Published in final edited form as:

Infant Behav Dev. 2006 April ; 29(2): 175–188.

Early Changes in Muscle Activation Patterns of Toddlers During Walking

Chia-Lin Chang, Masayoshi Kubo, Ugo Buzzi, and Beverly Ulrich

Motor Development Laboratory, Division of Kinesiology, The University of Michigan

Abstract

Early locomotor behavior has been the focus of considerable attention by developmentalists over several decades. Few studies have addressed explicitly patterns of muscle activity that underlie this coordination pattern. Our purposes were to illustrate a method to determine objectively the onset and offset of muscle firings during early walking and to investigate the emergence of patterns of activation of the core locomotor muscles. We tested eight toddlers as they walked overground at walking onset (max. of 3–6 independent steps) and after three months of walking experience. Surface electrodes monitored activity of the gastrocnemius, tibialis anterior, quadriceps, and hamstrings. We reduced EMG signals to a frame-by-frame designation of “on-off,” followed by muscle state and co-contraction analyses, and probability distributions for each muscle’s activity across multiple cycles. Our results clearly show that at walking onset muscle activity was highly variable with few, if any, muscles showing recurring patterns of behavior, within or among toddlers. Variability and co-activation decreased with walking experience but remained inconsistent, in contrast to the significant increase in stability shown for joint coordination and endpoint (foot placement) parameters. We propose this trend emerges because of the high number of options (muscle combinations) available. Toddlers learn first to marshal sufficient force to balance and make forward progress but slowly discover how to optimize these resources.

Keywords

Walking; Toddler; EMG; Kinematic; Coactivation; Variability; Motor development

1. Introduction

Developmental scientists have been studying the onset and subsequent changes in early walking behavior since the classic work of Shirley (1933) and Bayley (1935) in the 1930s. The timeless fascination with this skill reflects, perhaps, the fact that it is the first skill to emerge that requires the infant to manage significant movement among all body segments and that remains a staple of the functional repertoire throughout life. The complex nature of this global movement pattern, with its significant impact on many other behaviors, makes it an important component of studies addressing a range of theoretical as well as clinical issues (e.g., Adolph, Eppler, & Gibson, 1993; Clark & Phillips, 1993; Corbetta & Bojczyk, 2002; Ulrich, Ulrich, Angulo-Kinzler, & Yun, 2001).

Contemporary developmental scientists have increasingly gravitated toward a dynamic systems approach to studying the emergence of skills. One valuable characteristic of this approach is that it transcends levels of analysis and can be used as appropriately to study neural organization as interlimb coordination (Goldfield, 1995; Kelso, 1995). Further, patterns

emerge through exploration of available solutions and subsequent selection of preferred patterns (Thelen & Corbetta, 1994; Gibson, 1988; Sporns & Edelman, 1993; Turvey & Fitzpatrick, 1993). Solutions, though self-organized, are often unstable initially and become more stable with practice. In the example of walking, therefore, the emergence of populations of neurons that support bipedal locomotion, the coordination of segments within a limb, and interlimb coordination emerge from the self-organization of the relevant and interacting components of the system.

Within this multilayered system, all the levels at which we can observe the system do not progress apace. For example, Clark and colleagues (Clark & Phillips, 1991; Clark, Whittall & Phillips, 1988) demonstrated that mean leg interlimb phasing, considered by many to be the essence of walking, or its collective variable, was not significantly different from that of adults at walking onset. However, relative phasing between the thigh and shank required three months of walking practice to reach adult-like means. Arm patterns show a more protracted rate of change and a distinct sequence of shifts in coordination. Ledebt (2000) reported that new walkers tended to position their arms in “high guard,” with shoulders rotated outward and elbows flexed, gradually lowering them and achieving reciprocal swinging patterns five to six months after walking onset.

One important subsystem that has received minimal attention in new walkers and that may be one of the slowest subsystems to stabilize is that of muscle activation patterns. From a systems perspective we would argue that stable patterns of activation emerge, like patterns of limb coordination, via exploration and selection. That is, early activations may not be optimal or consistent, but they get the system within the boundaries of the functional workspace. With practice, stable and efficient patterns emerge. To date, Okamoto and colleagues (Okamoto & Goto, 1985; Okamoto & Okamoto, 2001; Okamoto, Okamoto, & Andrew, 2003) have published the most comprehensive electromyographic (EMG) data for early walking with regard to number of muscles monitored in a longitudinal study involving frequent and early collections (every 1 to 2 weeks from walking onset). They observed a shift over the first few months from excessive muscle activity and multiple patterns, with underlying “orderly patterns” of leg muscle activity; stable adult-like patterns were demonstrated by three years of age. Their sample size was, unfortunately, quite small and only exemplar data for 1–2 toddlers were presented, typically. As part of a larger mixed longitudinal study, Forssberg (1985) tested four toddlers within two weeks of walking onset. He characterized their EMG patterns as variable, with “tendencies” toward unique firing patterns for individual muscles, but also co-contractions, and short bursts in all muscles after foot contact. He reported no appreciable difference between the EMG patterns of younger infants during supported walking and new walkers. The data presented in the published report were limited, however; supported walkers were represented by two exemplar step cycles for one supported walker and no data, only text, were presented to describe new walkers’ muscle activations. Sutherland and colleagues are well known for their comprehensive description of walking parameters over the period of 1 to 7 years (chronological age) in a largely cross-sectional sample of nearly 450 children (Sutherland, Olshen, Biden, & Wyatt, 1988). The youngest age studied was 12 months. They reported walking onset mean to be 10.6 months, therefore their youngest walkers had an average of 1.4 months of walking experience by the time of their initial testing. These researchers monitored 5 muscles in the leg ($n=6$ to 20, depending on the muscle, for 1-year-olds) and reported data as bar graphs depicting the mean onset and end time for each muscle’s activation. The data imply that each muscle generated a single burst, beginning during swing (typically) or just before, and ending at some point during stance, suggesting considerable consistency among participants. The lack of standard deviation bars or raw data make it impossible to address the variability that underlies these data.

Limitations of the extant studies make it difficult to conclude with confidence how muscle activation patterns unfold in novice walkers as well as to generalize and replicate findings. In all of the studies cited above EMG data reduction was limited to visual inspection of time series graphs to determine the onset and termination of bursts of muscle activity and how often coactivation of muscles occurred. Small samples and mixed longitudinal data can also lead to skewed generalizations about the population and patterns of change. Although the researchers cited above conclude evidence for early, if limited, muscle pattern stability, other studies highlight the variability in timing and presence of muscle bursts. Hadders-Algra, Brogren, & Forssberg (1996) and Spencer & Thelen (2000), while providing evidence of correlations between direction of movement and muscles activated, nevertheless, latencies and consistency of individual muscles was highly variable for responses to directionally specific perturbations and for reaches to midline, respectively. This variability, dominant in nascent behavior, gave way over time to more stable patterns.

Our goals in this study were therefore, first, to illustrate a method by which researchers can objectively determine the onset and offset of leg and trunk muscle firings in walking. Second, we used this method to investigate the emergence of patterns of activation of the core locomotor muscles at walking onset and after three months of experience walking. Our hypotheses were that at walking onset EMG patterns would be highly variable, when toddlers were minimally able to control the large number of options available to them, with few if any muscles showing consistent behavior from cycle to cycle, within and across toddlers. We predicted that variability would decrease following three months of walking practice, as would cocontraction among agonist-antagonist pairs. Given that the number of muscles available to produce the forces required to walk is enormous and they can be combined in many ways, we predicted stability in muscle activation pattern would emerge more slowly than interlimb coordination, which, as a joint system, involves fewer degrees of freedom than the muscle system.

2. Method

2.1 Participants

Eight toddlers with typical development, three females and five males, participated in this longitudinal study. We recruited all toddlers from advertisements placed in the local newspaper and flyers distributed at local daycare centers. We communicated with parents via phone from the time they contacted us, prior to walking onset, until their infant was able to perform 3 to 6 independent steps. At that point the first test session occurred. Parents and toddlers came into the lab for multiple visits as part of a larger longitudinal study. For the questions addressed in this paper, we focused on assessing walking behavior at two specific time points. The first time point (T1) was their first visit to our lab, walking onset. Ages ranged from 48 to 74 weeks (mean = 60, SD = 9.55). The second time point (T2) occurred three months after their first visit (T1) to the lab. Mean height at T1 and T2 were 73.3 cm (SD = 3.3) and 77.2 cm (SD = 3.3), respectively. Mean weight at T1 and T2 were 9.9 kg (SD = 0.7) and 10.5 kg (SD = 0.8). Mean weight at birth was 3.15 kg (SD = .52) and mean gestational age was 37.56 weeks (SD = 2.13). Parental reports indicated no complications occurred at birth. Due to technical difficulties, our EMG data for the tibialis anterior and gastrocnemius muscles for two toddlers on one day were not usable. Thus, for muscle activity data our analyses are based on six toddlers. We also collected walking data for two young adults in order to create a baseline comparison of mature walking.

2.2 Procedures

All testing occurred in the Motor Development Laboratory in the Division of Kinesiology at the University of Michigan. 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. Toddlers had sufficient time to play with toys and with research staff in order to become comfortable with the environment.

Next, all clothes were removed from each toddler except diaper. We marked the skin surface of each site requiring a reflective marker with hypoallergenic eyebrow pencil, then attached 2cm 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 used alcohol pads to clean the skin surface prior to placing EMG electrodes on the left leg and lower trunk. Preamplified bipolar electrodes were placed over the muscle belly of the tibialis anterior (T), gastrocnemius (G), quadriceps (rectus femoris, Q), hamstrings (biceps femoris, H) (and rectus abdominus and erector spinae-not analyzed here). To minimize wire movement and infants' attention to them, infants wore a pair of dark tights with holes cut out for the feet and to expose the reflective markers. In addition, we used prewrap to encircle the lower trunk, covering and securing the trunk electrodes. During walking trials, a research assistant walked behind the toddler to support the trailing cables.

For each test trial, toddlers walked over a GAITRite mat placed in the middle of our walkway, from a researcher to a parent and toys at the other end of the walkway. The average number of trials needed to get sufficient data for T1 and T2 was 10 (range = 5 to 14) and 4 (range 3 to 6) respectively. Analog signals from mat sensors were transmitted to our laptop computer at 60Hz. 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, velocity, and foot angle. 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, and velocity was normalized by the square root of gravity times leg length.

To obtain kinematic data, we used a 6-camera Peak Motus™ real-time system to collect reflective marker position data 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 $2.5 \times 1.2 \times 1.2$ meters. 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.

2.3 Data reduction

For the purposes of this paper, we examined left strides only because EMG electrodes were placed on the left leg. We identified potentially usable left steps first, as ones with clear left heel and left toe marker data, second as ones with at least two continuous left foot contacts, and third, ones in which toddlers were not falling, stopping, or walking off the mat during the trial. To be selected, a left stride cycle also had to yield usable data at two levels, kinematic and EMG. For T1 we were able to identify a minimum of 3-left stride cycles for each toddler and used up to 6 left stride cycles if more were available. For T2 we were able to analyze a minimum of 5 left stride cycles for each toddler and set the maximum at 8 stride cycles. The gait events, touchdown and toe-off, were determined from kinematic data by using our custom-written MatLab programs (see Fig. 1 for exemplar EMG data with gait events). The algorithms to identify these gait events were developed by Hreljac and Marshall (2000). We determined the time of foot contact as the time of local minimum in the vertical acceleration of the heel marker. The time of toe-off was identified at the local maximum of horizontal acceleration of the toe marker. We used foot contact to identify onset of each stride cycle.

We filtered the EMG data with a band-pass filter; cutoff frequencies were set at 75 Hz and 300 Hz (Spencer and Thelen, 2000). The low-end cutoff of the filter removed electrical noise associated with wire sway and biological artifacts. The high-end cutoff eliminated extraneous tissue noise at the electrode site. After band-pass filtering, the EMG data were rectified. We eliminated the high-frequency components added after rectification by using boxcar averaging with a window size of seven samples. Next, each frame of the EMG data was converted into an on-off designation. To determine on-off activity, we used a 50-ms window moved frame by frame across each EMG signal. If the average EMG activity within a window exceeded a noise threshold, the center value of that window was considered 'on'. To determine the noise threshold, we computed the frequency histograms of the amplitudes for each EMG signal of each trial. In addition, we normalized the frequency histograms to the modal amplitude for each trial. We used a cutoff value of 0.15 of the normalized modal frequency to differentiate EMG on-off activity (Spencer and Thelen, 2000). Finally, the duration of 'on' activity was summed across small segments of 'on' activity if the period of inactivity between segments was less than 50 msec. Figure 1 illustrates an example of the EMG data at three processing stages: rectified raw data, filtered and smoothed data, on-off data. The goals of this technique were to operationalize the determination of EMG activation and to make the decision objective and reproducible, not subjective. Further, this technique facilitated examining the muscle activation patterns without baseline EMG activity in toddlers because this is generally not possible to do reliably with toddlers. This technique also allows us to investigate how muscle activation patterns change over developmental time.

We used three methods to summarize muscle activation patterns. The first method is a muscle state analysis, reflecting the "state" of all muscles for each frame of EMG activity, developed by Spencer & Thelen (1999). Their state analysis was a modification of previous work developed by Cocatre-Zilgien and Delcomyn (1993) related to assessing changes in cockroach gait. Each state indicates whether each muscle in the set of muscles monitored is "on" or "off" during that frame. For computer programming purposes, the activity of each muscle is characterized by 0 (off) or 1 (on). We combined the T, G, Q, and H to examine the state of the leg muscles, resulting in 16 possible muscle states, ranging from [0000] to [1111]. While [0000] indicated no muscle was active in the leg, [1111], indicated all four leg muscles were active. This method provided a way to quantify all possible muscle activation patterns, such as no muscle activation, single muscle activation, and co-activation among muscles, instead of identifying only one co-activation pattern, such as co-activation of T and G only, per trial. The duration of occurrence of each state can be analyzed to examine which muscles were active and how long they co-contracted.

The second method we used was to examine the probability of activation for each muscle across all stride cycles. A probability value of "one" means that the muscle was always "on" for all cycles for each toddler. A probability of ".5" means that the muscle was "on" for fifty percent of all cycles produced by these toddlers. A probability of "zero" indicates that the muscle was never activated. We summed all "on" values for each time point in the cycle, then divided by the total number of stride cycles to calculate the probability of activation across toddlers and across cycles.

In the third method, we summarized EMG data by calculating specific co-activation values for muscle pairs by using our modified method, which was similar to the method originally designed by Winter (1990). In contrast to Winter's method which take amplitude of EMG data into the equation, the equation we used focused only on the coincidence of frames during which the muscle pairs were on or off during the stride cycle. The co-activation equation we used is defined below.

$$\text{Co-activation value} = 2 \times (\text{number of frames when both muscle A and muscle B are on}) / (\text{number of frames when muscle A is on} + \text{number of frames when muscle B is on}).$$

2.3 Statistical analysis

We used a one-way ANOVA with repeated measures on time to analyze differences between T1 and T2 for each walking characteristic (means and variability). We used a 2 (Times) $\times$ 6 (Participants) MANOVA with repeated measures on time with each muscle state as a dependent variable to analyze change. The co-activation value was also analyzed by 2 (Times) $\times$ 6 (Participants) MANOVA with repeated measures on time. The significance level was 0.05.

3. Results

3.1 Kinematic and end point effector data

Table 1 summarizes descriptive walking characteristics of our toddlers at T1 and T2. Means for all variables changed significantly over time. ANOVAs for individual dependent variables show that step width ($F(1,7) = 8.148, p = 0.025$), normalized step width ($F(1,7) = 9.267, p = 0.019$), stance phase (%) ($F(1,7) = 7.595, p = 0.028$), and double support phase (%) ($F(1,7) = 34.439, p = 0.001$) decreased significantly over time. Step length ($F(1,7) = 89.619, p < 0.001$), normalized step length ($F(1,7) = 56.02, p < 0.001$), velocity ($F(1,7) = 64.102, p < 0.001$), and normalized velocity ($F(1,7) = 49.305, p < 0.001$) increased significantly. Variability was defined as coefficient of variation for step length, normalized step length, step width, normalized step width, and velocity, and as standard deviation for stance phase, double support phase, and foot angle. Coefficient of variation is defined as standard deviation divided by the mean. Variability of step length ($F(1,7) = 11.842, p = 0.011$), normalized step length ($F(1,7) = 11.894, p = 0.011$), stance phase ($F(1,7) = 5.769, p = 0.047$), and double support phase ($F(1,7) = 8.856, p = 0.021$) reduced significantly from T1 to T2. Variability for velocity ($F(1,7) = 4.169, p = 0.08$) showed a trend toward decreased variability. Only variability of step width ($F(1,7) = 7.86, p = 0.026$) and normalized step width ($F(1,7) = 7.898, p = 0.026$) statistically increased with time.

Figure 2 presents exemplar thigh, shank, and foot segmental angle trajectories for one toddler at T1 and T2 and for one young adult. The thigh segmental angle is the angle created by the thigh relative to horizontal; shank segmental angle is the angle between shank and horizontal. The foot segmental angle is the angle created by the foot relative to a vertical line. We illustrate segmental angle trajectory examples instead of using ensemble averages because toddlers, particularly at T1, produce a wide variety of trajectory patterns. This figure shows relatively high variability in their lower limb segmental angles at T1. In contrast, with three additional months of walking experience variability reduces significantly, although at T2 patterns remained less consistent than those of adults.

3.2 Muscle activation data

3.2.1 Muscle states: Exemplars—In Fig. 3, we first illustrate the on-off muscle activity across multiple stride cycles for all four muscles at T1 and T2 for two toddlers. This shows that the timing and duration of individual muscle activation from cycle to cycle at T1 were more inconsistent than at T2. However, it is also clear that the variability in muscle activity across multiple stride cycles is still quite apparent at T2. Figures 4a and 4b present muscle activation depicted as state data for two stride cycles for each of our 6 toddlers. These figures represent the percentage of time within the cycle when each of the 16 muscle states occurred at T1 and T2. Stacked bar graphs illustrate the high level of variability in muscle states with many combinations of muscles appearing when toddlers walk at T1. Variability in muscle states reduces after three months, but still remains inconsistent across toddlers and between cycles at T2. By T2, some similarity among toddlers and between cycles is beginning to emerge but

muscle activation patterns look distinctly different from those of young adults (Fig. 4c). In addition, muscle activation patterns at T1 and T2 were more variable than those of young adults. Note that adults, even when asked to walk at their preferred speed over ground, showed some variability between cycles. More specifically, the muscle activation patterns at T2 showed relatively consistent G-H co-activation and T-Q co-activation across toddlers compared to T1. The muscle activation patterns in young adults were more consistent through cycle to cycle, especially in generating more efficient and consistent single muscle activations, such as H (hamstrings) and G (gastrocnemius) muscle activations. In particular, young adults showed significant and quite stable muscle bursts compared to toddlers at T1 and T2.

3.2.2 Probability of activation for individual muscles—Figure 5 illustrates the probability of activation across all cycles and all participants for each muscle at T1 and T2 and in young adults. A probability value of 1 means that the muscle was active across all cycles and all participants at that particular point of time during the cycle. In other words, if the probability is closer to 1, the muscle is more likely to be active in all cycles and all participants; if it is close to 0, it is unlikely to be active. By looking at the probability of muscle activation, we can determine if any activation pattern is emerging within the overall variability of muscle bursts seen from cycle to cycle. We found that there was no clear pattern that reflects a consistent “on” and “off” across all cycles, for any muscle at T1, although G showed a ramping up of probability to a peak of just above .5 during stance. Due to the low probability value for most muscles, it is hard to predict when muscles were likely to be active within any particular cycle produced at T1. By T2, we could begin to differentiate some temporal similarities in muscle activation patterns. We start to see the emerging muscle activation patterns at T2 although they were still different from the patterns in young adults. Especially in the four leg muscles, a reciprocal muscle activation pattern of agonist and antagonist muscles began to emerge at T2 though the timing of muscle activities remained quite broad. In contrast to T1 and T2, there were clear muscle activation patterns across cycles in young adults. In summary, the variability of muscle activation pattern was extremely high when toddlers were able to perform only 3 to 6 consecutive independent steps, decreased slowly with three additional months of walking experiences, but remained distinctly different from that of young adults.

3.2.3 Muscle states, collapsed over participants—Figure 6 quantifies the muscle state activity illustrated in figure 4 a & b by averaging over all toddlers and all of their cycles. It shows the mean percentages of each stride cycle in which 16 muscle states for four major leg muscles (T, G, Q, and H) occurred at T1 and T2. We obtained a significant Time main effect (Wilks' Lambda = 0.012, $F(16,4) = 20.097$, $p = 0.005$), a significant Participants main effect (Wilks' Lambda < 0.001, $F(80,24) = 2.388$, $p = 0.01$), a significant Time $\times$ Participants interaction effect (Wilks' Lambda < 0.001, $F(80,24) = 2.139$, $p = 0.02$). Subsequent univariate ANOVAs and inspection of means indicated that toddlers at T1 used significantly more co-activation of all four muscles (T, G, Q, H) ($F(1,19) = 18.652$, $p < 0.001$), more co-activation in three muscles (T, G, Q) ($F(1,19) = 20.15$, $p < 0.001$), more co-activation in one muscle pair (T, G) ($F(1,19) = 6.801$, $p = 0.017$), and more activation of T alone ($F(1,19) = 22.134$, $p < 0.001$) and G alone ($F(1,19) = 7.8$, $p = 0.012$) than at T2. Toddlers at T2 used significantly more co-activation in T, Q ($F(1,19) = 19.846$, $p < 0.001$), and more activation of H alone ($F(1,19) = 9.368$, $p = 0.006$). Furthermore, the co-activations in all four leg muscles decrease as age and walking experiences increase, with young adults showing no time when all four leg muscles are concurrently active in a step cycle.

Univariate analyses of muscle state variables for the Participant main effect showed significant differences for single activation of H ($F(5,19) = 3.03$, $p = 0.035$), one muscle pair (T, H) ($F(5,19) = 4.119$, $p = 0.011$), three muscles activation of TQH ($F(5,19) = 3.967$, $p = 0.012$) and TGQ ($F(5,19) = 10.136$, $p < 0.001$), and all four leg muscle activation TGQH ($F(5,19) = 6.2$, $p = 0.001$).

Univariate analyses of muscle state variables for the Time $\times$ Participant main effect showed significant differences for no-activation ($F(5,19) = 2.779, p = 0.048$), single activation of G alone ($F(5,19) = 3.105, p = 0.032$), one muscle pair (T, H) ($F(5,19) = 2.815, p = 0.046$), three muscles (T, G, Q) ($F(5,19) = 3.052, p = 0.035$), and all four leg muscles (T, G, Q, and H) ($F(5,19) = 4.419, p = 0.008$).

3.2.4 Co-activation values calculated via conventional equation—In order to focus on specific agonist-antagonist pairs and address their respective co-activation as a proportion of the two muscles' total activity we used Winter's (1990) equation to derive a co-activation value. Figure 7 illustrates the co-activation values of four muscle pairs commonly cited in the gait literature as agonist and antagonist pairs. They are T & G (ankle dorsiflexor and ankle plantarflexor), Q & H (knee extensor and knee flexor), and G & Q (knee flexor and knee extensor) in T1 and T2. Results show a significant Time main effect (Wilks' Lambda = 0.517, $F(3,17) = 5.293, p = 0.009$), Participant main effect (Wilks' Lambda = 0.263, $F(15,47) = 1.961, p = 0.04$), and Time $\times$ Participant interaction effect (Wilks' Lambda = 0.186, $F(15,47) = 2.647, p = 0.006$). Subsequent univariate tests showed that there was a significant decrease in co-activation only of Q and H from T1 to T2 ($F(1,19) = 6.061, p = 0.024$). The between-participants effect were significant for Q-H ($F(5,19) = 6.682, p = 0.001$). In addition, we found a significant Time $\times$ Participant interaction effect only for Q-H ($F(5,19) = 6.901, p = 0.001$).

4. Discussion

Our goals for this study were a.) to illustrate an objective method to determine the onset and end of muscle bursts when muscle activity is particularly variable and unpredictable and b.) to examine the earliest patterns of leg muscle activity at walking onset. We believe our results suggest that the method outlined by Spencer and Thelen (1999, 2000) for infants' arm muscle activity during the onset of reaching works equally well for leg muscle activity as walking skill emerges. This method involves the normalization of frequency histograms of the amplitudes of EMG signals for each trial to find the modal amplitude and determine "cut-off" values as a minimum but uniform proportion of this modal value. Another procedure used as a reference for determining "cut-off" values for on-off events is to collect EMG activity during resting state (Hodges & Bui, 1996). However, this is typically not possible to accomplish when working with infants. Hadders-Algra et al (1996) provide another means to determine activation of muscle bursts in response to perturbation (platform translation) during sitting that uses the tonic activity of quiet sitting as the baseline. This seems a usable approach for perturbations of static posture but not well suited to gait. Our procedure, like Hodges & Bui, 1996 and Hadders-Algra et al. 1996, overcomes the ambiguity of traditional approaches in which events are selected manually based on visual review of EMG time series data. Identifying muscle onset and offset by visual inspection is particularly problematic when EMG amplitudes are small, making the signal to noise ratio low. This occurs when there is muscle weakness as in adults with spinal cord injuries, or in small in-tact systems, like toddlers. Thus, establishing a normative reference (modal amplitude, here) provides a standard against which increases beyond noise can be determined objectively. Replication of procedures and comparisons of data across research groups become feasible and quantifiable. After data have been converted to frames of "on" or "off," activity researchers can organize the data for a variety of subsequent analyses. We chose to focus largely, in this paper, on state analyses, or the frame by frame determination of combinations of muscles that were active within stride cycles.

Our results provide a unique addition to the literature on origins of walking in toddlers and, in so doing, illustrate the importance of an objective technique for reducing/analyzing muscle onset and offset. Previously, researchers who used only visual observation methods to characterize early leg muscle patterns concluded that new walkers utilized the basics of an inherent pattern from the outset (Forssberg, 1985; Okamoto & Okamoto, 2001; Okamoto et

al, 2003). This conclusion suggests that the core of rhythmic pattern generation was somehow built into the system. Such characterizations were, typically, based on very small samples of highly variable (cycle to cycle) EMG signals, making interpretation and generalization particularly challenging. Our results show high variability as well. But, with an objective technique for determining onset and offset applied to the data the characterization becomes one of a system that is exploring multiple options for generating necessary and sufficient force; a system that has not, at walking onset, selected one or even multiple preferred patterns.

The data we presented here are, in fact, consistent with results observed by several research groups for the emergence of muscle patterns during sitting and reaching (Harbourne, Giuliani, & Neela, 1993; Thelen et al., 1993; Van der Fits et al., 1999). For example, Hadders-Algra and colleagues (Hadders-Algra, Brogren & Forssberg, 1996) monitored the activity of neck and trunk muscle responses of infants during independent sitting when posture was perturbed via surface translations. Half of the infants received training to control their bodies while in a seated posture. Across ages (5.5–9.5 months) infants demonstrated directionally appropriate muscle activity. However, during early sitting infants also demonstrated a huge variety of responses that progressed through an “experientially guided selection and strengthening of the most appropriate responses” (p.297). Infants in the training group progressed significantly faster than those in the control group. Thelen and colleagues observed high variability across infants and trials in the upper trunk and upper arm muscle activity of infants, prior to and during early successful reaches (Thelen et al., 1993; Spencer & Thelen, 2000). Further, infants demonstrated some association between hand location at reach onset and muscle activity that shifted in the relative proportions of muscle activity and co-activity over several months. In this context infants were seated with their trunk strapped to a firm back support. This very stable base constrained the degrees of freedom in the system, thus increasing the likelihood that infants would select directionally relevant muscle activations.

Although muscle organization appears to emerge slowly and to require an enormous amount of practice before stable patterns begin to emerge, other walking parameters stabilize more quickly. Numerous scientists have proposed and supported the concept that the interlimb phasing (180° rhythmic coupling between the legs) is the essence of, or the collective variable for, walking (Schöner, Jiang, & Kelso, 1990; Thelen & Ulrich, 1991; Whittall, 1989). Conversely, this is the parameter by which walking is defined and differentiated from other gaits, such as galloping, jumping, or hopping. Mean values for interlimb phasing match that of adults at walking onset but with greater variability, achieving adult-like consistency quickly, after three months of practice (Clark et al., 1988). At the level of segmental patterns, at walking onset the variability in the timing of reversals and direction of rotations varied sufficiently to make calculation of ensemble averages impossible. Yet, in combination, the limb segments converged to produce functional stance and swing phases for short periods of time (3–6 strides). Three months of practice enabled toddlers not only to maintain this gait pattern for many cycles but to produce predictable and stable segmental trajectories that approached those of adults (see Fig 2). The stable interlimb and segmental patterns are, nevertheless, underscored by quite varied muscle patterns at walking onset and three months later. At walking onset we observed nearly all possibilities of muscle activation patterns and no activation pattern dominated. Three months of practice induced change. We saw a reduction in the early high levels of co-contraction and shifts in the relative contribution of muscle states; some muscle states increased while others decreased. Nevertheless, across the four surface leg muscles we monitored (leaving 26 muscles of the thigh and shank we did not monitor but which likely also contribute to the behavior), high variability continued to dominate across cycles and participants.

The differences we observed in the levels of analysis expressed here are consistent with a selectionist and dynamic theory of development. Stable patterns emerge via exploration, selection and practice. A complex and dynamic system self-organizes behavior at a task-

specific level; the constraints on producing steps are much stronger at the level of assembling the segmental movements than on the particular muscles to achieve them. To walk, one must alternate the limbs. The joints must, in some vector combination, flex and extend. The mechanics of the limb and leg segment connectivity allow variation but within this particular gait at least, the options are more limited than for the organization of the muscle patterns that underlie these kinematics. The enormous redundancy at the level of the muscles provides an abundance of resources that may be combined in numerous ways to complement the forces of gravity and motion-dependent forces to achieve flexion and extension of the legs.

For the human system to take advantage of this redundancy and produce all of the varied solutions needed simply to navigate the world in everyday life the neuromuscular system must be organized flexibly and continuously adapting to and coupling with sensory information and changing force fields. The complexity of the role the muscles play in limb movements was described by Bernstein many years ago (1967). He argued that body segments act continually in a changing field of forces due to gravity and mechanical actions of other parts of the body. Thus, a particular muscle contraction has different effects depending on the postural and movement context in which it occurs. In addition, muscles and joints have spring-like properties of tension and recoil that depend on their degree of stretch and their stiffness, but these relations are not simple or linear. Together, the biodynamic problem makes it impossible for unique and detailed solutions to be stored in the system in advance. Through interaction with the periphery the patterns of walking are selected and given shape. Stable patterns emerge when behaviors have been practiced sufficiently and when the context and task are unchanging. Yet, as one can see from our adult data (Fig. 2), even in a very stable situation, humans produce cycle to cycle variations in their muscle patterns, as the softly and adeptly assemble their available resources to perform this well-practiced, ontogenetic task.

That neural networks facilitate the muscle activity underlying alternating leg oscillations is undeniable. The nature of these networks, their origin and detail, remain a topic of some debate. One approach is to posit an innate complex system of spinal and higher nervous system neurons that generate rhythmic leg patterns, or, a central pattern generator (CPG) (Hadders-Algra, 2002). We lean toward a network, involving the spinal and higher levels, that emerges, as Edelman proposes (Edelman, 1987; Sporns & Edelman, 1993), through the process of repeated cycles of perception and action. The importance of activity in the connectivity of neurons in fetal development has been demonstrated (e.g., Hanson & Landmesser, 2004). Others have modeled self-organization of spinal neurons in the vertebrate in which the contributions from multiple sources (e.g., skeletal, muscular, sensory) are essential to the development of the network, not merely supplemental to it (e.g., van Heijst & Vos, 1997; Taga, Yamaguchi, & Shimizu, 1991).

To summarize, we posit that our data are consistent with an epigenetic explanation of development, one in which the driving force is exploration and selection. Motor skills, including that of an evolutionarily old skill such as walking, is functionally established and stabilized over time through repeated cycles of perceiving and acting, that is, goal-directed practice. Toddlers discover the boundaries of their workspace to achieve the task of alternately moving one limb forward then the other, balancing between periods of disequilibrium and recovery, to make progress upright toward their goal. Repetition allows the system to begin to settle into increasing stability across levels, first those with fewer and then those with more degrees of freedom. At the level of the nervous and muscle system the options are enormous, both demanding significant experience to achieve consistency and providing significant opportunities to adapt to inconsistencies in the functional demands of life.

Acknowledgements

We thank all of the participants and their families for their commitment to this study. This study was supported by NIH grant R01 HD42728-01 awarded to B.Ulrich.

References

- Adolph KE, Eppler MA, Gibson EJ. Crawling versus walking infants' perception of affordances for locomotion over sloping surfaces. *Child Development* 1993;64:1158–1174. [PubMed: 8404262]
- Bayley N. The development of motor abilities during the first three years. *Monographs of the Society for Research in Child Development* 1935;1(1):1–26.
- Bernstein, N. (1967). *The co-ordination and regulation of movements* New York: Pergamon.
- Breniere Y, Bril B. Development of postural control of gravity forces in children during the first 5 years of walking. *Experimental Brain Research* 1998;121:255–262.
- Bril B, Breniere Y. Steady-state velocity and temporal structure of gait during the first six months of autonomous walking. *Human Movement Science* 1989;8:99–122.
- Berger W, Quintern J, Dietz V. Pathophysiology of gait in children with cerebral palsy. *Electroencephalography & Clinical Neurophysiology* 1982;53:538–548. [PubMed: 6177498]
- Clark JE, Phillips SJ. The step cycle organization of infant walkers. *Journal of Motor Behavior* 1987;19:421–433. [PubMed: 15136270]
- Clark, J.E., & Phillips, S.J. (1991). The development of intralimb coordination in the first six months of walking. In J.Fagard & P. Wolff (Eds.), *The development of timing control and temporal organization in coordinated action* (pp. 245–257). Amsterdam: Elsevier Science Publishers.
- Clark JE, Phillips SJ. A longitudinal study of intralimb coordination in the first year of independent walking: A dynamical systems analysis. *Child Development* 1993;64:1143–1157. [PubMed: 8404261]
- Clark JE, Whittall J, Phillips SJ. Human interlimb coordination: The first 6 months of independent walking. *Developmental Psychobiology* 1988;21(5):445–456. [PubMed: 3402667]
- Cocatre-Zilgien JH, Delcomyn F. A new method for depicting animal step patterns. *Animal Behavior* 1993;45:820–824.
- Corbetta D, Bojczyk KE. Infants return to two-handed reaching when they are learning to walk. *Journal of Motor Behavior* 2002;34(1):83–95. [PubMed: 11880252]
- Dietz V, Quintern J, Berger W. Electrophysiological studies of gait in spasticity and rigidity. Evidence that altered mechanical properties of muscle contribute to hypertonia. *Brain* 1981;104:431–449. [PubMed: 7272709]
- Edelman, G.M. (1987). *Neural Darwinism* New York: Basic Books.
- Forssberg H. Ontogeny of human locomotor control. I. Infant stepping, supported locomotion and transition to independent locomotion. *Experimental Brain Research* 1985;57:480–493.
- Forssberg H, Hirschfeld H. Postural adjustments in sitting human following external perturbations: muscle activity and kinematics. *Experimental Brain Research* 1994;97:515–527.
- Gelfand IM, Latash ML. On the problem of adequate language in movement science. *Motor Control* 1998;2:306–313. [PubMed: 9758883]
- Gibson EJ. Exploratory behavior in the development of perceiving, acting, and the acquiring of knowledge. *Annual Review of Psychology* 1988;39:1–41.
- Goldfield, E.C. (1995). *Emergent forms: Origins and early development of human action and perception* Oxford Press: NY.
- Hadders-Algra M. Variability in infant motor behavior: A hallmark of the healthy nervous system. *Infant Behavior and Development* 2002;25:433–451.
- Hadders-Algra M, Brogren E, Forssberg H. Ontogeny of postural adjustments during sitting in infancy: Variation, selection, and modulation. *Journal of Physiology* 1996;493:273–288. [PubMed: 8735712]
- Hanson MG, Landmesser LT. Normal patterns of spontaneous activity are required for correct motor axon guidance and the expression of specific guidance molecules. *Neuron* 2004;43:687–701. [PubMed: 15339650]
- Harbourne RT, Giuliani C, Neela JM. A kinematic and electromyographic analysis of the development of sitting posture in infants. *Developmental Psychobiology* 1993;26(1):51–64. [PubMed: 8440403]

- van Heijst JJ, Vos JE. Self-organizing effects of spontaneous neural activity on the development of spinal locomotor circuits in vertebrates. *Biological Cybernetics* 1997;77:185–195. [PubMed: 9352632]
- Hodges PW, Bui BH. A comparison of computer-based methods for the determination of onset of muscle contraction using electromyography. *Electroencephalography and Clinical Neurophysiology* 1996;110:511–519. [PubMed: 9020824]
- Hof L. Scaling gait data to body size. *Gait and Posture* 1996;4:222–223.
- Hreljac A, Marshall RN. Algorithms to determine event timing during normal walking using kinematic data. *Journal of Biomechanics* 2000;33:783–786. [PubMed: 10808002]
- Kelso, J.A.S. (1995). *Dynamic patterns: The self-organization of brain and behavior* Cambridge, MA: MIT Press..
- Latash ML. Independent control of joint stiffness in the framework of the equilibrium-point hypothesis. *Biological Cybernetics* 1992;67:377–384. [PubMed: 1515515]
- Latash ML, Scholz JP, Schoner G. Motor control strategies revealed in the structure of motor variability. *Exercise and Sport Sciences Reviews* 2002;30(1):26–31. [PubMed: 11800496]
- Ledebt A. Changes in arm posture during the early acquisition of walking. *Infant Behavior and Development* 2000;23:79–89.
- Okamoto T, Kumamoto M. Electromyography study of the learning process of walking in infants. *Electromyography* 1972;12:149–158.
- Okamoto T, Okamoto K. Electromyographic characteristics at the onset of independent walking in infancy. *Electromyography and Clinical Neurophysiology* 2001;41:33–41. [PubMed: 11234565]
- Okamoto T, Okamoto K, Andrew PD. Electromyography developmental changes in one individual from newborn stepping to mature walking. *Gait and Posture* 2003;17:18–27. [PubMed: 12535722]
- Schöner G, Jiang WY, Kelso JAS. A synergetic theory of quadrupedal gaits and gait transitions. *Journal of Theoretical Biology* 1990;142:359–391. [PubMed: 2338828]
- Shirley, M.M. (1933). *The first two years: A study of twenty-five babies. Vol.1. Posture and locomotor development* Minneapolis: University of Minnesota Press.
- Spencer JP, Thelen E. A multimuscle state analysis of adult motor learning. *Experimental Brain Research* 1999;128:505–516.
- Spencer JP, Thelen E. Spatially specific changes in infants' muscle coactivity as they learn to reach. *Infancy* 2000;1(3):275–302.
- Sporns O, Edelman GM. Solving Bernstein's problem: A proposal for the development of coordinated movement by selection. *Child Development* 1993;64(4):960–981. [PubMed: 8404271]
- Sutherland, D.H., Olshen, R., Biden, & Wyatt (1988). *The development of mature walking* Oxford: MacKeith Press.
- Taga G, Yamaguchi Y, Shimizu H. Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment. *Biological Cybernetics* 1991;65(3):147–159. [PubMed: 1912008]
- Thelen E. Developmental origins of motor coordination: leg movements in human infants. *Developmental Psychobiology* 1985;18(1):1–22. [PubMed: 3967798]
- Thelen E. Motor Development. A new synthesis. *American Psychologist* 1995;50:79–95. [PubMed: 7879990]
- Thelen E, Corbetta D. Exploration and selection in the early acquisition of skill. *International Review of Neurobiology* 1994;37:75–102. [PubMed: 7883488]
- Thelen, E. & Smith, L. B. (1994). *A dynamics systems approach to the development of cognition and action* Cambridge, MA: Bradford Books/MIT Press.
- Thelen E, Ulrich BD. Hidden skills: A dynamic systems analysis of treadmill stepping during the first year. *Monographs of the Society for Research in Child Development* 1991;56(1, Serial No. 223)
- Turvey MT, Fitzpatrick P. Commentary: Development of perception-action systems and general principles of pattern formation. *Child Development* 1993;64(4):1175–1190. [PubMed: 8404263]
- Ulrich DA, Ulrich BD, Angulo-Kinzler RM, Yun JK. Treadmill training of infants with Down syndrome: Evidence-based developmental outcomes. *Pediatrics* 2001;108(5):1–7. [PubMed: 11433046]
- Whitall J. A developmental study of the interlimb coordination in running and galloping. *Journal of Motor Behavior* 1989;21:409–428. [PubMed: 15136254]

Winter, D. A. (1990). *Biomechanics and motor control of human movement*, 2nd Ed. New York: Wiley.

Figure 1.

Example of the tibialis anterior (T) EMG data for one trial with three complete strides and two incomplete strides (at the beginning and the end of trial) for one toddler. The solid vertical line (—) indicates foot contact with the floor. The dashed vertical line (----) identifies toe-off. On and off muscle activity are presented as 0 (off) or 1 (on).

Figure 2. Thigh, shank, and foot segmental angles for 3 exemplar step cycles. One toddler at T1 (a.) and T2 (b.), and one young adult (c.).

Figure 3.

The on and off muscle activation during T1 (left) and T2 (right). The solid line (—) indicates the timing of foot contact with the floor. The dashed line (----) identifies the timing of toe-off. The on and off muscle activities are presented as 0 (off) or 1 (on).

Figure 4.

Stacked bar graphs illustrating percent of time within a step cycle, for two exemplar cycles, that each combination of the 4 leg muscles monitored were activated, (a) T1, (b) T2, and (c) adults. (T = Tibialis anterior, G = Gastrocnemius, Q = Quadriceps femoris, H = Hamstrings). The sequence of the stacked bar graph is from bottom (No-activation) to top (all muscles active).

Figure 5.

The probability of each muscle activation during the stride cycle in toddlers (at T1 and T2) and in young adults. The probability 1 means that the muscle was “on” in all of the stride cycles. In contrast, the probability 0 means that the muscle was “off” in all of the stride cycles. The dash line (---) identifies the average timing of toe-off. The phase before the dash line during the stride cycle is the stance phase. The phase after the dash line during the stride cycle is the swing phase.

Figure 6.

The percentage of stride cycle for each of 16 leg muscle states. * indicates statistical difference ($p < 0.05$).

Figure 7.

The percentage of stride cycle in which each of three muscle pairs was co-activated during T1 and T2. * indicates statistical difference ($p < 0.05$).

Table 1

Walking Characteristics at T1 and T2

	Mean	T1 Variability	T2 Mean	Variability
Step Length (SL) (cm)	12.40 [*]	0.5166 [*]	25.05	0.1340
Step Width (SW) (cm)	16.12 [*]	0.0852 [*]	11.38	0.1558
Normalized SL ^{a1}	0.43 [*]	0.5166 [*]	0.85	0.1340
Normalized SW ^{a1}	0.55 [*]	0.0852 [*]	0.38	0.1558
Stance (%)	65.62 [*]	9.73 ^{*b}	56.33	5.36
Double Support (%)	38.78 [*]	13.65 ^{*b}	14.99	5.33
Velocity (cm/s)	23.05 [*]	0.2478 (p = .08)	82.08	0.1308
Normalized Velocity ^{a2}	1.40 [*]	0.2478 (p = .08)	4.70	0.1308
Foot Angle (FA) (deg)	10.4	10.09 ^b (p = .125)	5.89	6.48
(FA range)	(-2.86 to 17.90) ^c		(-8.09 to 27.28)	

^{*} indicates statistical difference between T1 and T2 ($p < 0.05$).

^{a1} SL and SW were normalized by leg length.

^{a2} Normalized Velocity = velocity/square root of ($g \times \text{leg length}$) (Hof, 1996)

^b Variation was calculated as coefficient of variation with the exception of stance, double support, and foot angle, for which standard deviation was used.

^c Negative foot angle means toe in; positive foot angle means toe out.