Published in final edited form as:

Hum Mov Sci. 2009 February ; 28(1): 141–154. doi:10.1016/j.humov.2008.08.004.

Developmental Trajectory of Dynamic Resource Utilization During Walking: Toddlers with and Without Down Syndrome

D. Black¹, C-L. Chang², M. Kubo³, K. Holt⁴, and B. Ulrich¹

¹*Division of Kinesiology, University of Michigan, Ann Arbor, MI USA 48109-2214*

²*Department of Physical Medicine & Rehabilitation, University of Pittsburgh, Pittsburgh, PA USA 15213*

³*Department of Physical Therapy, Niigata University of Health & Welfare, Niigata, Japan 950-3198*

⁴*Department of Physical Therapy and Athletic Training, Boston University, Boston, MA USA 02215*

Abstract

After years of walking practice 8-10-year-old children with typical development (TD) and those with Down syndrome (DS) show uniquely different but efficient use of dynamic resources to walk overground and on a treadmill (Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). Here we examined the use of global stiffness and angular impulse when walking emerged and across the ensuing months of practice in eight toddlers with TD and eight with DS. Participants visited our lab when first able to walk four to six steps, and at 1, 3, 4, and 6 months of walking experience. For all visits, toddlers walked overground at their preferred speeds and for the last two visits on a treadmill. Toddlers with TD and DS demonstrated clear and similar developmental trajectories over this period with more similarities than differences between groups. At 6 months stiffness and impulse values were higher than previously observed for 8-10-year-old children. Stiffness values increased significantly throughout this period, though rate of change slowed for the TD group by three months of experience. Impulse values rose sharply initially and slowed to plateau during the latter months. Treadmill data illustrated toddlers' capacity to adapt dynamic resource use to imposed changes in speed, particularly well after six months of practice. Consistent with our studies of preadolescents and older adults, toddlers with DS produced significantly wider normalized step width than their TD peers. We propose that the challenge of upright bipedal locomotion constrains toddlers with TD and DS to generate similar, necessary and sufficient stiffness and impulse values to walk as they gain control and adapt to playful and self-imposed perturbations of gait over the first six months. The plateau in impulse and slow-down of stiffness increases over the latter months may be the first signs of a downward trend to the lower values produced by older children with several years of walking experience.

Keywords

Motor processes; Down syndrome; dynamic resources; development

Beverly D. Ulrich, Ph.D. (Corresponding author), Division of Kinesiology, University of Michigan, 401 Washtenaw Ave., Ann Arbor, MI 48109-2214, Office number: 734-615-1494, Fax number: 734-763-6283, Email: bdulrich@umich.edu.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

1. Introduction

Mathematical models have been used by movement scientists to examine questions ranging from interlimb coupling and resonant frequencies to the passive dynamics of gait (Fuchs & Kelso, 1994; Goodman, Riley, Mitra, & Turvey, 2000; McGeer, 1993; Mochon & McMahon, 1980). The majority of this work has focused on explaining the behavior of adults or highly skilled and efficient movers. In a model developed by Holt and colleagues for gait, in particular, the goal is to understand how human movers utilize their dynamic resources. Model parameters incorporate constraints that arise from the organism, the environment, and the task (Holt, Fonseca, & LaFiandra, 2000; Obusek, 1995). Dynamic resources refer to the force-producing and conserving mechanisms that can be used during a particular task. They consist of the ability to generate an appropriate amount and direction of muscular force at the right state of the system to replace energy losses due to damping factors, the ability to store and return force from the soft-tissues, and the ability to use the segmental lengths and masses as pendular force conserving mechanisms. One fundamental assumption is that variations in behavior among performers on the same task emerge because of differences in the available resources at any particular moment in developmental time, and the ways performers utilize these resources. We believe this is a particularly useful approach for addressing the emergence of control over developmental time, as well as pattern differences that may be caused by variations in systems' intrinsic properties.

The model itself assumes that during the stance/push-off phase a walker's system can be described as an inverted pendulum, that conforms to natural mechanical and physical principles, with a small escapement function. This force initiates the forward and upward arc of motion of the center of mass which is sustained by gravity until the opposite limb touches down. Fig. 1 provides a heuristic of the inverted pendulum model; details of the parameters in the model are outlined in Appendix A. More thorough explanations are provided in Holt et al. (2000), Obusek (1995), and Ulrich et al. (2004). Simply stated, starting from an equation of motion that describes the movement of the pendulum we mathematically derive equations to estimate parameters in the system, such as the global stiffness of the system and the global muscle force (angular impulse) that generate forward motion. The model is called an escapement-driven, inverted pendulum and spring model of gait (EDIPS).

Previously we used the EDIPS model to examine differences in global stiffness and angular impulse utilized by stable walkers (preadolescents) with typical development (TD) and their peers with Down syndrome (DS) (Ulrich et al., 2004). Our data showed that, at this point in developmental time both groups used similar levels of stiffness (normalized to body size and speed) when walking overground but the energy cost, as reflected in angular impulse, was significantly higher for the group with DS. Further, when challenged with the novel context of treadmill walking, children with DS increased significantly their stiffness and impulse values compared to their peers. Because the population with DS is known to have high joint laxity and low tone (American Academy of Pediatrics, 2001), the lack of difference in stiffness overground was somewhat surprising. We proposed that, over developmental time they had settled into a very efficient (i.e., relatively low) use of stiffness particularly when walking on highly predictable flat surfaces and at their preferred speed. That is, they allowed the passive dynamics of the pendulum and gravity to be used more effectively. This may have reduced the co-contraction or global muscle tension observed by other researchers for adults with DS when performing novel tasks (Aruin, Almeida, & Latash, 1996; Latash, Almeida, & Corcos, 1993). When confronted with the novelty and challenge of a moving treadmill belt children may have perceived a threat to their control and shifted toward stiffening the system to affect greater control. In both contexts, overground and treadmill, the increased impulse values generated by children with DS suggest that they paid the price of increased energy expenditure with each stride. Contributing to this may be their characteristically flat-footed gait (Amirfeyz, Aspros,

& Gargan, 2006), ligamentous laxity and the relatively wider step width they use which may be optimal for stability but is energetically costly as well (Smith, Kubo, Black, Holt, & Ulrich, 2007).

The question remains, what is the origin of this synergistic use of resources? We argue that the levels of stiffness and impulse generated by children with TD and DS are not innate but emerge, over developmental time, to reach optimal levels for each system, as observed in preadolescents, following years of practice. If, in fact, the group similarity in stiffness when walking overground emerges only after practice, one might expect higher stiffness values for toddlers with DS compared to ones with TD at walking onset. Conversely, because early walking is quite unstable for all toddlers, typical or not (Looper, Wu, Angulo Barroso, Ulrich, & Ulrich, 2006), one might argue that both would show high stiffness that reduces over time to a more efficient level. As well, the early walker tends to be relatively flat-footed, uses a wide base of support, and has greater joint laxity and weaker muscles (Kubo & Ulrich, 2006; Medline Plus, 2007) suggesting increased stiffness but perhaps not impulse. All of these characteristics change over developmental time for both groups. Further, when we examined a series of gait parameters related specifically to control in the medial-lateral and anterior-posterior directions in new walkers with TD and DS, we found that for some variables, toddlers with DS seemed to show more mature values than their peers with TD (Kubo & Ulrich, 2006). However, those group differences reversed and increased after one month of walking experience. These results suggest that in order to let go and walk independently, toddlers with DS must achieve greater levels of control to avoid falling than their peers with TD. But, once upright and independent, infants with TD gain more from their experiences each day than their peers with DS.

Based on this complicated and incomplete set of developmental data we must make predictions. Thus, we propose that toddlers in both groups will show high levels of stiffness early that decrease with experience, with group differences favoring those with TD, at least following a month or two of practice. We predict lower impulse values initially that increase as toddlers gain strength and experience and then decrease as they refine their ability to preserve and insert energy efficiently; over time, toddlers with DS should demonstrate higher levels of impulse.

With this set of predictions duly noted, we also propose that they form a precarious set of statements. Discovery of control can take multiple pathways and only with rigorous longitudinal data can researchers uncover the manner in which behavior unfolds and the processes that underlie these behaviors. Thus, our overarching goal in this study was to uncover the developmental trajectory of toddlers' use of dynamic resources, specifically, stiffness and impulse, estimated via the EDIPS model. We examine change over the first six months of independent walking in the use of global stiffness and angular impulse in toddlers with TD and with DS when walking overground at their preferred speeds. Further, we sought evidence of their capacity to adapt their control strategies to a novel context, a motorized treadmill, when constrained by speeds higher and lower than their preferred speeds.

2. Method

2.1. Participants

Eight toddlers with TD (three females and five males) and eight with DS (four females and four males) participated in this longitudinal study. When families arrived at the lab, we explained all procedures to parents, who signed a consent form approved by the University of Michigan Institutional Review Board. We recruited toddlers with TD from the local community and toddlers with DS through flyers distributed to DS support groups as well as notices in their newsletters. We communicated with parents via phone from the time they contacted us, prior to walking onset, until their infant was able to perform four to six independent steps. At this point we scheduled their first test session, defined as walking onset.

2.2 Procedures

All testing occurred in the Motor Development Laboratory in the Division of Kinesiology at the University of Michigan. When families came to the laboratory we provided toddlers with sufficient time to play with toys and with research staff in order to become comfortable with the environment. Next, we removed all clothes from each toddler except his/her diaper. We marked the skin surface of each site requiring a reflective marker with hypoallergenic eyebrow pencil, then attached 2 cm diameter spherical markers to the lateral surface on each side of the body (temperomandibular joint, shoulder, elbow, greater trochanter, femoral condyle, mid-shank, heel, 3rd metatarsophalangeal joint). We also placed EMG electrodes on six muscles of the left leg and lower trunk but for purposes of the questions posed here we will not include these data. To maximize contrast of the markers relative to the legs and to constrain EMG leads, infants wore a pair of dark tights with holes cut out for the feet and to expose the reflective markers.

Parents and toddlers came into the lab for multiple visits as part of a larger longitudinal study. Toddlers with TD came monthly for seven visits (maximum six months of experience). Toddlers with DS came for six visits (maximum eight months of experience) with three breaks in the monthly routine for parents who, in all cases, drove one to two hours each way to our lab (see Fig. 2 for the timeline and Table 1 for mean ages). For all visits, the toddlers walked at their comfortable speed over a GAITRite mat, which was placed in the middle of our walkway. We collected a minimum of 3 trials and a maximum of 14 trials, depending on the temperament of the toddler and their ability/willingness to remain upright and follow a straight path from start to finish.

Analog signals from mat sensors were transmitted to our laptop computer at 60 Hz. We used GAITRite software to determine usable steps, that is, ones with clear footprints, and to calculate gait parameters: step length, step width, proportion of cycle in stance, double support, and foot angle in stance. To control for differences that may occur simply due to limb length, we used Hof's method (1996) to normalize step length and width by leg length. We also used GAITRite software to calculate each child's preferred speed overground. In addition, when walking was sufficient (month 3, 4) we asked the toddlers to walk on a treadmill at five different speeds below, at, and above their preferred overground speed. Because toddlers are cognitively unable to indicate their "preferred" speed on the treadmill and because preferred speed on a treadmill tends to be lower than overground, we operationalized preferred speed on the treadmill for each child as 75% of his/her overground speed (Ulrich et al., 2004). Subsequently, we asked the children to walk on the treadmill at their treadmill equivalent preferred speed as well as slower and faster than their preferred speed (40%, 57.6%, 75%, 92.5%, and 110% of overground speed). At each speed participants walked on the treadmill for 2 min (20-30 s intervals). For purposes of this paper, we analyzed only data at 40%, 75%, and 110% of their overground speed. At the end of each test session we took a series of anthropometric measurements: total body weight, height and segmental lengths of the upper arm, lower arm, thigh, shank, foot, trunk (sitting height to shoulder), and sitting height to head.

2.3. Equipment and lab set-up

To obtain kinematic data, we used a 6-camera Peak Motus™ real-time system to collect reflective marker position location at a sampling rate of 60 Hz. One camera was placed at the front and one at the back of the walkway, with two additional cameras on each side. Prior to each data collection session we used Peak hardware and software to calibrate the center area of the walkway, which allowed a viewing space of $2.5 \times 1.2 \times 1.2$ m. Acceptable summed measurement error of the calibration was set at $< .008$ m. Furthermore, a video camera was placed to the side and slightly forward of the center of the walkway to provide a visual

confirmation for usable data. EMG data were collected at a sampling rate of 600 Hz. EMG, kinematic, and video data were synchronized.

After overground data collection, the GAITRite mat was removed and the treadmill (Parker) was moved in the middle of the calibrated space for subsequent data collection. Treadmill speed control allowed precision to two decimals (km/h).

2.4. Data reduction

To determine gait events, touchdown and toe-off, we used our kinematic data and custom-written MATLAB programs. The algorithms were developed by Hreljac and Marshall (2000). Time of foot contact was the time of local minimum in the vertical acceleration of the heel marker. Time of toe-off was at the local maximum of horizontal acceleration of the toe marker. We used foot contact to identify onset of each stride cycle.

In order to examine changes in the way toddlers use dynamic resources to walk independently we used an escapement-driven inverted pendulum and spring model to reflect the forward motion of the center of mass. Fig. 1 provides a heuristic of this model that illustrates the contributing components. Our equation of motion was based on this model and used to derive estimates for global stiffness and global impulse. We wrote customized Matlab programs to apply these stiffness and impulse algorithms that allowed us to insert individuals' anthropometric data and kinematic data. Appendix A provides our equations and extended details concerning the algorithms and their derivation are published in Ulrich et al. (2004).

We converted the stiffness and impulse values to dimensionless quantities to make our normalized parameter values independent of specific units of measurement. The stiffness (k) and impulse (I) are normalized to the specific body mass (M) and length of individual participants (L_e) in order to compare groups with different anthropometric characteristics. According to Hof (1996), normalized stiffness ($\hat{k}$) and impulse ($\hat{I}$) is computed using the following equations:

$$\hat{k} = \frac{k}{ML_e g} \quad (1)$$

$$\hat{I} = \frac{I}{ML_e^{3/2} g^{1/2}} \quad (2)$$

Gait parameters were also converted to dimensionless values in order to account for the effect of differences in body size between groups and among participants (Ulrich et al., 2004).

3. Results

3.1. Participant characteristics

Table 1 presents age and anthropometric characteristics of participants by group and walking experience. As anticipated, walking onset occurred about one year earlier for toddlers with TD ($M = 60.25$ weeks, $SD = 9.66$) than toddlers with DS ($M = 116.25$ weeks, $SD = 28.93$).

To examine anthropometric differences we used three 2 (Group) $\times$ 5 (Visit) MANOVAs with repeated measures on visit to test related sets of dependent variables. Set One variables were seven body segment lengths; Set Two included three body segment ratios, and Set Three

consisted of height, weight and BMI. Set One showed a significant effect of visit, Wilks' Lambda = 0.091, $F(7, 49) = 6.13$, $p < .001$. Follow-up univariate analyses revealed significant increases over visits for head-neck, trunk, thigh, shank, foot, upper arm, lower arm; for all F values, $df = 4, 52$ and $p < .001$. Set Two also showed a significant effect of visit, Wilks' Lambda = 0.650, $F(3, 11) = 2.11$, $p < .05$. Follow-up univariate analyses revealed that the upper extremity/trunk ratio and foot/height ratio increased with walking experience: for both, F values' $df = 4, 52$ and $p < .05$. We found a significant effect of visit for Set Three variables as well, Wilks' Lambda = 0.094, $F(3, 11) = 17.23$, $p < .001$. Follow-up univariate analyses showed a significant increase over visits for weight and height; F values' $df = 4, 52$ and $p < .001$. BMI was not significant at the univariate level. No group or interaction effects were significant for anthropometrics.

3.2. Overground gait characteristics

We used a 2 (Group) $\times$ 5 (Visit) MANOVA with repeated measures on visit to compare toddlers' overground walking characteristics (dependent variables were % stance, % double support phase, dimensionless speed, dimensionless stride frequency, dimensionless stride length, and dimensionless step width). Group means and SDs are presented in Table 2. We found a significant effect of group, Wilks' Lambda = 0.638, $F(6, 5) = 7.32$, $p < .001$. Post hoc ANOVA results suggested that the significant Group effect was largely due to differences in dimensionless step width, $F(1, 14) = 17.69$, $p < .001$; toddlers with DS walked with larger step widths. We also found a significant effect of visit, Wilks' Lambda = 0.215, $F(6, 30) = 5.58$, $p < .001$. Follow-up univariate ANOVAs revealed significant visit differences for all gait characteristics; for all F values the $df = 4, 56$ and $p < .001$ except for stance phase for which $p < .05$. Dimensionless step width, % stance phase, and % double support phase decreased over time, while dimensionless stride length, frequency, and speed increased.

3.3. Treadmill gait characteristics

We conducted a separate 2 (Group) $\times$ 2 (Visit) $\times$ 3 (Speed) ANOVA with repeated measures on visit and speed for each of three dependent variables; dimensionless step width, dimensionless stride length, and dimensionless frequency. For step width, we obtained a significant effect of group, $F(1, 30.45) = 19.98$, $p < .001$. Inspection of the means (see Table 3) revealed that toddlers with DS had a wider step than their peers with TD. For stride length, we found a significant effect of speed, $F(2, 33.08) = 47.64$, $p < .001$. As speed increased, both groups produced larger stride lengths. Also, there was a trend toward a significant Group $\times$ Visit interaction, $F(1, 36.37) = 4.07$, $p = .051$. The stride lengths of toddlers with DS decreased at their preferred and faster-than-preferred speed after two months of walking experience while the stride lengths of toddlers with TD increased after two months of walking experience. For frequency, we found a significant effect of speed, $F(2, 32.84) = 10.37$, $p < .001$. A follow-up inspection of the means revealed that toddlers increased stride frequency as speed increased.

3.4. Stiffness means

For the overground conditions, we conducted a 2 (Group) $\times$ 5 (Visit) ANOVA with repeated measures on visit to examine the use of dimensionless stiffness. We obtained a significant visit effect, $F(2.64, 34.33) = 16.24$, $p < .001$ but not a group effect (see Fig. 3). Inspection of the means revealed stiffness increased across time for both groups. Fig. 4 presents a scatterplot of all individual toddler's stiffness data during overground walking as a function of walking speed rather than walking experience. This figure reinforces the lack of group differences. It also illustrates that as children with TD and DS walk faster, they do so by producing more stiffness.

For the treadmill conditions, we conducted a 2 (Group) $\times$ 2 (Visit) $\times$ 3 (Speed) ANOVA with repeated measures on visit and speed. We observed a significant speed effect, $F(2, 23) = 30.26$,

$p < .001$. Fig. 5 illustrates that as speed increased stiffness increased. There were no group or visit effects and no significant interaction effects.

3.5. Impulse means

For the overground conditions, we conducted a 2 (Group) $\times$ 5 (Visit) ANOVA with repeated measures on visit to examine the use of dimensionless impulse during walking. We found a significant visit effect, $F(2.92, 37.99) = 9.20, p < .001$ but not a significant group or interaction effect. Fig. 6 indicates that impulse increases as toddlers gain more walking experience up until three months, then their use of impulse gradually levels off and begins to decrease. Fig. 7 presents all individual toddler's dimensionless angular impulse values as a function of dimensionless speed. Similar to Fig. 4, walking faster results in generating more impulse for both groups.

For the treadmill conditions, we conducted a 2 (Group) $\times$ 2 (Visit) $\times$ 3 (Speed) ANOVA with repeated measures on visit and speed. We found a significant visit effect, $F(1, 10) = 5.58, p < .05$, and a significant speed effect, $F(2, 23) = 21.60, p < .001$ but no significant group or interaction effects. Fig. 8 shows that toddlers with more walking experience produced higher impulse values. Also, increasing speed led to greater impulse production.

3.6. Stiffness and impulse slopes

Here we extend our examination of the data with the goal of merging the developmental trajectory of the rate of change with the subtlety of the positive and negative slopes. Thus we chose a qualitative descriptive approach, rather than a quantitative test; our intent is, of course, not to infer statistical significance in these characterizations of the behavior observed.

Toddlers in both groups showed increases in stiffness between each test session but the group with TD steadily decreased the rate of change over this time period while the group with DS increased its rate of change throughout. For impulse, toddlers with TD showed a small but positive slope over the first two periods of walking practice but by months four and six the slope turned to small but negative, reflecting a gradual decrease in impulse. Toddlers with DS similarly showed a positive slope over the first two intervals of walking experience and by months four and six seemed to plateau, with very small slopes, negative between visit three and four and positive between four and six (see Table 4).

4. Discussion

Our overarching goal for this study was to determine how toddlers with TD and DS utilize their dynamic resources at walking onset and over the first six months of walking experience. We succeeded in this regard but we failed in being able to predict accurately differences between groups in the shape of developmental trajectories. Our data show few differences between groups, but they also indicate high variability for both groups, particularly after the first three months of walking, for both stiffness and angular impulse. We have previously proposed that learning to control one's body to produce new skills is highly exploratory and involves two phases (Haehl, Vardaxis, & Ulrich, 2000; Holt et al., 2007; Thelen, 1995). First, brand new walkers discover how to produce forces that project them in the intended direction, forward toward mom or toys in this case, rather than side to side. Second, they discover that by applying appropriate sagittal force they can allow their center of mass to oscillate over the foot axis as an inverted pendulum, and stiffen their soft tissues to act like springs, energy conservation is enhanced. They learn to be efficient (Holt et al., 2006, 2007). While the first phase occurs within the first month of walking (Holt et al., 2006), the second phase requires longer than the period we assessed these toddlers. Our previous results on swing leg dynamics similarly fail to settle into the natural frequency during this period (Holt et al., 2007). This

phase is highly exploratory, providing the means by which efficient uses of resources can be learned by the neuromotor control system. Toddlers, we argue, spend several months exploring (and possibly much longer), including the period we studied here, prior to settling into a stable and efficient pattern.

Neither of our predictions for stiffness values (trajectory and group differences) were supported by our data, although angular impulse values conformed relatively well to our trajectory predictions, but not group differences. Normalized stiffness values started low and increased over time throughout all six months of walking practice. Impulse values increased during the first few months and then tended to level off. At walking onset normalized values for toddlers with TD, at least, appear to be lower even than those produced by highly practiced preadolescent walkers (Ulrich et al., 2004, see Fig. 3). Nevertheless, during the first six months of walking a different trend of resource utilization between groups is emerging. Both groups showed a relatively linear increase in stiffness over time but the rate of change between visits steadily decreased for the group with TD while it continued to increase throughout for those with DS. Both groups increased impulse values relatively linear during the first few months, after which values began to slope downward for toddlers with TD but not those with DS. These subtle changes in global stiffness and impulse that occur during the latter months, we propose, are the foundation for the more stable and significant group differences in resource utilization that emerge at some time between our testing period and preadolescence (Ulrich et al., 2004).

In retrospect, perhaps we should not have been surprised to find an increase over time in stiffness, given the work of Bril and her colleagues (Brenière & Bril, 1992; Ledebt & Bril, 2000). They have shown an increase in progression velocity over the first several months of walking in toddlers with TD which is paralleled in our data for both groups. Children get bigger and they can go faster; but even when normalized to body size, speed increases. In the EDIPS model stiffness and step frequency are interdependent. Frequency of oscillation significantly affects speed and is directly impacted by global stiffness. When adults walk slower, step frequency decreases; when they walk faster, frequency increases. Fig. 4 shows a similar trend for toddlers, but with a low to moderate correlation between speed and stiffness. This suggests that the system has not yet settled into a stable and efficient pattern of resource; exploration and playful use of this new skill continue beyond this point.

This process by which the neuromotor system learns to map energy input and conservation onto the biomechanical system is highly driven by exploration. Inspection of the standard deviation bars for stiffness and impulse shows an increase in variability in performance with age, particularly during the second half of this longitudinal period. At around three months variability (SD) starts to increase rapidly, while the rate of increase in mean stiffness and impulse slows down. Toddlers at this point clearly enjoy speed and have improved their capacity to explore their resource capabilities; they take short steps and long steps, they hesitate and speed up within steps sequences, attempt to jump, swing their arms and lean their trunks in varied directions. Each change in overall body movements/mechanics requires global stiffness and impulse resources to be used to a greater or lesser extent, and in different configurations. That toddlers can exact these changes suggests that their current mean stiffness and impulse levels are under their control to some extent, and not inevitable. They are capable of affecting a range of levels of stiffness and impulse. This ability to adapt was demonstrated nicely by their behavior on the treadmill. In this context toddlers in both groups reduced stiffness and impulse markedly when the treadmill was set to speeds slower than their freely chosen overground speeds. They also increased their use of these available resources markedly at speeds higher than their preferred speeds.

Stiffness and angular impulse values generated by toddlers walking on the treadmill showed values both lower and higher than those overground, depending on the speed at which we set

the treadmill belt. Nevertheless, the highest speed settings (faster than their preferred overground speeds) were the most difficult for them to manage, perhaps because they self-selected walking speeds overground that were close to their maximum. In particular, angular impulse values increased more than what might be expected for the relative increase in speed, only 10% faster than their self-selected overground speed). To be able to maintain treadmill walking at the highest speed we required, may have caused them to shift to a particularly inefficient, though effective, forcing strategy to maintain their alternating leg activity.

To put our gait data into a broader context it is important to remind readers of a basis for the EDIPS model. The model was created with a focus on the primary and strong task constraint of walking that is to project the body forward. Thus, this is a sagittal plane model, emphasizing movement in the intended direction. A limitation of this model is, of course, the capacity to assess side-to-side motion which is out of the sagittal plane, such as foot placement in the medial-lateral direction. Reflective of motion in this direction, potentially, is the gait parameter: step width. Our data for gait characteristics showed that toddlers with DS produced significantly wider step widths than their TD peers across months, which is meaningful for its persistence throughout the lifespan (Ulrich et al. 2004; Smith & Ulrich, in press). Differences in available dynamic resources, when faced with the same strong constraint in the A-P direction, may force persons with DS to behave differently in the M-L direction. Kubo and Ulrich's (2006) analyses of the center of mass (COM) motion and energy recovery in new walkers suggest that by positioning their feet farther apart, toddlers with DS are better able to constrain the kinetic energy of their COM to the A-P direction. They actually move the COM forward with less wasted M-L motion than their peers with TD.

5. Summary

In previous work we identified similarities and substantial differences in the ways in which well-practiced 8-10-year olds with TD and with DS used their dynamic resources, specifically, normalized global stiffness and angular impulse, to walk (Ulrich et al., 2004). Here we found substantial similarities: no significant group differences over the first six months of walking for these variables. Yet more subtle changes in the slope of toddlers' developmental trajectories over the latter half of this time period indicate that these two groups are taking different routes over time. To determine exactly when and how these slowly emerging differences progress to the stable differences known to exist in late childhood will require the collection of data for this missing link in the developmental continuum.

We argue that the process of developing neuromotor control shifts over this broad period of time, from toddlerhood to preadolescence, from exploration to settling into a preferred and energy efficient pattern of resource utilization. Adults and preadolescents use finely tuned conservation of resources. Stiffness characteristics of the system match the gravitational stiffness associated with the leg pendulum dynamics (Holt et al., 1991; 1995, 2007). The combined resonance frequency of the hybrid pendulum and spring system becomes the neural control system's pattern of choice. Exploration of the possible combinations of these resources not only results in the highly variable movement patterns we saw, but provides the system the experiences to distinguish efficient and inefficient patterns. It can be argued, therefore, that the dynamics may, in fact, teach the neuromotor control system to develop and "choose" preferred locomotor patterns.

Appendix A

The stiffness coefficient (k) will be given by the following equation:

$$k = ML_e^2 \omega^2 + ML_e g = ML_e^2 \left(\frac{2\pi}{\tau} \right)^2 + ML_e g$$

where M is the total body mass minus the mass of the stance foot, L_e is the equivalent length of the body, g is the gravity coefficient, ω is the natural frequency of the system, and τ is the period of the oscillation.

The angular impulse (IR) during pushoff is estimated as:

$$I_R = \int_{HC_i}^{TO_j} F(\theta, \dot{\theta}) L_e dt = ML_e^2 \int_{HC_i}^{TO_j} \ddot{\theta} dt + (k - ML_e g) \int_{HC_i}^{TO_j} \theta dt + c \int_{HC_i}^{TO_j} \dot{\theta} dt$$

where i and j represent the contralateral sides of the body, TO represents toe-off, HC represent heel contact, and $F(\theta, \dot{\theta})$ is the escapement force.

References

- American Academy of Pediatrics, Committee on Genetics. Health supervision for children with Down syndrome. *Pediatrics* 2001;107:442–449. [PubMed: 11158488]
- Amirfeyz R, Aspros D, Gargan M. Down syndrome. *Current Orthopaedics* 2006;20:212–215.
- Aruin AS, Almeida GL, Latash ML. Organization of a simple two-joint synergy in individuals with Down syndrome. *American Journal of Mental Retardation* 1996;101:256–268. [PubMed: 8933900]
- Brenière Y, Bril B. Development of postural control of gravity forces in children during the first 5 years of walking. *Experimental Brain Research* 1992;121:255–262.
- Fuchs A, Kelso JAS. A theoretical note on models of interlimb coordination. *Journal of Experimental Psychology: Human Perception and Performance* 1994;20:1088–1097. [PubMed: 7964529]
- Goodman L, Riley MA, Mitra S, Turvey MT. Advantages of rhythmic movements at resonance: Minimal active degrees of freedom, minimal noise, and maximal predictability. *Journal of Motor Behavior* 2000;32:3–8. [PubMed: 11008266]
- Haehl V, Vardaxis V, Ulrich BD. Learning to cruise: Bernstein's theory applied to skill acquisition during infancy. *Human Movement Science* 2000;19:685–715.
- Hof L. Scaling gait data to body size. *Gait and Posture* 1966;4:222–223.
- Holt KG, Fonseca ST, LaFiandra ME. The dynamics of gait in children with spastic hemiplegic cerebral palsy: Theoretical and clinical implications. *Human Movement Science* 2000;19:375–405.
- Holt KG, Hamill J, Andres RO. Predicting the minimal energy costs of human walking. *Medicine and Science in Sport and Exercise* 1991;23:491–498.
- Holt KG, Jeng SF, Ratcliffe R, Hamill J. Energetic cost and stability during human walking at the preferred stride frequency. *Journal of Motor Behavior* 1995;27:164–179. [PubMed: 12736125]
- Holt KG, Saltzman E, Ho C-L, Kubo M, Ulrich BD. Discovery of the pendulum and spring dynamics in the early stages of walking. *Journal of Motor Behavior* 2006;38:206–218. [PubMed: 16709560]
- Holt KG, Saltzman E, Ho CL, Ulrich BD. Scaling of dynamics in the earliest stages of walking. *Physical Therapy* 2007;87:1458–1467. [PubMed: 17878431]
- Hreljac A, Marshall RN. Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics* 2000;33:783–786. [PubMed: 10808002]
- Kubo M, Ulrich BD. Early stages of walking: development of control in the mediolateral and anteroposterior directions. *Journal of Motor Behavior* 2006;38:229–237. [PubMed: 16709562]
- Latash ML, Almeida GL, Corcos DM. Preprogrammed reactions in individuals with Down syndrome: The effects of instruction and predictability of the perturbation. *Archives of Physical Medicine and Rehabilitation* 1993;73:391–399. [PubMed: 8466421]

- Ledebt A, Bril B. Acquisition of upper body stability during walking in toddlers. *Developmental Psychobiology* 2000;36:311–324. [PubMed: 10797252]
- Looper J, Wu J, Angulo Barroso R, Ulrich D, Ulrich BD. Changes in step variability of new walkers with typical development and with Down syndrome. *Journal of Motor Behavior* 2006;38:367–372. [PubMed: 16968682]
- McGeer T. Dynamics and control of bipedal locomotion. *Journal of Theoretical Biology* 1993;163:277–314. [PubMed: 8246506]
- Medline Plus, U.S. National Library of Medicine and the National Institutes of Health. *Medical Encyclopedia*. 2007. Retrieved August 30, 2007, from <http://www.nlm.nih.gov/medlineplus/ency/article/001262.htm>
- Mochon S, McMahon T. Ballistic walking: An improved model. *Mathematical Biosciences* 1980;52:241–260.
- Obusek, J. The force-driven hybrid oscillator model in the control of human walking speed and stride frequency. Doctoral dissertation, Boston University; Boston, USA: 1995.
- Smith B, Kubo M, Black DP, Holt K, Ulrich BD. Effect of practice on a novel task – walking on a treadmill: Preadolescents with and without Down syndrome. *Physical Therapy* 2007;87:1–12.
- Smith BA, Ulrich BD. Early onset stabilizing strategies for gait and obstacles: older adults with Down syndrome. *Gait & Posture*. in press
- Thelen E. Motor development: A new synthesis. *American Psychologist* 1995;50:79–95. [PubMed: 7879990]
- Ulrich BD, Haehl V, Buzzi U, Kubo M, Holt KG. Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science* 2004;23:133–156. [PubMed: 15474174]
- Ulrich BD, Ulrich DA. Spontaneous leg movements of infants with Down syndrome and nondisabled infants. *Child Development* 1995;66:1844–1855. [PubMed: 8556903]

Fig. 1.

Inverted pendulum model, where M is the total of mass of the body minus the mass of the stance foot, g is the gravity constant, L_e is the equivalent length of the body (see Obusek, 1995), $F' = F'(\theta, \dot{\theta})$ is the escapement force provided by the muscle contraction during push off phase by the opposite leg, k is the coefficient of stiffness determined by the elastic tissues and active muscle tension, and c is the damping coefficient. θ is the angular displacement of the inverted pendulum with reference to vertical-up direction measured in clockwise direction.

Fig. 2.
Time line of data collection sessions for toddlers with TD and DS, ellipses reflect points in time at which groups had equal numbers of months of walking experience.

Fig. 3.

Mean overground dimensionless stiffness plotted by group across walking experience. Preadolescents with TD and DS from Ulrich et al. (2004) are included for comparison purposes (see discussion).

Fig. 4.

Dimensionless stiffness for each toddler with TD and DS at each test session, as a function of dimensionless speed, with line of best fit for each group.

Fig. 6. Mean overground dimensionless impulse values plotted by group across walking experience. Preadolescents with TD and DS from Ulrich et al. (2004) are included for comparison purposes (see discussion).

Fig. 7. Dimensionless impulse for each toddler with TD and DS at each test session, as a function of dimensionless speed, with line of best fit for each group.

Fig. 8.

Mean treadmill impulse values plotted by group, by speed, by age. Mean overground impulse at the same ages superimposed in the graph for comparison. Note: The number of participants decreased as speed increased (mean number of toddlers at 40% [7], 75% [6.25], and 110% [4.25]).

Table 1
Age and anthropometric data, M(SD), for participants by group(TD and DS) and visit (walking experience)

	Group	Walking Experience				
		0 months	1 month	3 months	4 months	6 months
Age (Weeks)	TD	60.3 (9.70)	64.8 (9.82)	73.1 (9.96)	77.6 (10.31)	86.1 (9.69)
	DS	116.3 (28.93)	121.0 (29.01)	126.3 (30.42)	133.6 (28.23)	142.5 (29.51)
Weight (Kg)	TD	9.9 (.07)	10.2 (.74)	10.5 (.78)	10.8 (.79)	11.7 (.78)
	DS	11.5 (1.50)	11.6 (1.46)	12.0 (1.43)	12.3 (1.50)	12.7 (1.39)
Height (m)	TD	0.7 (.03)	0.7 (.03)	0.7 (.03)	0.8 (.03)	0.8 (.03)
	DS	0.8 (.06)	0.8 (.05)	0.8 (.05)	0.8 (.05)	0.8 (.05)
BMI	TD	18.3 (1.14)	18.3 (1.37)	17.7 (1.28)	17.5 (.88)	18.1 (1.44)
	DS	17.9 (1.11)	17.7 (1.29)	17.8 (1.31)	18.0 (1.49)	17.8 (1.19)
Leg:Trunk Ratio	TD	1.0 (.11)	1.0 (.09)	1.0 (.07)	1.0 (.07)	1.0 (.06)
	DS	1.0 (.09)	1.1 (.09)	1.1 (.092)	1.1 (.05)	1.1 (.06)
Arm:Trunk Ratio	TD	0.8 (.01)	0.8 (.08)	0.8 (.06)	0.8 (.06)	0.8 (.06)
	DS	0.7 (.06)	0.8 (.04)	0.8 (.04)	0.8 (.07)	0.8 (.05)
Foot:Total Height Ratio	TD	0.2 (.01)	0.2 (.01)	0.2 (.01)	0.2 (.01)	0.2 (.01)
	DS	0.2 (.01)	0.2 (.01)	0.2 (.00)	0.2 (.01)	0.2 (.01)
Head/Neck (cm)	TD	17.0 (1.32)	17.8 (1.33)	18.2 (.92)	19.1 (.81)	19.2 (1.03)
	DS	18.4 (1.54)	19.2 (1.19)	19.5 (1.27)	19.8 (1.0)	20.1 (.89)
Trunk (cm)	TD	28.0 (1.62)	28.4 (1.64)	29.3 (1.20)	29.9 (1.48)	30.9 (1.35)
	DS	29.8 (1.31)	30.4 (1.11)	31.1 (1.73)	31.8 (2.26)	32.7 (2.24)
Thigh (cm)	TD	13.9 (1.24)	14.5 (1.39)	15.0 (1.32)	15.3 (.78)	16.2 (1.19)
	DS	14.9 (1.36)	15.9 (1.67)	16.4 (2.12)	16.7 (2.07)	17.2 (1.96)

		Walking Experience				
Group		0 months	1 month	3 months	4 months	6 months
Shank (cm)	TD	14.4 (1.44)	14.4 (1.22)	15.2 (1.13)	15.6 (1.11)	16.2 (.99)
	DS	15.6 (1.75)	16.1 (1.89)	16.5 (1.88)	16.9 (1.51)	17.6 (1.85)
Foot (cm)	TD	11.3 (.48)	11.5 (.56)	12.1 (.55)	12.4 (.57)	13.2 (.77)
	DS	12.6 (1.12)	12.8 (.81)	13.0 (.69)	13.2 (.66)	13.7 (.94)
Upper Arm (cm)	TD	11.0 (1.17)	11.8 (1.53)	11.9 (.85)	12.4 (.70)	12.6 (.65)
	DS	11.1 (.85)	12.1 (.75)	12.5 (.93)	13.2 (1.42)	13.5 (1.30)
Lower Arm (cm)	TD	10.5 (1.70)	10.8 (1.29)	11.2 (.92)	11.5 (.88)	12.2 (.95)
	DS	10.6 (1.09)	11.1 (1.17)	11.6 (1.09)	11.8 (1.31)	12.1 (1.09)

Table 2
Descriptive characteristics of overground gait parameters, M(SD), for participants by group(TD and DS) and visit (walking experience)

	Group	Walking Experience			
		0 months	1 month	3 months	6 months
Dimensionless Step Width	TD	0.6 (.06)	0.6 (.10)	0.4 (.09)	0.3 (.08)
	DS	0.7 (.15)	0.6 (.12)	0.6 (.17)	0.4 (.09)
Dimensionless Stride Length	TD	0.8 (.29)	1.4 (.19)	1.7 (.28)	1.6 (.35)
	DS	0.8 (.36)	1.1 (.46)	1.4 (.25)	1.5 (.29)
Dimensionless Frequency	TD	0.2 (.03)	0.2 (.03)	0.3 (.02)	0.3 (.04)
	DS	0.2 (.06)	0.2 (.03)	0.2 (.03)	0.3 (.05)
Dimensionless Speed	TD	0.1 (.06)	0.3 (.07)	0.5 (.10)	0.5 (.14)
	DS	0.2 (.09)	0.3 (.14)	0.4 (.08)	0.4 (.15)
% Stance Time	TD	0.7 (.12)	0.6 (.03)	0.6 (.04)	0.5 (.05)
	DS	0.6 (.12)	0.6 (.06)	0.6 (0.3)	0.6 (.04)
% Double Support Time	TD	0.4 (.14)	0.2 (.05)	0.2 (.05)	0.1 (.04)
	DS	0.3 (.20)	0.2 (.10)	0.2 (.04)	0.2 (.05)

Table 3
Descriptive characteristics of treadmill gait parameters, toddlers with TD and DS

		Walking Experience					
		TD			DS		
		4 months	6 months	4 months	6 months	4 months	6 months
	% OVG Speed						
	40	0.367 (.097)	.319 (.081)	.570 (.129)	.473 (.107)		
	75	0.348 (.092)	.312 (.091)	.470 (.067)	.457 (.062)		
	110	0.342 (.105)	.281 (.077)	.422 (.007)	0.436 (.114)		
	40	0.746 (.217)	.823 (.224)	.744 (.219)	0.791 (.162)		
	75	1.169 (.274)	1.362 (.270)	1.355 (.248)	1.244 (.156)		
	110	1.448 (.162)	1.680 (.261)	1.773 (.499)	1.503 (.115)		
	40	0.261 (.036)	.263 (.059)	.253 (.036)	0.280 (.030)		
	75	0.293 (.036)	.287 (.025)	.292 (.014)	0.297 (.031)		
	110	0.343 (.010)	.323 (.035)	.329 (.022)	0.318 (.060)		
	40	.188 (.044)	.209 (.045)	.179 (.055)	.215 (.023)		
	75	.340 (.084)	.389 (.077)	.395 (.090)	.368 (.062)		
	110	.495 (.068)	.542 (.106)	.588 (.202)	.472 (.052)		

Table 4

Slope (rate of change) for stiffness and impulse for toddlers with TD and DS

Walking Experience	Stiffness		Impulse	
	TD	DS	TD	DS
0 - 1 month	2.018	0.791	0.381	0.155
1 - 3 months	1.739	0.928	0.351	0.405
3 - 4 months	0.978	1.047	-0.051	-0.064
4 - 6 months	0.378	1.180	-0.060	0.064