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Early Complexity Supports Development of Motor Behaviors in the First Months of Life

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Variability

Variability is a general concept and term used in developmental and biomechanical literature to describe a system which is apt to vary or change. Rather than an 'error' of a system attempting to produce a gold standard, variability is now a well-recognized concept in both developmental theory and empirical studies. For example, a dynamic systems view of development highlights how behavior can be conceptualized as having fluctuating periods of stability and variability (Thelen & Smith, 1994). Moreover, Gibson (Gibson, 2000) and Edelman (Edelman, 1987) propose that during development of new behaviors the system explores possible strategies for that behavior, selects a few strategies which are most efficient, and reduces the use of the non-preferred strategies. Variability is frequently described as a key indicator of typical motor development from fetal movements, to standing, sitting, and walking behaviors.(Adolph & Berger, 2006; Chen, Metcalfe, Chang, Jeka, & Clark, 2008; Hadders-Algra, 2002; Harbourne & Stergiou, 2003) This study extends previous research by looking at the magnitude and complexity of *center of pressure (COP) displacement as a measure of postural control* variability during the emergence of motor behaviors. In the following sections we will outline the significance of describing changes in complexity during early development.

Complexity: General

The majority of research on motor behavior variability early in development *focuses* on the magnitude of variability, however, the temporal structure or 'complexity' of variability provides insights into the developmental process. (Harbourne & Stergiou, 2003; Smith, Stergiou, & Ulrich, 2010). Optimal complexity is described as an intermediate state midway between excessive order or predictability and excessive disorder or no predictability.(Stergiou & Decker,

2011) Optimal *complexity* is proposed to characterize healthy human body function and signify effective cooperation between the participating subsystems which enhances the system's ability to adapt to changing task demands. (Pincus, 2001, 2006; Stergiou & Decker, 2011; Stergiou, Harbourne, & Cavanaugh, 2006) In general, behavior which is highly regular and predictable**,** can be said to lack temporal complexity and *is* associated with cardiac conditions, concussions, and inactive elderly.(Cavanaugh, et al., 2005; Cavanaugh, Kochi, & Stergiou, 2010; Pincus, 2001; Pincus, Cummins, & Haddad, 1993; Sosnoff & Newell, 2008).

Complexity: Motor Behavior Development

Studies that investigate the changes in complexity during the development of motor behaviors could provide insight into the process by which typically developing infants learn new behaviors. (Dusing, Kyvelidou, Mercer, & Stergiou, 2009; Harbourne & Stergiou, 2003; Smith, et al., 2010) Harbourne and Stergiou describe changes in the magnitude and complexity of postural sway variability longitudinally, during the development of sitting in typically developing infants (Harbourne & Stergiou, 2003). Complexity *decreases* as sitting ability *improves* from 'prop sitting' to 'free hand sitting'. The authors propose this change *reflects* the infant's ability to control the body and use the available degrees of freedom(Harbourne & Stergiou, 2003). Further research is needed to determine if a similar process occurs during the development of other motor behaviors.

If complexity varies in the same way during the development of multiple behaviors, it may be possible to identify infants who are at risk for atypical development, based on a deviation from the typical progression. Our previous work *demonstrates* that infants born full term and preterm *differ* in both the magnitude and temporal structure of their *center of pressure (COP) displacement* in the supine position at 1 to 3 weeks of adjusted age (Dusing, et al., 2009). Specifically, the *COP displacement* patterns of infants born preterm *are* more repetitive (less complex) and *have* larger magnitudes than infants born full term (Dusing, et al., 2009). This lack of complexity may be an early indicator of an atypical, advanced, or delayed developmental process. An understanding of the developmental changes in complexity of typically developing infants is needed to determine the significance of reduced complexity in infants at high-risk for developmental delays.(Deffeyes, Harbourne, Kyvelidou, Stuberg, & Stergiou, 2009; Dusing, et al., 2009) The current study *addresses* the need for a longitudinal study of change in complexity in the postural control system during the emergence of early motor behaviors.

The **first purpose of this study** is to investigate behavioral complexity of typically developing infants during the emergence of early motor behaviors. Specifically, we quantify *postural control variability using* the magnitude and temporal structure of the *variability in center of pressure (COP) displacement* during the emergence of two early motor behaviors: midline head control and initial reaching. Head control and reaching were selected because they emerge very early in infancy, rely on postural control and are important for future object exploration, social interaction, and cognitive development (Barrett, Traupman, & Needham, 2008; Corbetta & Snapp-Childs, 2009; Thelen & Spencer, 1998). Based on the research outline above, we hypothesize that infants will demonstrate minimal change in the magnitude of the variability *in COP displacement* as head control and reaching emerge. In contrast, we hypothesized that the complexity or temporal structure of the *variability in COP displacement* will be greatest early in development and will decrease as head control and reaching emerge.

Complexity: Adaptation

Complexity supports the use of adaptive strategies to perform motor behaviors.(Stergiou & Decker, 2011) Behavioral skills, such as with reaching, can be influenced by age, experience, condition, and body position (Bhat & Galloway, 2006; Carvalho, Tudella, Caljouw, & Savelsbergh, 2008; Lobo, Galloway, & Savelsbergh, 2004). For example, infants bring head and hands to midline more frequently with a toy in sight than without a toy in sight starting weeks before reach onset.(Bhat & Galloway, 2006; Robertson, Johnson, Masnick, & Weiss, 2007) Carvalho and colleagues (Carvalho, et al., 2008; Carvalho, Tudella, & Savelsbergh, 2007) *demonstrate* that young infants are able to adapt to both intrinsic (age or experience) and extrinsic (body position) factors while reaching. Less experienced and younger infant are affected more by changes in body position than are older or more experienced infants. Likewise the limited research on the postural *control* patterns suggest that the ability to adapt postural control in different conditions varies at different ages. (Chen, et al., 2008; Haddad, Van Emmerik, Wheat, & Hamill, 2008; Newell, 1997; Riach & Hayes, 1987) However, no studies to our knowledge, have evaluated the changes in postural complexity in different conditions during early development of postural control.

The **second purpose of this study** is to investigate the influence of condition and age on the magnitude and complexity of postural c*ontrol* in early infancy. Two conditions; spontaneous movement with and without a visual stimulus are used in order to keep the task as similar as possible while prompting change in the infant's movement strategy. Previous research suggests that infants keep the head midline and reduce spontaneous arm movements when a toy is present compared to the no toy condition. (Bhat, Lee, & Galloway, 2007; Robertson, et al., 2007) Consistent with the proposal that infants with optimal complexity will adapt to changing conditions, we hypothesize that healthy infants *will* reduce the magnitude of their COP displacement between the two conditions. We hypothesize that complexity will not change between conditions, but will change with age, as infants move from a stage of early exploration to strategy selection. (Dusing & Harbourne, 2010; Stergiou, et al., 2006)

Methods

Postural control involves controlling the body's position for multiple purposes such as: (a) *orientation*, the ability to maintain an appropriate relationship between body segments and the environment or a goal, (b)*stability*, control of the center of mass in relationship to the base of support.(Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996) (c) *preparation* for a movement or action, (d) reaction to an internal or external perturbation. Postural control is a dynamic process which enables an individual to remain in a stable position while interacting with the environment or a task and is thus a foundation for most motor skills.(Goldfield, 1995; Reed, 1982) Postural control is frequently measured using the center of pressure (COP) at the base of support.(Prieto, et al., 1996) The variability in COP displacement over time is used to assess the variability of postural *control* in a supine position, prior to the infant learning to sit or stand independently (Dusing, et al., 2009; Fallang, Saugstad, & Hadders-Algra, 2000).

In this paper we use both linear and nonlinear measures for a comprehensive quantification of the variability of postural control. We quantify the magnitude of the variability of postural control using the linear measure of root mean squared (RMS) of the COP displacement. RMS is a reflection of the amount of variability in the COP displacement, but does not describe the temporal structure of the variability or how the COP is displaced over time. The temporal structure of the variability of *the COP displacement* can be quantified using the nonlinear measure of Approximate Entropy (ApEN)(Stergiou, Buzzi, Kurz, & Heidel, 2004). ApEN quantifies the repeatability or predictability of data patterns within a time series. Thus ApEN of the COP displacement time series provides an indicator of how regular or repeatable the postural control strategies are which is a measure of complexity of the postural control system.(Stergiou, et al., 2004)

Subjects:

Twenty-two infants born full term (37-42 weeks of gestation) without medical complications participated in this longitudinal study (Table 1). Infants born preterm, with genetic or musculoskeletal complications, or requiring neonatal intensive care were excluded from this study. Infants were recruited from the community using birth records and investigator contacts. Parents signed consent for their infant(s) to participate prior to the first study visit and the study was approved by the committee for human subjects.

Data Collection Procedures:

In order to capture changes in postural control during the development of head control and early reaching behaviors, study visits were twice per month through 3 months of age and monthly from 3 to 6 months of age. Study visits were completed in the infant's home or child care setting. Each study visit included assessment of COP displacement and motor behaviors during 2 conditions, a Toy Condition and a No Toy Condition described below. Developmental assessments were preformed to ensure the infants included in this study were typically developing. A total of 156 visits were completed for this study with an average of 7 visits per infant (range 4-9 visits). Infants began study visits between 0.5 and 1.5 months of age with the exception of 3 infants who started at 2, 2.5 and 3.0 months. One infant dropped out of the study after the 3 month old visit due to scheduling challenges. This infant's data are included. Two infants missed visits due to illness. Equipment related errors resulted in data loss for 4 visits.

Given the intensive nature of this data collection schedule for families, no infants were excluded from the study for missing visits or having incomplete data. Visits were cut short do to fussiness or fatigue were rescheduled within 1-2 days whenever possible.

COP measurement was completed using a Conformat* pressure sensitive mat sampling at 5 Hz with the infant in supine for 5 minutes in each Condition (Dusing, et al., 2009). A frequency analysis of a representative sample of COP time series indicated that 99.99% of the signal power was below 0.5 Hertz. Therefore, pressure data were sampled with a frequency of 5 Hertz in order to stay a factor of ten above the highest frequency contained in the signal.

The first condition was the No Toy Condition in which the infant was positioned in supine without a visual stimulus or toy for 5 continuous minutes. The examiner or parent was nearby to provide reassurance as needed without contacting the infant and providing as little visual distraction as possible. The second condition was the Toy Condition in which the infant remained in supine and a rattle was suspended over the infant at 75% of the infant's arm length, midway between the infant's shoulders. A new toy was presented every minute for 5 minutes to maintain interest in the visual stimulus. Infants were allowed to grasp the toy, but not remove it from the examiners hand.

The entire COP measurement was video recorded from 2 views, lateral and overhead, and synchronized with the COP data (Figure 1). The Test of Infant Motor Performance (Campbell, 2005) was completed following the COP and video assessments for all infants 0 to 4 months of age (not presented in this manuscript). The Bayley Scales of Infant Development was completed

*Tekscan 307 West First St. South Boston, AM 20127-1309, USA at 3 and 6 months of age to document the anticipated typical development of this sample of infants. Three infants were not assessed using the Bayley scales at either 3 or 6 months. One infant was not assessed at 3 months and another was not assessed at 6 months due to scheduling issues or fussiness.

Data Analysis:

Video of the COP assessments were used for behavioral coding. Time periods in which the infant was in supine, alert, and not crying were identified from the 5 minutes (300 seconds) of video under each Condition and used for behavioral coding and COP analysis. Time periods were on average 294±28 seconds for the No Toy Condition and 279±51 seconds for the Toy Condition. Behavioral coding was completed using the MacShapa verson1.1.2a[†] coding program and coders trained to 85% agreement with the formula: Agree/(Agree+Disagree)*100. Twenty percent of all visits were coded twice to ensure ongoing reliability.(Lobo, et al., 2004) Agreement on behavioral coding variables for head in midline was 90.5% and for toy contacts was 95.8%. To quantify the development of early motor behaviors, two variables were defined. HMidline was operationally defined as the percent of the duration of the No Toy Condition in which the infant's head was in midline. TContact was operationally defined as the percent of the duration of the Toy Condition in which either of the infant's hands was in contact with the toy (TContact).

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The first study purpose required the comparison of the COP data when all infants were at the same developmental level. Since all infants did not learn to keep their head in midline or reach at the same age, time was normalized to the onset of the motor behavior. The first visit in which an infant's head was in midline at least 50 percent of the No Toy Condition period was reported as the age of onset of head midline (AgeHMidline = 0). Likewise the first visit an infant's hand was in contact with a toy 15 percent of the Toy Condition period was reported as the age of onset of early reaching in supine (AgeTContact =0). The criteria of 50 percent and 15 percent were selected after reviewing the data for all infants to determine the percentage in which most infants continually met the criteria after the initial visit in which they met the criteria. For example, once an infant was able to keep his head in midline 50 percent of the time the infant maintained the head in midline at least 50 percent of the time for all subsequent visits. To compare postural control between visits during the emergence of head control and early reaching, COP and behavioral data from 1.5 months before onset to1.0 months after onset were included in the skill specific analysis for our first purpose.

The behavioral coding data was used to identify continuous COP time series in which the infant was in supine, alert, no one was touching the infant and the infant was not touching the toy. As in our previous work(Dusing, et al., 2009), COP time series of 500 data samples or 100 seconds in length were identified from the data collection period. The dependent variables of RMS and ApEN in the caudal cephalic (cc) and medial lateral (ml) directions were calculated (RMScc, RMSml, ApENcc, and ApENml) for each time series using custom Matlab[‡] (version 2008a) programs. RMS was calculated as described by Prieto et al.(Prieto, et al., 1996) The ApEn was calculated using Matlab code developed by Kaplan and Staffin,(Kaplan D, 1996)

[‡] The MathWorks, Natick, MA

implementing the methods of Pincus et al,(Pincus, Gladstone, & Ehrenkranz, 1991) using a lag value of 1, an *r* value of 0.2 times the standard deviation of the data file, and a vector length *m* of 2. These *r* and *m* values are typically used in the calculation of ApEn for human physiologic time series(Stergiou, et al., 2004). The average of all time series of length 500 for each visit and Condition was calculated and used in all statistical analysis. If an infant was unable to stay in a quiet alert state or was in contact with the toy frequently (preventing the identification of a 500 sample time series) then no COP data was included for that visit and Condition. Thus the number of infants included at each age varies with a mean of 17 infants included in the No Toy Condition at each age and 14 infants included in the Toy Condition at each age. There was no systematic trend in the amount of data at each age with the exception of the Toy Condition, after the onset of reaching and at 0.5 months of age, which is addressed in the next section.

Statistical analysis

The dependent variables RMScc, RMSml, ApENcc and ApENml were transformed using a (natural) logarithmic transformation to more closely approximate a normal distribution, Ln(RMScc), Ln(RMSml), Ln(ApENcc), and Ln(ApENml) respectively. All analyses were conducted using these transformed dependent variables. All statistic analysis was completed using SAS® version 9.2.[§]

Two mixed linear models were used to address our first purpose by evaluating changes in the magnitude and temporal structure of the variability of the COP time series [Ln(RMScc), Ln(RMSml), Ln(ApENcc), and Ln(ApENml)] during the development of each motor behavior separately. Model one *reflected* change in the COP measures during the development of head in midline during spontaneous movement without a visual stimulus (AgeHMidline). Model two

[§] SAS Institute INC. , Cary NC, USA

reflected change in the COP measures during early reaching motor behaviors with a visual stimulus (AgeTContact). AgeHMidline and AgeTContact were fitted in to the models as categorical variables without assumptions regarding linearity of the model. There were no visits for an AgeTContact of 0.5 or 1.0 in which the COP time series was greater than 500 samples because once an infant was able to make contact with the toy consistently (AgeTContact=0) the infant did so very frequently preventing collection of the 500 continuous data samples needed for analysis. Thus Model Two utilized AgeTContact from -1.5 to 0 to reflect change during the development of early reaching motor behaviors when each infant was learning to control the arms and makes occasional contacts with the toy, but not consistent or prolonged contacts.

Another mixed linear model was used to address the second purpose where we investigated the impact of Condition over time (Age) on the change in the magnitude and temporal structure of the variability of the COP time series. The model included Condition (Toy and No Toy Conditions), age and an interaction term to predict the transformed dependent measures of Ln(RMScc), Ln(RMSml), Ln(ApENcc), and Ln(ApENml). The Age term included 1 to 4 months of age as there were few visits at 0.5 months or at greater than 4 months in which the infant was supine, alert, not crying, and not in contract with the Toy. At 0.5 months of age the infants were usually fussy after already completing the No Toy Condition. At 5 months of age more than 50 percent of the infants were contacting the toys regularly.

Post-hoc analyses were completed for all significant F tests to determine which mean values were significantly different from each other for each model. A Bonferroni adjustment was used to adjust the p-value of 0.05 for multiple comparisons in each model.

Results

Sample: All 22 infants were typically developing with low risk of developmental delays based on birth history. Mean birth weight was 7.3 (1.1) lbs and mean gestational age was 39.5 (1.1) weeks. The sample was 55 percent female and 9 percent (2 infants) were twins. The infants were primarily Caucasian (86%) with 3 infants being African American (14%). Bayley Scales of Infant Development (Bayley, 2006) score for the 18 infants who completed this measure at 3 and 6 months of age confirmed that these infants were typically developing (Table 1).

Motor Behavior Development: On average infants maintained their head in midline more than 50 percent of the time in the No Toy Conditions at 2.4$\pm$ 0.6 months of age (range 1.5-3.7 months). Model 1 evaluated changes in postural control with increasing proficiency keeping the head in midline during spontaneous movements without a toy present. There was no main effect on the magnitude of variability in the COP displacement as measured by the linear measures Ln(RMScc) or Ln(RMSml) with increasing AgeHMidline, $F=0.90$, $p=0.48$ and $F=0.87$, $p=0.51$ respectively (Figure 2A). This suggests that the magnitude of variability of the COP displacement was not influenced by the infant's proficiency keeping the head in midline. There was a significant main effect in the nonlinear measures Ln(ApENcc) and Ln(ApENml) with increasing AgeHMidline (Table 2, Figure 2B).This suggests that the temporal structure of variability of the COP time series was influenced by the infant's proficiency keeping the head in midline. Post-hoc analysis revealed that Ln(ApENcc) was higher when the infant first learned to keep the head in midline and decreased during the following month (Table 2). The conservative post-hoc analysis could not identify the timing of the differences in Ln(ApENml) with increasing Age HMidline even though a main effect was present. Figure 2B represents changes in

Ln(ApENml) during multiple phases of development of head in midline which cannot be fully described with the statistical models.

On average infants met the reaching criteria (Toy contact 15% of the assessment period) at 4.5$\pm$0.9 months of age (range 2.9 – 6.1 months). Model 2 evaluated the change in the magnitude and the temporal structure of variability of postural sway with increasing proficiency contacting toys. There was no significant main effect on the magnitude of variability in the COP displacement as measured by the linear measures Ln(RMScc) or Ln(RMSml) with increasing AgeTContact, F=0.13, p=0.88 and F=0.18, p=0.83 respectively (Figure 3A). This suggests that the magnitude of variability of the COP displacement was not influenced by the infant's proficiency with early reaching behaviors. There was a significant main effect in the nonlinear measures of the temporal structure of COP variability in the caudal cephalic direction as measured by Ln(ApENcc)with increasing AgeTContact (Table 2). Post-hoc analysis revealed that complexity decreased from 1.5 month before contacting the toy to 1.0 month before contacting the toy. There was no significant main effect of increasing AgeTContact on the nonlinear measure of Ln(ApENml) F=0.69, p=0.53 (Figure 3B). This suggests that complexity in the caudal cephalic but not the medial lateral direction was influenced by the infant's proficiency with early reaching movements.

Adaptation: The final model addressing aim 2 evaluated the impact of Condition (No Toy and Toy) and age on the magnitude and temporal structure of variability of postural sway from 1 to 4 months of age. There was no significant interaction between Condition and age so the interaction term was removed from the model. There was a significant main effect for Condition on the magnitude of the variability of the COP displacement: Ln(RMScc) and Ln(RMSml) $F_{1,21}$ = 5.41, p=0.03 and $F_{1,21}$ = 18.21, p=0.0004 respectively (Figure 4A). Ln(RMScc) and

Ln(RMSml) were both lower in the Toy Condition than in the No Toy Condition. There was no main effect for Condition on the temporal structure of the variability of the COP time series: Ln(ApENcc) and Ln(ApEnML) $F_{5,76} = 0.78$, p=0.57 and $F_{5,76} = 1.80$, p=0.12 respectively (Figure 4B). There was no significant main effect for age on the magnitude of the variability of the COP displacement: Ln(RMScc) and Ln(RMSml) $F_{1,21} = 0.71$, p=0.41 and $F_{1,21} = 0.33$, p=0.57 respectively (Figure 4A). However, there was a significant main effect for age on the temporal structure of the variability of the COP time series: Ln(ApENcc) and Ln(ApEnML) (Table 2, Figure 4B). Post-hoc analysis revealed that Ln(ApENcc)was significantly lower at 4.0 months of age than at 1.5, 2.0, 2.5, or 3 months of age. Ln(ApENcc) did not differ between visits from 1.5 to 3 months of age. Ln(ApEnML) increased between 1 and 3 months of age. Ln(ApEnML) decreased at 4 months of age with significant differences between 2.5 or 3.0 months and 4.0 months of age. The same general pattern was observed in both Conditions.

Discussion:

Complexity supports the emergence of motor behaviors:

The results of this study provide evidence that postural control changes systematically during the emergence of early behaviors. Specifically, the temporal structure of the variability, complexity, of the COP time series but not the magnitude of the variability of the COP time series are influenced by the emergence of head control and reaching in supine. This is especially true in the caudal cephalic direction. These finding are consistent with changes in the magnitude and complexity of postural control variability during the initial emergence of sitting.(Harbourne & Stergiou, 2003) Taken together, we propose that complexity of postural control is modified during the emergence of 3 early behaviors -- head in midline, reaching, and sitting even as magnitude of the variability does not change or changes inconsistently.

Our current data supports the dynamic systems view that a newly emerging behavior increases in stability and decreases in variability as infants gain experience with the behavior(Thelen & Smith, 1994). Viewed from the theories proposed by Gibson (Gibson, 2000) and Edelman (Edelman, 1987), we suggest that postural control complexity during the learning of midline head control and reaching in supine represents variable, non-repetitive, self-generated exploratory postural behavior. We propose that postural control complexity provides perceptual information which helps the infant select a few strategies which are efficient for midline head control or early reaching in supine. Only the selected strategies are used, on a regular basis which is reflected as an increase in repeatability of postural control. Whether the infants are working on keeping the head in midline, reaching, or sitting, we propose that infants proceed through this same process: 1. Exploration of postural control strategies required to complete the behavior 2. Strategy selection and 3.Reduced use of non preferred strategies to accomplish the behavior, thereby reducing complexity.(Edelman, 1987; Gibson, 2000)

Complexity supports adaptation in different conditions:

The results of this study provide evidence that healthy infants can alter the *magnitude of their COP displacement* under different conditions. This is the first study, to our knowledge, to evaluate the impact of condition and age on the magnitude and complexity of COP displacement in early infancy. Our finding that the *magnitude of COP displacement variability decreases* between the No Toy and Toy Condition is consistent with reports of decreased spontaneous activity when *infants look at an object.(Robertson, Bacher, & Huntington, 2001; Robertson, et al., 2007). In a series of studies Robertson and colleagues provide evidence of a tight coupling between gaze and body movementt(S. S. Robertson, et al., 2001; Robertson, et al., 2007). Young infants at 1 and 3* *months of age reduce their general body movements while gazing at the toy and increase body movement just prior to shifting their gaze. While the methodology used by Robertson {Robertson, 2001 #2924} focuses on body movement during the short time scale immediately surrounding an infant gaze event, our results are very similar. We demonstrate a reduction in RMS or the magnitude of the variability of COP displacement during a 100 second time series in which an object is visible to the infant. Robertson and colleagues {Robertson, 2007 #2922} suggests that the ability of the infant to reduce body movement during gaze enhances the infant's ability to attend to the object. This reduction in body movement during gaze reduces the infant's susceptibility to distraction during small bursts of spontaneous motor activity.(Friedman, Watamura, & Robertson, 2005; Robertson, et al., 2007) We did not specifically investigate the coupling between gaze and body movement. However, our study supports previous findings that infants alter their body movements or in our case, the magnitude of the variability of COP displacement when visualizing an object.*

In contrast to the reduction in the magnitude measures presented above, complexity of COP displacement was not influenced by the presence of a visual stimulus. The nearly constant level of complexity reflects the infant's ability to use non-repetitive patterns of postural control under both Toy and No Toy conditions. This data suggests that regardless of the magnitude of the COP displacement variability, the temporal pattern remains complex or non-repetitive. Similarly, Robertson and colleagues (Robertson, Huntington, & Bacher, 2001) describe irregular cyclic motility in healthy infants as a property of early neurobehavioral organization.

We propose that the ability of the healthy infants *in our study* to adapt to different conditions, reflected as a change in the magnitude of *COP displacement* variability, is directly related to the presence of optimal complexity.(Dusing & Harbourne, 2010; Stergiou & Decker, 2011) Because the infants have experience exploring different postural control strategies during early emergence of the motor behavior, the infants are able to select different strategies *(reduced magnitude*) to match each *Condition (Toy or No Toy) without using repetitive strategies.* This finding is consistent with previous literature suggesting that even young infants can adapt *their motor behaviors* to different conditions.(Carvalho, et al., 2008; Carvalho, et al., 2007) *In the next section we will discuss the implications of this work for infants who are at risk for atypical development.*

Adaptability of Postural Control During the Emergence of Motor Behaviors is a hallmark of typical development:

The ability to move through the organized progression of 1) Exploration of postural control strategies, 2) Strategy selection and 3) Reduced use of non preferred strategies to accomplish the behavior during the emergence of early skills may be a hallmark of typical development. (Edelman, 1987; Gibson, 2000) *The theory of optimal complexity suggests that excessive or limited complexity may be of concern. However. research on the postural control of infants with disabilities has consistently identified reduced complexity or increased repeatability in postural control strategies in children with or at high risk of disabilities.(Dusing & Harbourne, 2010) Children with cerebral palsy and infants at risk for cerebral palsy demonstrate more repetitive postural control strategies in sitting than typically developing infants. However there is no specific trend in the magnitude of COP displacement (increased or decreased). (Deffeyes, et al., 2009). Preterm infants demonstrate more repetitive COP displacement with a larger magnitude of sway in the caudal cephalic direction than healthy full term infants in the first weeks of life.(Dusing, et al., 2009) Similarly, reduced complexity is present in the kicking patterns of infants with Myelomeningocele.(Smith, Teulier, Sansom, Stergiou, & Ulrich, 2011)*

While this study supports the growing body of evidence that complexity in postural control differs between typically developing infants and those with disabilities, it also demonstrates the need to measure change in complexity longitudinally and during different conditions. The typically developing infants in this study demonstrated changes in complexity during the development of new skills. We speculate that infants who have disabilities may demonstrate lower levels of complexity early in development and as a result will not have as large a decrease in complexity during development of motor behaviors. In addition, we speculate that the lack of complexity during early skill development will limit the infant's ability to alter their postural control strategy under different conditions. This would be reflected as a lack of change in the magnitude of COP displacement when comparing the No Toy and Toy condition. This speculation is consistent with recent research indicating that infants who do not reduce their body movements during initial gaze are more likely to have attention problems at 8 years of age.(Friedman, et al., 2005)

Future studies can build on *our work describing changes in magnitude and complexity of postural control variability of typically developing infants by describing similar changes in at-risk populations. Likewise the relationship between early postural complexity, vision, attention, and play based cognitive skills may enhance our understanding of the influence of postural complexity on the infant's ability to act on the world around him.*

Limitations

This initial study of postural control complexity during early behaviors has several limitations which should be considered in interpreting the results. First, data from all infants included in the study was not available at each visit age due to illness, infant fussiness, and equipment errors.

However, mixed linear models were used for statistical analysis minimizing the impact of this missing data on the models. Second, the order of Conditions was not randomized in order to maximize the number of visits in the No Toy Condition which were used for the head midline analysis in the youngest infants who fatigued quickly. As a result it is possible that the Condition effect is the result of the assessment order. Third, infants may have met the criteria for head in midline and reaching at anytime between study visits. Thus infants may have met the criteria a day to a few weeks before they were categorized as meeting the criteria for the study. Visits every 2 weeks initially during the most rapid period of change and then monthly was determined to be a feasible schedule for this study based on our previous research, pilot work, funding, and family's feedback during previous studies. Lastly, the longitudinal nature of this study was important to capture the emergence of the motor behaviors. However, the methods and length of follow-up limit our ability to comment on postural control during well developed head control, proficient reaching, or reaching in other positions. These limitations should be considered in future research.

Conclusion

The results of this study provide insight into the role of complexity in the development of new motor skills. The important role of early experience and complexity in postural control is supported. Future research is needed to compare the magnitude and temporal structure of variability in postural control between healthy infants and those at high risk for disabilities.

Notes:

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Table 1: Developmental Testing Results

Bayley Scaled Scores(Bayley, 2006) n=18	3 mo	6 mo
Cognitive Mean (SD)	9.1 (2.2)	8.8 (2.3)
Receptive Language Mean (SD)	10.6 (1.9)	7.6 (1.9)
Expressive Language Mean (SD)	13.2 (1.5)	10.4 (2.1)
Fine Motor Mean (SD)	9.9 (2.2)	9.8 (3.0)
Gross Motor Mean (SD)	12.7 (1.5)	9.1 (2.6)

Table 2: Post-hoc comparisons for significant F-tests with Bonferroni Adjustments.

Dependent Variable	Covariate	F Test	p value	Significant Differences
Model 1: Change in Postural Sway with Increasing Midline Head Control (Figures 2A and 2B)				
Dependent Variable	Covariate	F Test	p value	Significant Differences
Ln(ApEncc)	AgeHMidline	$F_{5,55}$ = 3.31	0.0111	0.0 vs. 1.0 – Adjusted p value=0.0158 0.5 vs. 1.0 – Adjusted p value=0.0423 Based on 15 comparisons
Ln(ApEnml)	AgeHMidline	$F_{5,55}$ = 2.86	0.0231	No differences detectable using the Bonferroni adjustment Based on 15 comparisons
Model 2: Change in Postural Sway with Increasing Early Reaching (Figures 3A and 3B)				
Dependent Variable	Covariate	F Test	p value	Significant Differences All ages
Ln(ApEncc)	AgeToyContact	$F_{2,9}$ = 6.27	0.0197	-1.5 vs.-1.0 – Adjusted p value=0.0191 Based on 3 comparisons
Model 3: Change in Postural Sway by Condition and Age (Figures 4A and 4B)				
Dependent Variable	Covariate	F Test	p value	Significant Differences All Ages
Ln(ApEncc)	Age	$F_{5,76}$ = 6.94	< 0.0001	1.5 vs. 4.0 – Adjusted p value < 0.0001 2.0 vs. 4.0 – Adjusted p value=0.0007 2.5 vs. 4.0 – Adjusted p value=0.0004 3.0 vs. 4.0 – Adjusted p value=0.0003 Based on 15 comparisons
Ln(ApEnml)	Age	$F_{5,76}$ = 4.63	0.0010	1.0 vs. 3.0 – Adjusted p value=0.0311 2.5 vs. 4.0 – Adjusted p value=0.0453 3.0 vs. 4.0 – Adjusted p value=0.0032

				Based on 15 comparisons

Figure 1: General data collection set up. Center of pressure data synchronized with lateral view and overhead view of video during a no Toy trial.

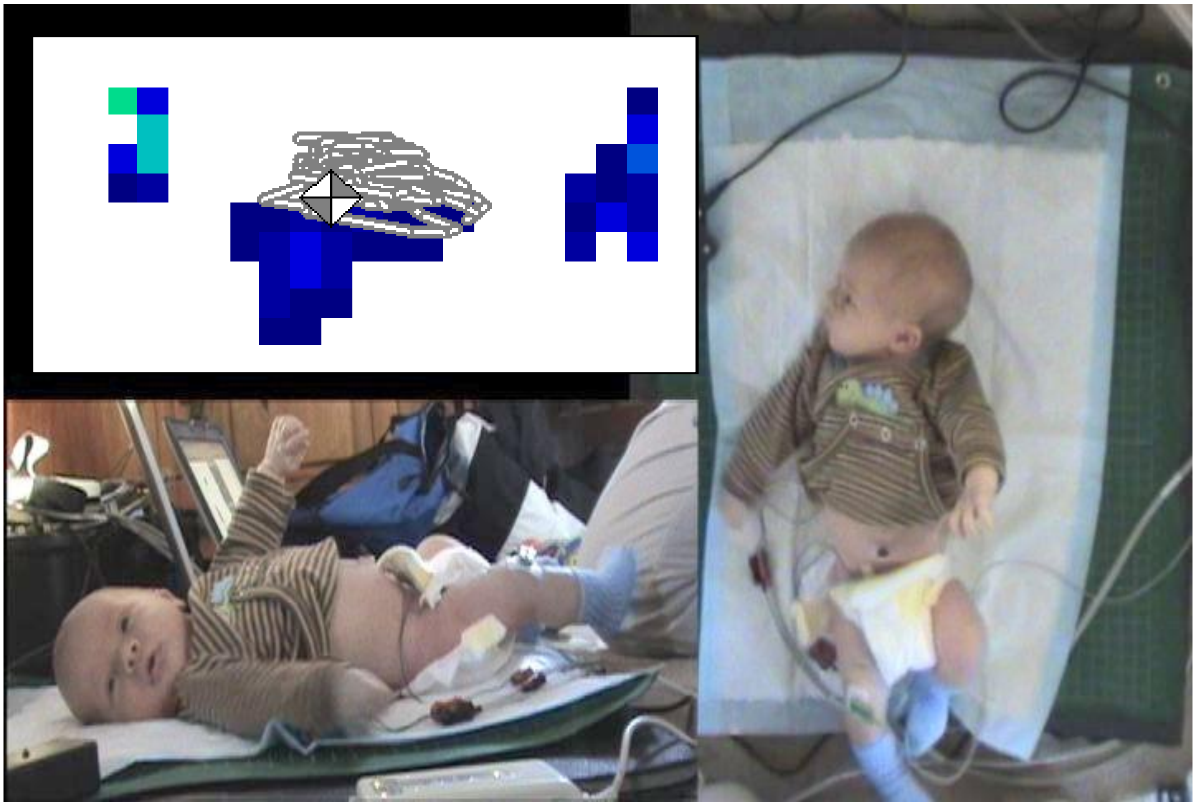
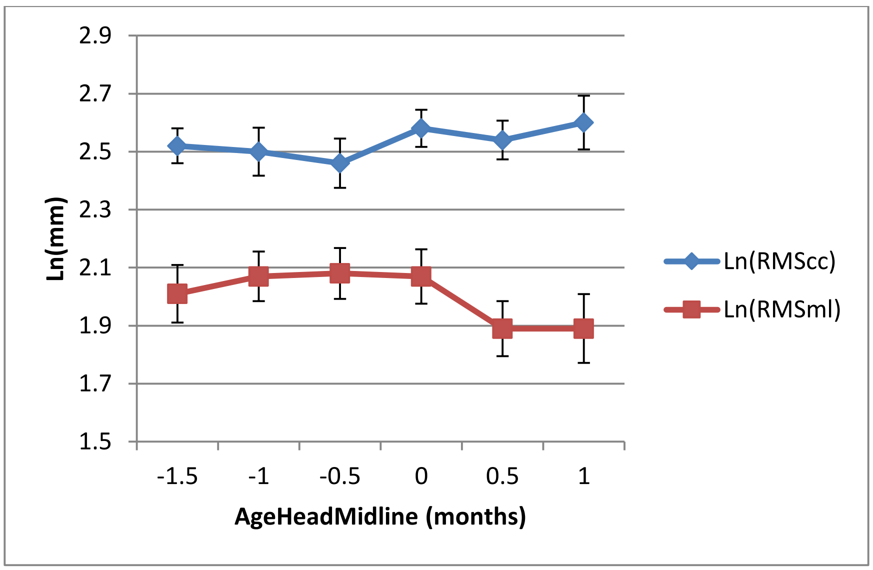


Figure 2: Model 1: Postural *Control* Assessment During Emergence of Head in Midline.

Curves represent the average of the dependent variable under each Condition. Error bars represent the standard error of the mean. The negative AgeHeadMidline values represent the time when the infant was attempting the skill but was unable to meet to criterion and the positive values represent the month after meeting the criterion.

2A: Magnitude of the Variability of COP Displacement



2B: Temporal Structure of the Variability of the COP Time Series

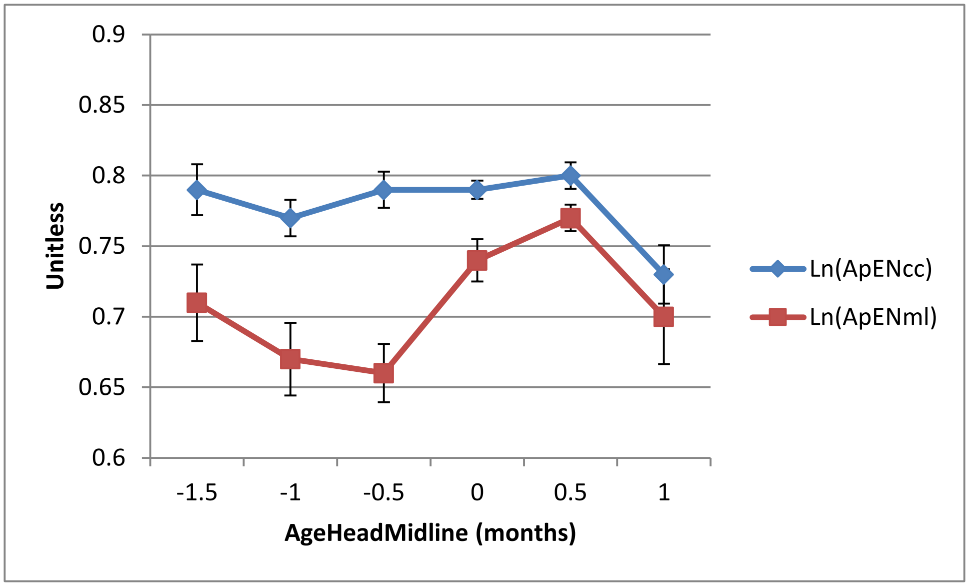


Figure 3: Model 2: Postural *Control* Assessment During Emergence of Reaching.

Curves represent the average of the dependent variable under each Condition. Error bars represent the standard error of the mean. The negative AgeToyContact values represent the time when the infant was attempting the skill but was unable to meet to criterion.

3A: Magnitude of the Variability of COP Displacement

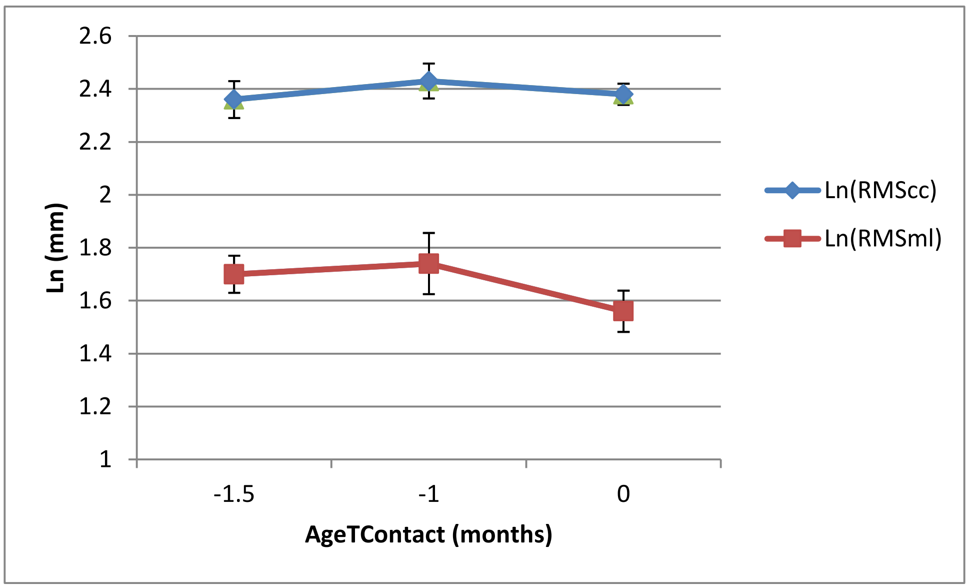


Figure 3B: Temporal Structure of the Variability of the COP Time Series

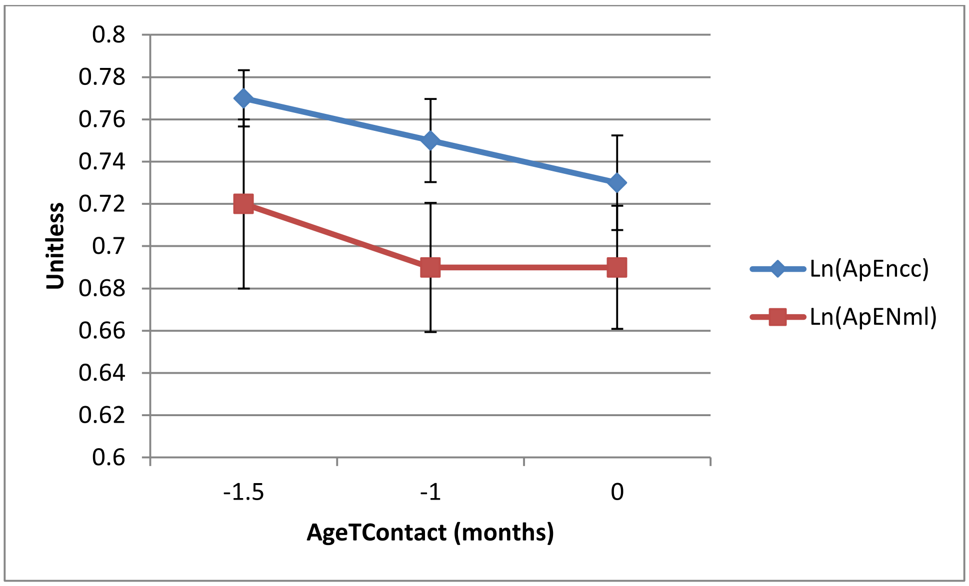
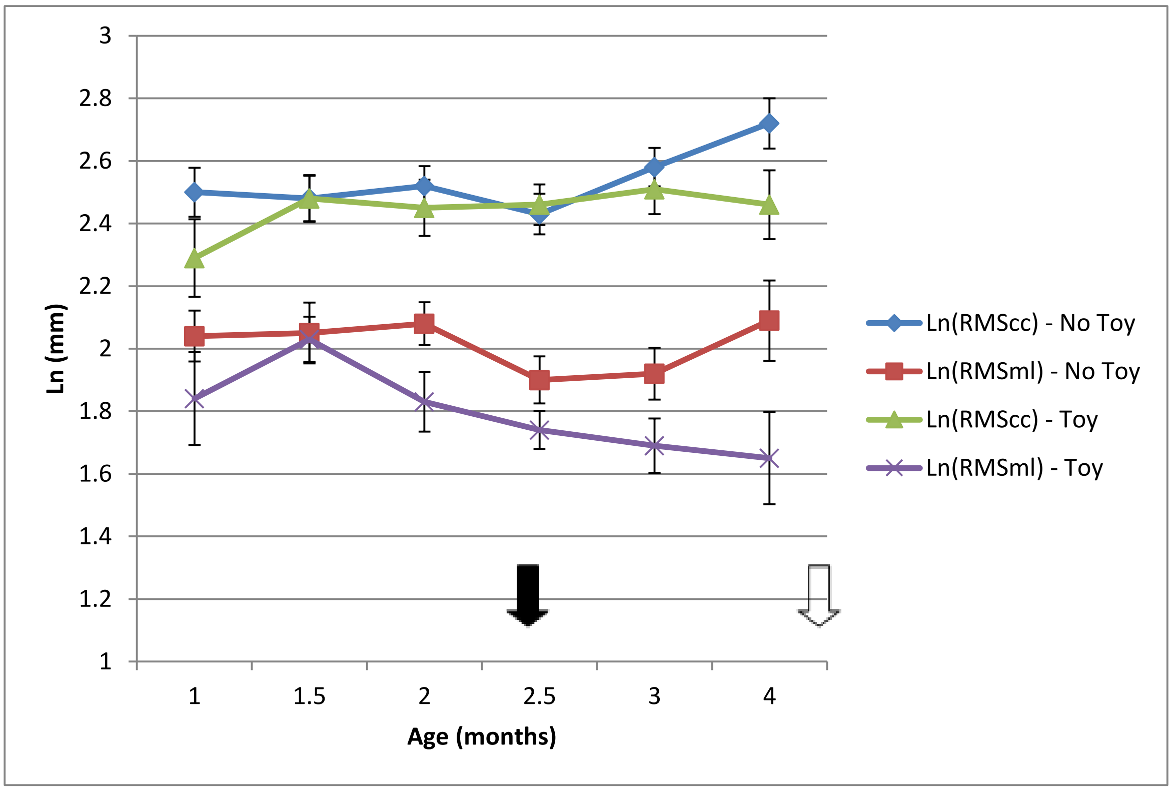
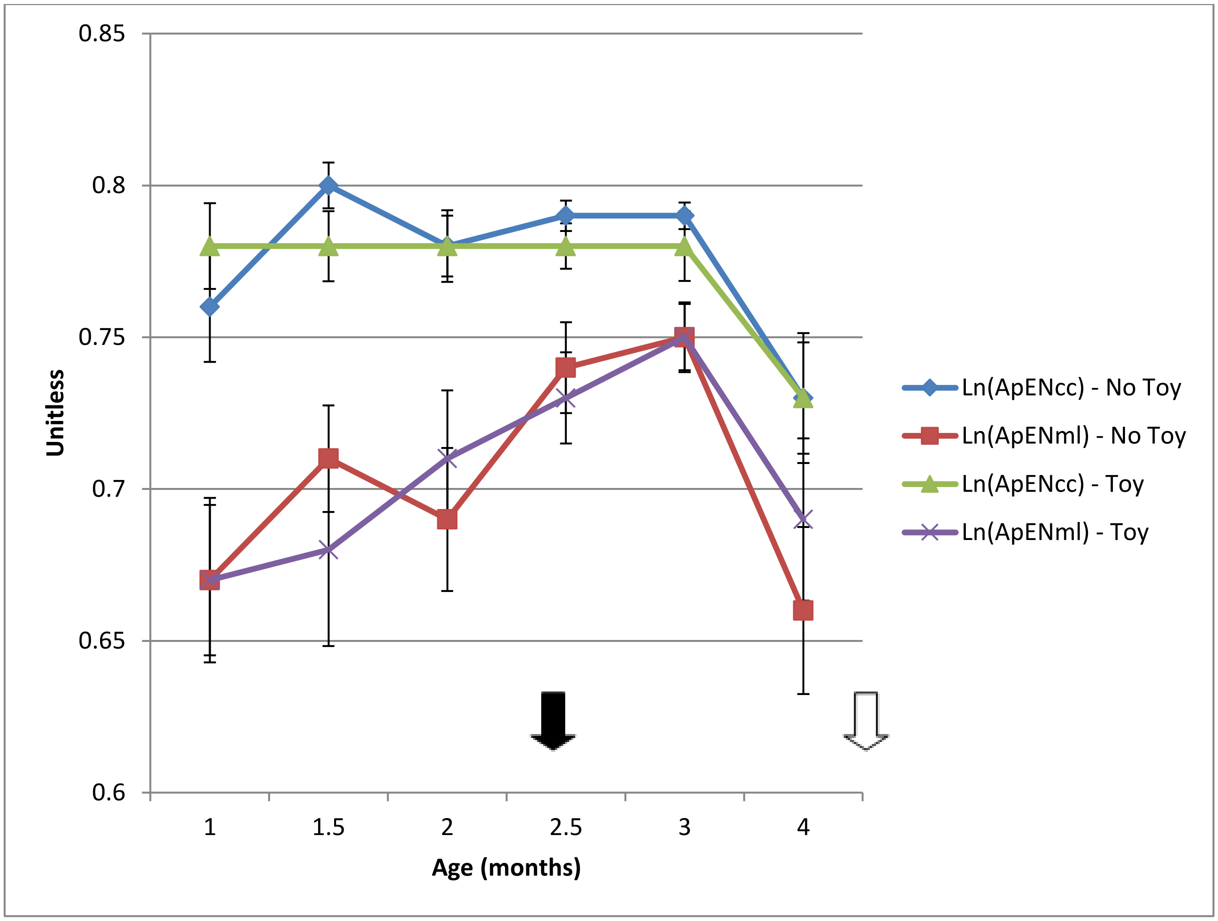


Figure 4: Model 3: Postural*Control* by Condition and Age. Curves represent the average of the dependent variable in each Condition. Error bars represent the standard error of the mean. Black arrow represents mean age infant kept the head in midline in the no Toy Condition. White arrow represents mean age infant made contact with a Toy in the Toy Condition.

4A: Magnitude of the Variability of COP Displacement



4B: Temporal Structure of the Variability of COP Time Series.



Figures with Legends

Figure 1: General data collection set up. Center of pressure data synchronized with lateral view and overhead view of video during a no Toy trial.

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Curves represent the average of the dependent variable under each Condition. Error bars represent the standard error of the mean. The negative AgeHeadMidline values represent the time when the infant was attempting the skill but was unable to meet to criterion and the positive values represent the month after meeting the criterion.

2A: Magnitude of the Variability of COP Displacement

2B: Temporal Structure of the Variability of the COP Time Series

Figure 3: Model 2: Postural *Control* Assessment During Emergence of Reaching.

Curves represent the average of the dependent variable under each Condition. Error bars represent the standard error of the mean. The negative AgeToyContact values represent the time when the infant was attempting the skill but was unable to meet to criterion.

3A: Magnitude of the Variability of COP Displacement

Figure 3B: Temporal Structure of the Variability of the COP Time Series

Figure 4: Model 3: Postural *Control* by Condition and Age. Curves represent the average of the dependent variable in each Condition. Error bars represent the standard error of the mean. Black arrow represents mean age infant kept the head in midline in the no Toy Condition. White arrow represents mean age infant made contact with a Toy in the Toy Condition.

4A: Magnitude of the Variability of COP Displacement

4B: Temporal Structure of the Variability of COP Time Series.