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Infants Born Preterm Exhibit Different Patterns of Center-of-Pressure Movement Than Infants Born at Full Term

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Infants Born Preterm Exhibit Different Patterns of Center-of-Pressure Movement Than Infants Born at Full Term

Stacey C. Dusing, Anastasia Kyvelidou, Vicki S. Mercer and Nick Stergiou

Abstract

Background Infants born preterm are at risk for developmental impairments related to postural control.

Objective The purpose of this study was to determine whether infants born preterm and infants born at full term differed in postural control at 1 to 3 weeks after term age.

Design This study included 17 infants born preterm (mean gestational age=31.9 weeks, range=25.0–34.6) and 15 infants born at full term (mean gestational age=38.9 weeks, range=37.3–40.6). All infants were without diagnosed neurological or genetic conditions.

Measurement Center-of-pressure (COP) data were recorded at 5 Hz while each infant was positioned supine on a pressure-sensitive mat in an alert behavioral state. Root mean square (RMS) displacement and approximate entropy (ApEn) were used to describe the COP movement variability in the time series. Differences between groups were identified using independent t tests.

Results The COP time series were found to be deterministic, suggesting order in the time series. Infants born preterm exhibited significantly larger RMS values in the caudal-cephalic direction than infants born at full term (1.11 and 0.83 cm, respectively; \( t = -2.6, df = 30, P = .01 \)). However, infants born at full term had significantly larger ApEn values in the caudal-cephalic direction (1.19 and 1.11, respectively; \( t = 2.4, df = 30, P = .02 \)). The 2 groups did not differ in RMS or ApEn values in the medial-lateral direction or the resultant.

Conclusions Infants born at full term exhibited COP displacements in the caudal-cephalic direction that were smaller in amplitude, but may be considered more complex or less predictable, than those of infants born preterm. One explanation is that infants born preterm exhibited more stereotypic patterns of movement, resulting in large, but repetitive, COP excursions. A combination of linear and nonlinear measures may provide insight into the control of posture of young infants.

Infants who are born at full term and are developing typically exhibit complex and variable movements, maintain their trunks in a flexed position, kick their legs, and visually explore the environment in the first weeks of life.\(^1\)\(^-\)\(^3\) In contrast, many infants born preterm have limited antigravity trunk flexion and difficulty maintaining a quiet alert state, and some infants exhibit repetitive movement patterns.\(^4\)\(^,\)\(^5\) Infants born preterm frequently have atypical trunk and extremity positioning, muscle tone (velocity-dependent resistance to stretch), and muscle power in the first 6 months of life compared with infants born at full term.\(^6\)\(^,\)\(^7\) Although these findings may be transient in nature, they are associated with deficits in posture, reaching, hand function, sitting balance, coordination, and cognition at 2 to 7 years of age.\(^8\)\(^-\)\(^12\) Early assessment of postural control may provide insight into the developmental trajectories of infants and aid in early identification of those at greatest risk for developmental difficulties.
Postural control involves controlling the body's position in space for the dual purpose of: (1) *orientation*, which is the ability to maintain an appropriate relationship between body segments and the environment, and (2) *stability*, which is the ability to control the center of mass in relation to the base of support.\textsuperscript{13} The center of pressure (COP), or the ground reaction force, at the base of support traditionally has been considered a reflection of the organization of posture and is commonly used in both research and clinical quantification of postural control.\textsuperscript{13} Center of pressure provides a measure of posture in any position and is influenced by extremity, head, trunk, and pelvic position in standing, sitting, or supine positions.\textsuperscript{13,14} Because young infants spend a large portion of their nonsupported play time in a supine position,\textsuperscript{15} this is a functional position for postural control assessment in these infants and has been described previously in 4- and 6-month-old infants.\textsuperscript{8} Adequate postural control in a supine position is critical to enable the infant to maintain a stable base while performing active trunk and extremity movements or to reorient the body by rolling. In this study, we used COP movement variability to characterize the ability to maintain a stable base during spontaneous movements in infants born preterm and in infants born at full term. In this model of supine postural control, COP is used to describe the location of the ground reaction force while the infant moves. Movements of the trunk (including the pelvis) into anti-gravity flexion or pushing into extension on the support surface, as well as head and extremity movements, may influence the COP location (Figs. 1 and 2). Although a supine infant maintains much of his or her body in contact with the support surface, the challenges of lifting the extremities against gravity and flexing or extending the trunk require postural control or trunk stability.

**Figure 1.** Example of pressure mapping method and pictorial display of pressure distribution: (A) a preterm infant positioned supine on the pressure-sensitive mat while awake and active, (B) a screen shot from the data collection software representing one frame of pressure data (in millimeters of mercury) and the center-of-pressure trace for the preceding 10 seconds.
Movement variability has been a major theme in the motor control literature. The motor program perspective viewed variability as the result of errors in the ability to scale the essential parameters to perform a movement. Schmidt and Lee suggested that specificity in practicing a skill would lead to the elimination of errors and thus to the optimization of the movement pattern. In contrast, dynamic systems theory appreciated variability from the perspective that while an individual is in a stable phase, there is little variability. However, an individual developing a new skill moves through an unstable phase in which variability increases. Increasing variability in an individual may predict the development of a new skill or the transition to a new phase of development. Thelen and Smith suggested that individuals transition through stable and unstable periods during acquisition of new skills. However, this appreciation of variability does not recognize the rich organization of motor behavior that may be observed in elite athletes and musicians during stable phases of development. Limited recognition of this important aspect of motor behavior may be due to the prevalence of research that addresses only the magnitude of variability. Specifically, variability of postural control can be investigated in terms of both magnitude and organization. Magnitude is evaluated using traditional linear measures of centrality, such as standard deviations. Organization or structure is evaluated using nonlinear analysis that determines the evolution of behavior over time.

The absence of utilization of both types of analyses has led to contradictory results regarding the evaluation of the COP. For example, there are conflicting interpretations of linear measures of COP such as the path length, excursion, and path area. Hughes and colleagues described subjects with increased COP path area as having greater postural control, whereas Riach and Hayes interpreted similar results as representing decreased postural control. In addition, clinical measures of postural control do not correlate well with linear measures of COP movement variability. Inconsistent interpretation and lack of clinical correlations led Palmieri et al to argue that linear COP measures do not quantify stability of the postural control system and that new measures are needed to examine the COP signal and quantify change. Therefore, nonlinear tools such as approximate entropy (ApEn) are being used increasingly in
several medical fields to describe complex conditions for which linear techniques are inadequate or scientifically confounding.23–25

The use of nonlinear measures to describe COP movement variability provides new insights concerning the complexity and temporal organization of postural control.26 Temporal organization or “structure” is quantified by the degree to which values emerge in an orderly (ie, predictable) manner across a range of time scales.27 Approximate entropy measures the complexity of the COP time series28,29 and can be used to quantify the regularity or predictability of a time series.30 A more predictable and regular time series also is less complex. A change in complexity may be indicative of learning and a reorganization of the available degrees of freedom.29,31 Approximate entropy measures the logarithmic probability that a series of data points a certain distance apart will exhibit similar relative characteristics on the next incremental comparison with the state space.28,30 Time series with a greater likelihood of remaining the same distance apart upon comparison will result in lower ApEn values, whereas data points that exhibit large differences in distances between data points will result in higher values. Values typically range from 0 to 2. Values closer to 0 are consistent with greater periodicity (less complexity). Conversely, values nearing 2 represent greater irregularity (higher complexity).

Nonlinear analysis of COP data can provide a window into infant neurological status, increasing our understanding of the complex strategies infants use to control posture. Previous research has shown that nonlinear analysis is useful in examining small increments of change in postural control before behavioral changes can be identified.18,27 However, this type of analysis has never been used to describe supine postural control of young infants.

The purpose of this study was to determine whether infants born at full term and infants born preterm differed in their COP movement variability characteristics, evaluated both linearly and nonlinearly, while positioned supine at 1 to 3 weeks after term age. Based on our previous research32 and that of other researchers,33 we expected differences between groups in both linear and nonlinear postural control measures. We hypothesized that infants born preterm would have larger and more repetitive or predictable COP movement patterns compared with infants born at full term.

Methods

Participants

A sample of convenience comprising 17 infants born preterm and 15 infants born at full term was used in this study. Infants were recruited from the neonatal intensive care unit and newborn nursery of 2 medical centers, and their parents provided informed consent. Medical records were reviewed to ensure the infants met the inclusion and exclusion criteria for the study. All infants were born at weights that were appropriate for their gestational age and had been discharged from the hospital prior to their participation. Infants born preterm were born at a mean (SD) of 31.9 (3.0) weeks of gestation, and infants born at full term were born at a mean (SD) of 38.9 (1.1) weeks of gestation. Infants were excluded from participation if they had periventricular leukomalacia, grade 3 or 4 intraventricular hemorrhage, a history of seizures, congenital abnormalities, a genetic or endocrine system syndrome, or drug or alcohol exposure or if they required supplemental oxygen at the time of the assessment. Infants also were excluded if they did not have a parent or guardian who spoke English. Infants born preterm
were assessed at 41 to 43 weeks of post-conceptual age (mean [SD]=41.7 [0.7] weeks of post-conceptual age) and infants born full term were assessed 1 to 3 weeks after delivery (mean [SD]=41.0 [1.1] weeks of post-conceptual age) (Tab. 1).

**Table 1.**
Participant Demographics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Preterm Infants</th>
<th>Full-Term Infants</th>
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<td><strong>n</strong></td>
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<tr>
<td>Female</td>
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<td>Gestational age at birth (wk)</td>
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<td></td>
</tr>
<tr>
<td>Mean</td>
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<td>38.9</td>
</tr>
<tr>
<td>SD</td>
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<td>1.1</td>
</tr>
<tr>
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<td>37.3–40.6</td>
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<tr>
<td>Birth weight (g)</td>
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<td></td>
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<tr>
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<td>SD</td>
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<td>565.3</td>
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<tr>
<td>Age at assessment (d)</td>
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<td></td>
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<tr>
<td>Mean</td>
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<td>14.5</td>
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<tr>
<td>SD</td>
<td>22.9</td>
<td>5.1</td>
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<td>Range</td>
<td>45–124</td>
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</table>

**Instrumentation and Procedure**

Center of pressure traditionally is measured using a force platform. However, force platforms are limited in their clinical utility by their size, weight, and lack of portability. Pressure-sensitive mats have been used in clinical and research settings to evaluate the pressure between a patient's body and a wheelchair seat, chair, or bed. Center-of-pressure movements measured in a sitting position using pressure-sensitive mats are both reliable and valid compared with force platforms. Validation of COP measured using a pressure-sensitive mat in a supine position has not been published. The portability, noninvasiveness, reliability, and validity of pressure-sensitive mats make them ideal measurement tools for assessing supine postural control of both infants who are healthy and infants born preterm and at high risk for developmental difficulties in their natural environments. A frequency analysis of representative COP time series indicated that 99.99% of the signal power was below 0.5 Hz. Therefore, pressure data were sampled for a minimum of 5 minutes with a sampling frequency of 5 Hz in order to stay a factor of 10 above the highest frequency contained in the signal.

All data were collected in the infant's home with one or more parents present. The parent placed the infant in a supine position on a pressure-sensitive mat (FSA UltraThin Seat Mat*), which was positioned on the same close cell foam mat for all assessments (Figs. 1 and 2). The infant wore a diaper and a thin, one-piece outfit or T-shirt. The locations of the infant's head and pelvis were recorded in reference to
the pressure-sensitive mat's grid system. During each data collection session, the examiner documented each behavioral state change (deep sleep, light sleep, drowsy, quiet alert, active alert, crying) using the criteria of Brazelton. The examiner also documented each time the infant was touched by an adult (for calming or repositioning) or rolled out of the supine position with one side of the pelvis and one shoulder off the support surface. Each state change, adult contact, and roll was documented in the data collection software and synchronized with the pressure data. The infant's parent was permitted to talk to or look at the infant as needed to keep the infant happy and awake. If the infant began to cry, the parent calmed the infant and then returned the infant to the pressure-sensitive mat. A total of 1,500 data samples were collected in several shorter segments if the infant had difficulty remaining calm and awake in a supine position without swaddling for a full 5 minutes.

Data Reduction

Center-of-pressure coordinates, behavioral state, adult contact, and roll notations for each data sample were exported for analysis. Using the notations exported from the data collection software, data segments consisting of 500 sequential data samples (100 continuous seconds of data collection) meeting the following criteria were identified: (1) the infant was in a quiet or active alert behavioral state, (2) no adult was in contact with the infant, and (3) the infant was not rolling. This data length is considered adequate for the type of nonlinear analysis performed in this study. Three segments of 500 data samples were identified for 16 infants born preterm and for 12 infants born at full term. Three infants born at full term and 1 infant born preterm had frequent behavioral state changes during data collection and, therefore, had only 2 segments of 500 sequential data samples, which were included in the analysis.

The COP movement was analyzed with both linear and nonlinear measures for each continuous block using MATLAB version R2007a. We used the procedure of surrogation to validate whether postural control in the supine position of the infants born preterm and at full term was deterministic (has order) or stochastic (random) in nature. Surrogate data sets were generated for all original COP time series. This procedure was performed in MATLAB using the algorithms developed by Theiler et al. The surrogates were produced from the original COP data, but the deterministic structure from the original data set was removed, generating a random equivalent with the same mean, variance, and power spectra as the original. To compare the original with the surrogate data sets, we also computed ApEn from all the surrogate data sets.

Linear measures included root mean square (RMS) of the COP in caudal-cephalic and medial-lateral directions and the resultant or total COP movement. Nonlinear measures included the ApEn and surrogation analysis. Both measures were calculated from the COP time series in the caudal-cephalic and medial-lateral directions and resultant. The ApEn was calculated using MATLAB code developed by Kaplan and Staffin, implementing the methods of Pincus et al 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.

Data Analysis

For the surrogation procedure, the statistical comparisons were made with an infant-to-infant analysis and also across the entire sample by using a dependent t test. If the original value of ApEn for one infant was lower than the corresponding surrogate, then a value of 1 was given. If the original value of ApEn
for one infant was greater than the corresponding surrogate, then a value of 0 was given. When all comparisons were made, a percentage between values of 0 and values of 1 was estimated. In order for the data to be deterministic, we would expect to have numerous values of 1. This percentage was estimated for the 2 surrogation algorithms published by Theiler et al.\textsuperscript{37} For one algorithm, this percentage was 99%, and for the other algorithm, the percentage was 96%, which suggests that the data were deterministic.\textsuperscript{37}

Descriptive statistics were used to describe the samples and dependent variables. Differences between infants born preterm and infants born at full term in linear and nonlinear parameters were calculated using independent t tests for the caudal-cephalic and medial-lateral directions and the resultant. All statistical analysis was completed using SPSS version 14.0,\textsuperscript{2} with the alpha equal to .05.

Role of the Funding Source

Dr Dusing and Dr Stergiou were each funded by National Institutes of Health/National Institute of Child Health and Human Development career development awards (1K12HD055931–01 and K25HD047194, respectively), allowing time for this secondary data analysis and manuscript preparation. Dr Stergiou and Ms Kyvelidou were supported by consecutive National Institute on Disability and Rehabilitation Research grants (H133G040118 and H133G080023) and the McDonald Fellowship and Bukey Fellowship from the University of Nebraska Medical Center. A portion of Dr Mercer’s time in preparation of this manuscript was funded by a Competitive Research Leave from the Office of the Provost, University of North Carolina at Chapel Hill. Initial study design and data collection were funded by a grant to Dr Dusing from the University of North Carolina at Chapel Hill Human Movement Science Student Research Fund. None of the funding sources had any role in the study design or analysis or the reported outcomes.

Results

Surrogation analysis revealed that the fluctuations observed in the COP data in all directions were deterministic in nature. This finding was indicated by the significantly larger ApEn values found for the surrogate data sets compared with the original ($P<.05$). The findings from the surrogation analysis revealed that the variability observed in the COP data was deterministic across both preterm and full-term infants. Thus, both preterm and full-term infants have significantly different structure than stochastic noise. These findings provided the basis to continue with the nonlinear analysis.

Our group analysis identified that the infants born preterm exhibited larger RMS values in the caudal-cephalic direction than infants born at full term ($F=1.94$, $df=30$, $P=.01$; Tab. 2, Fig. 3A). There were no significant differences in RMS values in the ml direction or in the resultant (Tab. 2, Fig. 3A). Infants born preterm had smaller ApEn values in the caudal-cephalic direction than infants born at full term ($F=2.33$, $df=30$, $P=.02$; Tab. 2, Fig. 3B). There were no group differences in the ApEn values in the medial-lateral direction or the resultant (Tab. 2, Fig. 3B).
Figure 3. Group differences in center-of-pressure (COP) movement variability: (A) group differences in root mean square (RMS) of the COP in caudal-cephalic (cc) and medial-lateral (ml) directions and the resultant, (B) group differences in approximate entropy (ApEn) calculated from the COP time series in the caudal-cephalic and medial-lateral directions and the resultant. Asterisks represent statistically significant differences (P<.05). Error bars represent the 95% confidence intervals.

Discussion

The COP time series was deterministic in nature, confirming that variability within the COP time series is structured and it is not random noise. This result further emphasizes the importance of investigating COP time series, because invaluable information about postural control may be hidden in the structure of the COP time series. Thus, description of this variability serves to enhance our understanding of the organization of postural control in infants. Infants born preterm were found to exhibit larger COP displacements in the caudal-cephalic direction than infants born at full term, as quantified by linear analysis of the COP movement variability. Infants born preterm also were found to have less-complex COP movement in the caudal-cephalic direction compared with infants born at full term, as quantified by nonlinear analysis of COP movement variability. These findings support our hypothesis that infants born preterm differ from infants born at full term with respect to supine postural control at 1 to 3 weeks after term age.
The findings from this study complement our previous research with the same cohort. In the previous study, we found that infants born at full term, but not infants born preterm, were successful in maintaining antigravity trunk flexion or a neutral position more than two thirds of the time. Together, these studies suggest that infants born at full term maintain antigravity trunk flexion or a neutral position and exhibit minimal COP sway with varied organization. In contrast, infants born preterm exhibit large and predictable COP sway in the caudal-cephalic direction.

Linear and nonlinear analyses combined provide complementary information about postural control in this group of infants. Although the linear measures (RMS of the COP in the caudal-cephalic direction) identified greater variability in the infants born preterm, the nonlinear measures (ApEn in the caudal-cephalic direction) identified smaller alterations in the organizational structure of the variability in the COP time series for infants born preterm. The purpose of this study was not to describe the specific movement patterns of the infants. However, the COP movement provides us with a summary of how the infants moved their entire bodies during spontaneous movement. The results from this study provide preliminary evidence that infants born preterm exhibit a less stable posture and move in a repetitive manner in the caudal-cephalic direction compared with infants born at full term. These findings may be the result of variations in extremity, trunk (including the pelvis), or head movements observed during spontaneous movements. Figure 2 represents 2 postures of an infant who was developing typically demonstrated during an assessment of spontaneous movement. If this infant moved back and forth between only these 2 postures using the same COP trajectory each time, the infant's ApEn in the caudal-cephalic direction would be low (similar to the infants born preterm). If the infant moved between these 2 postures using different COP trajectories with each change in posture, the infant's ApEn would be larger (similar to the infants born at full term).

Previous research has documented the importance of movement variability and complexity in fetuses, infants, and young children during spontaneous movements, sitting, and kicking. Robertson proposed that the temporal patterns of fetal and neonatal cyclical movements might be altered or abolished by perinatal stress or central nervous system damage. Generalized movement assessment describes extremity movements in neonates based on their complexity, variability, speed, and amplitude. Infants who have repetitive or rigid movements are more likely to have abnormal brain imaging or be diagnosed with cerebral palsy or coordination problems. The complexity of COP movement in a supine position can be quantified and, with additional research, may be useful in identifying infants with postural control deficits, as well as furthering our understanding of the development of infant postural control.

Our results concerning the deterministic nature of COP movement in supine infants are consistent with the results of previous studies of sitting and spontaneous arm movements. These results support the principle of self-organization, as described in dynamic systems theory and the theory of optimal variability. Both of these theories support the concept that variability within the system is not random error but a necessary source of solutions that allow the system to self-organize and be flexible to changing conditions. Although further longitudinal research is needed to gain understanding of these self-organizing processes, this cross-sectional study provides some early evidence that infants born preterm and infants born at full term may differ in the nature or timing of self-organization or their movement flexibility. Only with longitudinal studies will we be able to further describe the development of postural control in very young infants. The combination of both linear and nonlinear tools will be more effective at describing the emergence of postural control and its influence on development.
This study had several limitations, which must be acknowledged and addressed in future studies. The pressure-sensitive mat used in this study measures only vertical ground reaction forces. Therefore, we were unable to report on the influence of shear forces that may result from movement. The precision of the pressure-sensitive mat used in this study is reported to be 0.25 cm in a sitting position. Although this is not as precise as a force platform, the minimum RMS observed was 0.52 cm in the caudal-cephalic direction and 0.25 cm in the medial-lateral direction. The lack of measurement precision may have contributed to the lack of significant findings in the medial-lateral direction. However, it is unlikely that the lack of precision affected the findings in the caudal-cephalic direction, given the RMS values. Further research is needed to validate the use of the pressure-sensitive mat to evaluate COP in young infants.

The type of nonlinear analysis used in this study was limited by the length of the time series. Ideally, longer data collection periods should be included in future studies to allow for the use of additional nonlinear assessment tools. However, we should mention here that the number of input data points for ApEn computations has been as low as 50. The fact that such small data sets can be used for the calculation of ApEn is one of the advantages of ApEn in comparison with other nonlinear tools (eg, Lyapunov exponent). For noisy and medium-sized data sets, ApEn has been shown to produce stable values.

Videotape of the infants’ behavior and spontaneous extremity movement was not recorded, limiting our understanding of the correlation between limb movement and postural control in this sample. The frames of data in which an infant rolled or was not in a quiet or active alert state or an adult was touching the infant were eliminated from the analysis. The frames immediately prior to these activities may have included changes in COP movement that were different from those observed during supine spontaneous movements. The infants born preterm in our sample had a mean gestational age of 31.9 weeks, with only 3 infants born at less than 30 weeks of gestation. Future studies should include a stratified sample of infants born preterm to ensure that infants born at a variety of gestational ages are included and described separately. The addition of infants with a history of brain injuries such as periventricular leukomalacia or intraventricular hemorrhage would lead to better insight into the predictive value of this assessment and analysis protocol.

Lastly, the cross-sectional nature of this study prohibits us from speculating on the developmental trajectory of the infants who participated. Longitudinal designs with data collection at key time points during development will be needed to elucidate the dynamics of the postural control system in young infants.

Although we are only beginning to understand the complexity of infant postural control, our results and those of previous researchers highlight the importance of both the magnitude and the organization of variability in postural control. When observing developing infants, clinicians should consider both types of factors, noting not only the extent and speed of movement but also the variety. Future longitudinal studies are needed to provide insights concerning optimal variability in typical development and critical periods for intervention and to facilitate evaluation of intervention strategies.
Dr Dusing, Dr Mercer, and Dr Stergiou provided concept/idea/research design and writing. Dr Dusing provided data collection, project management, fund procurement, and participants. Ms Kyvelidou and Dr Stergiou provided data analysis. Dr Mercer provided facilities/equipment. All authors provided consultation (including review of manuscript before submission).

This study was approved by the Committee on the Protection of the Rights of Human Subjects at the University of North Carolina and Wake Medical Center.

An abstract of the data was presented at the Combined Sections Meeting of the American Physical Therapy Association; February 9–12, 2009; Las Vegas, Nevada.

Dr Dusing and Dr Stergiou were each funded by National Institutes of Health/National Institute of Child Health and Human Development career development awards (1K12HD055931-01 and K25HD047194, respectively), allowing time for this secondary data analysis and manuscript preparation. Dr Stergiou and Ms Kyvelidou were supported by consecutive National Institute on Disability and Rehabilitation Research grants (H133G040118 and H133G080023) and the McDonald Fellowship and Bukey Fellowship from the University of Nebraska Medical Center. A portion of Dr Mercer’s time in preparation of this manuscript was funded by a Competitive Research Leave from the Office of the Provost, University of North Carolina at Chapel Hill. Initial study design and data collection were funded by a grant to Dr Dusing from the University of North Carolina at Chapel Hill Human Movement Science Student Research Fund. None of the funding sources had any role in the study design or analysis or the reported outcomes.
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