\times$ Group, were significant for $nCOM_Y$, $F(1, 14) = 9.91$, $p = .0090$, and $F(1, 14) = 12.50$, $p = .0033$, respectively. The main effect of group was not significant. In Visit 1, toddlers with DS showed significantly lower $nCOM_Y$ values than their TD peers, $F(1, 14) = 19.68$, $p = .0006$, but that difference disappeared by Visit 2. The decrease in $nCOM_Y$ observed between two visits was significant only for toddlers with TD, $F(1, 14) = 21.57$, $p = .0004$ (Figure 3B).

Predictors of Stride Frequency

Multiple regression analysis, using the R^2 selection method (with one predictor in the model), revealed that R^2 for $nCOM_Y$ and $nPELVIS_Y$ as the predictor of $\hat{f}_{STRIDE}$ were .4620 and .3663, respectively, whereas R^2 for $\hat{w}_{STEP}$ was .0314. The correlation coefficient between $nCOM_Y$ and $nPELVIS_Y$ was .97 ($p < .001$); the correlation coefficient between $nCOM_Y$ and $\hat{w}_{STEP}$ was .29 and was not significant.

Discussion

In this study, we observed the very early stages of the onset of independent bipedal gait. In our analyses, we specifically focused on the kinematic and kinetic changes in gait in the AP and ML directions, as a set. Within a month after the onset of independent gait, two populations with different dynamic resources showed significant interaction effects between group and visit. By examining the different developmental paths of two populations observed in a short period of time, we believe we have gained valuable insight into the constraints affecting and the solutions discovered as humans generate early bipedal gait patterns.

Comparison of Performance Between Toddlers With TD and Those With DS

Our results suggested that when toddlers with DS start walking independently (i.e., Visit 1 in this study), several variables seem to indicate that their walking performance is as skillful or even more advanced than that of toddlers with TD. For example, their normalized speed and normalized stride length were at least as good as, if not better than, that of their peers with TD. With respect to Recovery Values 1 and 2, toddlers with DS had a tendency to show higher values, suggesting that they used their system like an inverted pendulum mechanism as effectively as, or more effectively than, those with TD at the onset of bipedal gait. In addition,

a higher rEK_X value suggests that toddlers with DS are better able to constrain the kinetic energy of their COM to the AP direction. Their lower $rCOM_{AMP}$ suggests that they also could move their COM forward with less displacement of the COM in the ML direction than could their TD peers. That is, they produced less wasted motion.

However, the results of normalized stride frequency indicated that the toddlers with DS may simply not have been better walkers in Visit 1. Their higher normalized stride frequency and similar normalized stride lengths indicate that they accomplished comparable walking speeds by relying more on increased frequency than on increased stride length. The higher stride frequency seems to represent an emergent adaptation of toddlers with DS, who have greater joint stability constraints than toddlers with TD, in order to realize the task of independent bipedal walking.

The difference between the two groups was revealed dramatically by Visit 2, and the directional comparisons seem to provide some insights into the underlying mechanisms responsible for that difference. Whereas toddlers with TD walked more than twice as fast as they did in Visit 1, by increasing both stride length and stride frequency, toddlers with DS showed an increase in their walking speed to a lesser degree over 1 month of practice, and only their stride length increased significantly during that period. Normalized step width of toddlers with DS remained wide and did not show a significant decrease by Visit 2, unlike that of toddlers with TD. In simulation studies, a wider step width has been identified as one of the mechanisms that can stabilize oscillations in the ML direction during bipedal gait (Kuo, 1999). In developmental studies of gait, reductions in step width over practice time have been proposed to reflect improvement in balance control as walking skill progresses (Bril & Brenière, 1992). Although movements of bipedal locomotion in adults occur mostly in the sagittal plane, early forms of independent walking seem to be characterized by substantial movement in the frontal plane. By comparing the relative motion in each direction in those groups, we can propose not only what but why that phenomenon emerges.

We captured the difference in the degree of involvement of ML movement between the two groups of toddlers by analyzing the potential energy and kinetic energy conversion. Ivanenko et al. (2004) used two versions of recovery values, similar to the R_1 and R_2 variables used in this study, and found greater energy transfer between potential energy and kinetic energy in the ML direction for toddlers with TD than for adults. However, the exchange between potential energy and overall kinetic energy failed to differentiate our two groups of toddlers. In Figure 3A of the present study, R_1 indicated only that the overall exchange between potential energy and kinetic energy via an inverted pendulum mechanism improved significantly over two visits for both groups, although that value in Visit 2 remained lower than the 65% obtained for adults (Tesio, Lanzi, & Detrembleur, 1998). In contrast, the results from R_2 indicated that tod-

dlers with TD developed more rapidly the capability to convert potential energy into forward kinetic energy. That finding was supported by the significant increase in rEK_X and the corresponding significant decrease in rEK_Y observed only in toddlers with TD. It should be noted that in the adult walking study (Hallemans et al., 2004), rEK_Y was reported to be negligible, whereas rEK_Y for toddlers with TD reached as high as 30% in Visit 1.

The characteristic of significant motion in the ML direction in new walkers was observed in the kinematics as well. Yaguramaki and Kimura (2002) observed decreasing ML displacement of joints after the onset of independent walking and related it to the development of ML balance in walking. Although our results for COM displacement in the ML direction (Figure 3B) are compatible with theirs, the displacement in the ML direction no longer differentiated the two groups at Visit 2. The reason the two groups did not differ may then be that ML displacement at joints and COM are also a function of walking speed. As walking speed increases, the absolute amplitude of ML motion decreases. Therefore, one must consider the relative motion of ML and AP displacement of the joints and COM.

In our study, we successfully captured the differences between those two groups over developmental time by creating a ratio between the displacements of COM in both directions. In Visit 1, the ratio of COM amplitude in the ML direction to that in the AP direction was as high as .4 in toddlers with TD. The increase in speed between the two visits coincided with the decrease in $rCOM_{AMP}$, which we observed only in toddlers with TD.

AP-ML Coupling in the Emergence of Independent Walking

Because of the gravity constraint, the ML oscillation, which creates a single-stance phase, must be coupled with AP oscillation (i.e., forward stepping) for bipedal walking. Therefore, the emergence of AP-ML oscillation coupling would be the essence of the onset of bipedal walking under gravity. It should be noted that ML oscillation can exist by itself (e.g., marching in place), whereas AP oscillation (i.e., stepping forward) cannot emerge without ML oscillation. It is interesting that very early in life, infants show alternate kicking and even air steps when their body is supported in the air. Although those behaviors share common characteristics with forward stepping, the behaviors are performed independently of ML oscillation (Thelen & Fisher, 1982).

We argue that ML oscillation is a necessary condition for AP oscillation and that the early stage of independent walking involves a phase in which the new walker explores AP-ML coupling under gravity. From that viewpoint, we interpret the difference between our two groups of toddlers as follows. Very slow frequency is a characteristic of the onset of walking of toddlers with TD. The slow frequency is present only during very early months of walking experience, and then the frequency abruptly increases and subsequently gradually decreases in later months (Bril &

Brenière, 1992). The slow frequency is accompanied by a large ML displacement of the COM. From a stability viewpoint, larger displacements of the COM require a greater level of control, which may be available for toddlers with TD but may not be possible for those with DS. Because of significant difficulty in ML stability in toddlers with DS, those children require an additional year before they can manage the coupling of AP–ML oscillations and start independent walking.

Seen from the perspective of stability in the ML direction, the slower frequency and accompanying larger COM displacement in the ML direction observed in the earliest stage of walking of toddlers with TD may not be an obvious mechanical solution. It would be less demanding in terms of stability for new walkers to generate a higher frequency because it requires less displacement of COM in the ML direction. But, the specific slow frequency may emerge from a different set of constraints in the AP direction. For example, in the AP direction, translation as well as oscillation of the limbs are required. In addition, one needs to establish a coupling between AP and ML oscillations. A long double-stance phase, characteristic of early walkers, may be an indicator that they need a period of time to establish the AP–ML coupling in walking. As a result of competition between constraints in both directions, the slow frequency and large ML displacement may have emerged as the most manageable solution at the onset of bipedal walking for toddlers with TD.

Contrary to the hypotheses of some authors (e.g., Bril & Brenière, 1992), we found the correlation between step width and ML displacement of the COM to be low. Mechanically, it may make sense that wider step widths yield a larger COM displacement in the ML direction. When we included populations with different constraints in this study sample, however, alternative hypotheses surfaced. In our study, specifically, toddlers with DS showed wider step widths but not a larger ML displacement than those with TD. We speculate that the increase in step width contributes to ML stability by creating a wider base of support. But toddlers with DS cannot allow their nascent walking system to rock from side to side more than minimally, without losing control. Therefore, the ML sway is constrained and short, frequent steps emerge.

We wish to note that we do not intend to separate postural control from locomotor control, especially at these very early stages of walking. Both ML and AP oscillations are equally necessary conditions for the onset of independent walking. Movement of the upper part of the body (e.g., head–arms–trunk segment) and the lower part of the body (e.g., pelvis and legs) must be mutually coupled in independent gait. Therefore, for our questions regarding the earliest strategies used to control walking, we do not believe there is a functional separation between a postural system and a locomotor system. At that stage, a more integrated posture-in-locomotion system may be needed.

In addition, although it was not statistically tested, tod-

dlers with TD tended to show much less variability between individuals in Visit 2 than peers with DS in many dependent variables, including normalized stride length, normalized step width, R_2 , rEK_X , rEK_Y , $rCOM_{AMP}$, and $nCOM_Y$. The reduction of variability among individuals seems to agree with the transition of walking strategies in new walkers from a mixture of multiple walking strategies to a single strategy in which they use the pendulum properties of body segments (Ivanenko, Dominici, Cappellin, & Lacquaniti, 2005). Apparent variability differences between groups by Visit 2 may have resulted from different degrees in their transition in walking strategies, but that notion needs to be confirmed in future studies. One additional unknown is the relative amount of practice toddlers in those two groups' experience subsequent to walking onset. Although parents of toddlers with DS report their excitement about the emergence of this new skill, they may nevertheless overprotect and limit the children's practice of walking to contexts that are most safe, should falls occur.

In summary, even at the onset of independent gait, toddlers with TD and those with DS show qualitatively different forms of gait because of the difference in the dynamics resources at hand. The onset of independent gait in toddlers with DS is not simply a delayed version of that available to toddlers with TD. Moreover, within- and across-groups solutions changed, given sufficient opportunities to explore and strengthen neuromuscular pathways. Nevertheless, the establishment of coupled oscillations in the AP–ML direction seems a likely key component responsible for the emergence of independent bipedal gait.

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REFERENCES

- Assaiante, C., Thomachot, B., & Aurenty, R. (1993). Hip stabilization and lateral balance control in toddlers during the first four months of autonomous walking. *NeuroReport*, 4, 875–878.
- Bauby, C. E., & Kuo, A. D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics*, 33, 1433–1440.
- Bril, B., & Brenière, Y. (1992). Postural requirements and progression velocity in young walkers. *Journal of Motor Behavior*, 24, 105–116.
- Cavagna, G. A., Heglund, N. C., & Taylor, C. R. (1977). Mechanical work in terrestrial locomotion: Two basic mechanisms for minimizing energy expenditure. *American Journal of Physiology*, 233, R243–261.
- Donelan, J. M., Kram, R., & Kuo, A. D. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London Series B*, 268, 1985–1992.
- Halleman, A., Aerts, P., Otten, B., De Deyn, P. P., & De Clercq, D. (2004). Mechanical energy in toddler gait. A trade-off between

- economy and stability? *The Journal of Experimental Biology*, 207, 2417–2431.
- Henderson, S. E. (1986). Some aspects of the development of motor control in Down's syndrome. In H. T. A. Whiting & M. G. Wade (Eds.), *Themes in motor development*. (pp. 69–92). Boston: Martinus Nijhoff.
- Hreljac, A., & Marshall, R. N. (2000). Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics*, 33, 783–786.
- Ivanenko, Y. P., Dominici, N., Cappellini, G., Dan, B., Cheron, G., & Lacquaniti, F. (2004). Development of pendulum mechanism and kinematic coordination from the first unsupported steps in toddlers. *The Journal of Experimental Biology*, 207, 3797–3810.
- Ivanenko, Y. P., Dominici, N., Cappellini, G., & Lacquaniti, F. (2005). Kinematics in newly walking toddlers does not depend upon postural stability. *Journal of Neurophysiology*, 94, 754–763.
- Kuo, A. D. (1999). Stabilization of lateral motion in passive dynamic walking. *The International Journal of Robotics Research*, 18, 917–930.
- Ledebt, A., Bril, B., & Wiener-Vacher, S. (1995). Trunk and head stabilization during the first months of independent walking. *NeuroReport*, 6, 1737–1740.
- Sun, H., & Jensen, R. (1994). Body segment growth during infancy. *Journal of Biomechanics*, 27, 265–275.
- Tesio, L., Lanzi, D., & Detrembleur, C. (1998). The 3-D motion of the center of gravity of the human body during level walking. I. Normal subjects at low and intermediate walking speeds. *Clinical Biomechanics*, 13, 77–82.
- Thelen, E., & Fisher, D. M. (1982). Newborn stepping: An explanation for a “disappearing” reflex. *Developmental Psychology*, 18, 760–775.
- Ulrich, B. D., Haehl, V., Buzzi, U. H., Kubo, M., & Holt, K. G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science*, 23, 133–156.
- Yaguramaki, N., & Kimura, T. (2002). Acquirement of stability and mobility in infant gait. *Gait and Posture*, 16, 69–77.

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