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Nonlinear analysis of sitting postural sway indicates developmental delay in infants

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ABSTRACT

Background: Upright sitting is one of the first developmental motor milestones achieved by infants, and sitting postural sway provides a window into the developing motor control system. A variety of posture sway measures can be used, but the optimal measures for infant development have not been identified.

Methods: We have collected sitting postural sway data from two groups of infants, one with typical development (n = 33), and one with delayed development and either diagnosed with or at risk for cerebral palsy (n = 26), when the infants had developed to the point where they could just maintain sitting for about 10 s. Postural sway data was collected while infants were sitting on a force platform, and the center of pressure was analyzed using both linear and nonlinear measures.

Findings: Our results showed that a nonlinear measure, the largest Lyapunov exponent, was the only parameter of postural sway that revealed significant differences between infants with typical versus delayed development. The largest Lyapunov exponent was found to be higher for typically developing infants, indicating less repeated patterning in their movement coordination.

Interpretations: A nonlinear measure such as largest Lyapunov exponent may be useful as an identifier of pathology and as a yardstick for the success of therapeutic interventions.

1. Introduction

Cerebral palsy is a result of damage that occurs to the brain early in development, typically before, during or shortly after birth. While cerebral palsy is non-progressive in that there is no further degradation in neurological function with age, the result of the early damage influences the rest of the infant's life in many ways, both medical and social. Motor control abnormalities due to the initial neurological insult give rise to atypical movement patterns, which in turn give rise to atypical development (Bleck, 1990). Motor development in infants with cerebral palsy is delayed, meaning that developmental milestones such as sitting, standing, or walking may occur later than in infants with typical development, and in severe cases these milestones may never be met.

There is both strong theoretical support for the idea that early intervention may result in more desirable outcome (Landsman, 2006), as well as evidence-based support (Blauw-Hospers, et al., 2007; Blauw-Hospers & Hadders-Algra, 2005). Certainly intervention early in development is seen as being beneficial among clinical practitioners (Gardner, 2005). Early intervention requires early identification of infants who would benefit from the intervention, however current methods for early identification of cerebral palsy are inadequate (Donohue & Graham, 2007). Not only are many infants with cerebral palsy difficult to identify early, but false positives can occur (Nelson & Ellenberg, 1982). Early and accurate identification of infants with cerebral palsy allows appropriate allocation of resources to help those who would benefit, avoid use of resources on those who would not, and avoids the unnecessary anxiety for parents that an incorrect identification brings. Unfortunately, early identification is difficult; however, a lack of complexity and low variation of movement is thought to be an indication that physical therapy intervention is appropriate (Hadders-Algra, 2001).

Learning how to maintain upright sitting posture is an important motor developmental milestone. Upright sitting allows visual exploration of the environment and serves as a stable platform for reaching nearby objects. If sitting posture is not developed by age 2 years, there is a significant chance that walking will never be achieved (Wu, et al., 2004; Fedrizzi, et al., 2000). Additionally, because sitting is one of the first motor developmental milestones an infant achieves in life, detecting abnormalities in infants' sitting posture control provides an opportunity to identify infants with motor control pathologies much earlier in life than, for example, waiting until the walking or talking milestones have been missed. Thus characterizing sitting posture differences in infants with cerebral palsy and infants with typical development has the potential to allow early and objective identification of infants who would benefit from intervention (de Graaf-Peters, et al., 2007).

Linear techniques such as path length or range of movement can be used to describe how much the center of pressure moves around (quantity of movement), but these techniques don't give any information about how well controlled the movement is (quality of movement) (Stergiou, et al., 2006). For example, one infant may have a large amount of postural sway due to poor control of movement, whereas another infant may have a large amount of postural sway due to exploration of the environment after good posture control skills have been learned. Thus measures of the quantity of movement do not necessarily indicate the progress that an infant has made in control of movement. What are needed are measures of the quality of the center of pressure (COP) movement in order to develop a more complete understanding of the development of postural control. Measures from nonlinear dynamics, such as the largest Lyapunov exponent (LyE), approximate entropy (ApEn), and correlation dimension (CorrDim) are promising new additions to the analytical tools used for physiologic time series analysis

(Stergiou, et al., 2004). Because these nonlinear analysis techniques are sensitive to patterns in the data, rather than the overall magnitude of the fluctuations, they could be ideal tools for quantifying the quality of postural sway, thus making them potentially clinically useful for studying both the typical and pathological development of motor control in infants. There are a number of different nonlinear analysis techniques, including ApEn, LyE, and CorrDim. ApEn is a measure of system complexity made by counting how often patterns of different lengths repeat in the time series (Pincus, 1991). The LyE is a measure of how rapidly trajectories diverge in phase space, and the CorrDim estimates the dimensionality of the system (Sprott & Rowlands, 1998). See Stergiou, et al., (2004) for a more complete discussion of these nonlinear measures.

These three nonlinear measures are derived from chaos theory and from information theory, and have higher values for a random signal and lower values for a periodic signal. A random signal has no patterns in it, and a periodic signal, such as a sine function has a simple pattern that repeats over and over again. While the analysis of the ideal signals can often be interpreted in terms of randomness or complexity, the interpretation of physiologic signals is considerably more difficult. Part of the difficulty lies in the fact that precise definitions of basic terminology are still evolving. For example, whether a high value for approximate entropy should be interpreted as higher complexity of the system (Vaillancourt and Newell, 2002a, b) or merely as more random (Goldberger, et al., 2002) has not been resolved. A clear definition of "complexity" is lacking. In comparing the results from different studies, one must be careful with the language used, as "complexity" defined by one author may differ from "complexity" defined by a different author.

In this paper we will speak of "optimal movement variability" as being indicative of the middle ground between random and periodic (Stergiou, et al., 2006). A random response to a

stimulus would be maladaptive, just as an overly rigid pattern of response would be maladaptive. In fact, the mid-ground between these extremes is likely the best control region for maintaining appropriate responses. The mathematical theory of chaos, a branch of dynamical systems theory, suggests that the middle-ground, the region of optimal movement variability, is likely chaotic. The nonlinear measures that we have selected to use, ApEn, LyE, and CorrDim, all have high values for random signal (no structure), low values for a periodic sine function (overly rigid structure), and intermediate values for chaotic region where optimal movement variability is found.

The actual assessment of chaos in experimental data is somewhat controversial due to limitations of the experimental data (Rapp, 1994), but despite the mathematical controversy, these algorithms have been successfully applied to many different biological and physiological systems, including postural sway data. In standing posture, nonlinear techniques have been used successfully to give insight into posture control. Nonlinear measures have been shown to be able to discriminate between pathologic and non-pathologic populations using standing COP data, and thus someday may be clinically useful measures. Patients with stroke (Roerdink, et al., 2006), traumatic brain injury (Cavanaugh, et al., 2006), and Parkinson's disease (Vaillancourt & Newell, 2000; Schmit, et al., 2006) have all been shown to differ from non-pathologic controls using nonlinear measures applied to standing COP data. Most encouraging for the present study is that COP data from standing posture in children with cerebral palsy has been found to differ from typically developing children, using both linear and nonlinear measures (Rose, et al., 2002; Donker, et al., 2008). Nonlinear measures of posture sway tend to decrease with pathology, when significant changes are observed. This might be interpreted as being more periodic, less complex, or less random.

The purpose of this paper was to investigate the use of sitting postural sway as a measure of health of the motor control system in infants. To accomplish this, we have used several linear and nonlinear time series analysis techniques to determine how sitting postural sway in typically developing infants differs from developmentally delayed infants. We hypothesized that the infants with developmental delay will have more periodic postural sway than typically developing infants. Additionally, to further explore the relationships between these various measures of postural sway, Pearson product-moment correlation coefficients were calculated, since highly correlated measures may be providing redundant information.

2. Methods

2.1. Participants

Twenty-six infants with developmental delay and 33 typically developing infants participated in the study. Recruitment was done through newsletters, flyers, and pediatric physical therapists employed at the University. Infants in the developmentally delayed group were diagnosed with cerebral palsy, or else were developmentally delayed and at risk for cerebral palsy (Table 1). At risk infants met one or more of the following conditions: premature delivery, brain abnormality based on ultrasound or MRI, or significantly delayed gross motor development as measured on standardized testing with no current diagnosis. Because a definitive diagnosis of cerebral palsy had not been made, we refer to these infants as developmentally delayed, because all scored below 1.5 SD below the mean for their corrected age on the Peabody Gross Motor Scale (Folio and Fewell, 2000). However, the development is likely not just delayed, but also atypical (Chen and Wollacott, 2007).

This study is part of a longitudinal study in which the infants with developmental delay

will have one of two different interventions. This analysis is of the data from the first month only, before any interventions had started, so all infants with developmentally delay were analyzed as a single group. A consent form was signed by a parent or guardian of all infant participants, and all procedures were approved by the University of Nebraska Medical Center Institutional Review Board.

2.2. Inclusion and exclusion criteria

Inclusion criteria for entry into the study for the typically developing infants were: a score on the Peabody Gross Motor Scale of greater than 0.5 SD below the mean, age of 5 months at the time of initial data collection, and sitting skills as described below in beginning sitting. Exclusion criteria for the sample of infants who are typically developing were: a score on the Peabody Gross Motor Scales less than 0.5 SD below the mean, diagnosed visual deficits, or diagnosed musculoskeletal problems. If a typically developing infant was found to be less than 0.5 SD below the mean, and did not qualify for the study, the parents were informed of the score, the possibility of error in the measurement, and advised to have the infant re-evaluated within the next 3 months. Operational definitions of beginning sitting were used to determine the child's readiness for entry into the study. Beginning sitting was defined as (a) head control such that when trunk is supported at the mid-trunk, head is maintained for over one minute without bobbing; (b) infant can track an object across midline without losing head control; (c) infant may prop hands on floor or legs to lean on arms, but should not be able to reach and maintain balance in the prop sit position; (d) when supported in sitting can reach for toy; (e) can prop on elbows in the prone position for at least 30 s.

For the infants with developmental delay the inclusion and exclusion criteria were as follows. Inclusion criteria were: age from 5 months to 2 years, score less than 1.5 SD below the

mean for their corrected age on the Peabody Gross Motor Scales, and sitting skills as described above for beginning sitting. Exclusion criteria were: age over 2 years, a score greater than 1.5 SD below the mean for their corrected age on the Peabody Gross Motor Scale, a diagnosed visual impairment, or a diagnosed hip dislocation or subluxation greater than 50%.

2.3. Data collection

For data acquisition (Fig. 1), infants sat on an AMTI force plate (Watertown, MA), interfaced to a computer system running Vicon data acquisition software (Lake Forest, CA). Markers can be seen on the infant in Fig. 1, and kinematic data was also collected, but is not discussed in this paper. COP data were acquired through the Vicon software at 240 Hz. A frequency analysis of both the medial-lateral and anterior-posterior components of all the COP time series from our preliminary data indicated that the range of signal frequencies that contain 99.99% of the overall signal power is between 1 and 29 Hz. Therefore, the sampling frequency was set at 240 Hz in order to be above a factor of ten higher than the highest frequency that might contain relevant signal.

For all data collection sessions, the infants were allowed time to get used to the laboratory setting, and were at their parent's side or on their lap for preparation and data collection. Infants were provided with a standard set of infant toys for distraction and comfort. All attempts were made to maintain a calm, alert state by allowing the infant to eat if hungry, be held by a parent for comforting, or adapting the temperature of the room to the infant's comfort level. Testing was only proceeded when the infant was in a calm and relaxed state, not crying or otherwise making extended vocalization. A blanket was placed over the plate for warmth and was securely adhered with double sided tape on the ground. The investigator and the parent remained at one side and in front of the infant respectively during all data collection, to assure

the infant did not fall or became insecure. The child was held at the trunk for support, and gradually the infant was guided into a prop sitting position while being distracted by toys presented by the parent. Once the examiner could completely let go of the infant, data were collected for 10 s while the child attempted to maintain sitting postural control. Trials were performed until we had collected three trials that are acceptable for our criteria, or until the infant was indicating that they were done. At any time the child became irritated; the session was halted for comforting by the parent or a chance for feeding, and then resumed only when the child was again in a calm state. In some cases, if the infant was crying for a long period of time, then data was not collected at that session. Infants came to the lab twice within a single week, and we attempted to get three trials in each of the two sessions.

Segments of usable (described below) data were analyzed using custom MatLab software (MathWorks, Nantick, MA). No filtering was performed on the data in order to not alter the nonlinear results (Rapp, et al., 1993). Trials were recorded including force plate data and video data from the back and side views. Afterwards segments were selected by viewing the corresponding video. Segments of data with 2000 time steps (8.3 s at 240 Hz) were selected from these trials by examination of the video. Acceptable segments were required to have no crying or long vocalization, no extraneous items (e.g. toys) on the force platform, neither the assistant nor the mother were touching the infant, the infant was not engaged in rhythmic behavior (e.g. flapping arms), and the infant had to be sitting and could not be in the process of falling.

2.4. Data Analysis

Linear measures of the variability present in postural sway were calculated using customized MatLab software from the COP time series, using the methodology of Prieto, et al., (1996), and included root-mean-square (RMS), maximum minus minimum (range), length of the

path traced by the COP (sway path), the area of a circle (circle area) that contains 95% of the COP data points, and the area of an ellipse (ellipse area) that contains 95% of the COP data points. Additionally, two frequency measures were included, median frequency and frequency dispersion. These parameters were selected according to Chiari, et al., (2002), as being relatively independent of biomechanical factors (e.g. height and weight), which might be expected to change with development. These linear measures characterize the quantity or amount of movement variability present in the data (Stergiou, et al., 2006).

Three nonlinear measures of variability were used, approximate entropy, largest Lyapunov exponent, and correlation dimension. Nonlinear measures of the variability present in postural sway were calculated from the COP time series as described by Harbourne and Stergiou (2003) and Stergiou, et al., (2004). Specifically, the nonlinear measures of largest Lyapunov Exponent (LyE) and the Correlation Dimension (CorrDim) were calculated using the Chaos Data Analyzer software (professional version, Physics Academic Software; Sprott & Rowlands, 1998) using an embedding dimension of six for all files, which had been determined as one higher than the highest value for a representative sample of data segments using the Tools for Dynamics software (Applied Nonlinear Sciences, LLC and Randle, Inc, Del Mar, CA). Using too low of an embedding dimension results in points being next to each other in the phase space that do not belong next to each other (i.e. too many false nearest neighbors); using too high of an embedding dimension can lead to too few nearby trajectories to do the analysis. For consistency in the analysis, the same embedding dimension was used for all files, even if they had a dimension lower than 6. The Approximate Entropy (ApEn) was calculated using MatLab code developed by Kaplan and Staffin (1996), implementing the methodology of Pincus (1991), using a lag value of 4, 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 physiologic time series (Pincus and Goldberger, 1994), and the lag 4 values was used due to slight contamination of the 240 Hz signal with a 60 Hz sinusoidal line noise. This noise was due to the electric power distribution in North America being at 60 Hz, which can result in contamination at this frequency, and at harmonics of this frequency. All the above mentioned nonlinear measures characterize the "quality" of movement variability present in the data by examining the patterns and the order that exist in the COP time series by evaluating point-by-point the entire data set (Stergiou, et al., 2006).

Infants came to the lab twice within a single week, and we attempted to get three trials in each of the two sessions. Sometimes the infant would cry, or not stay seated on the force plate, and data could not be collected for these sessions. Thus the analysis results for six trials in most cases, or fewer if we could not collect all six trials, were averaged, and statistical analysis performed on the average. The infants in the developmental delay group were somewhat less willing to sit for multiple trials, compared to infants in the typical development group. Infants with developmental delay on average had 5.15 trials per infant; where as infants with typical development had 5.55 trials per infant.

2.5. Statistical Analysis

Independent *t*-tests were used to compare the measures of postural sway from the infants with typically development and the infants with delayed development. There were thirteen different measures of postural sway that were compared, so significance was set at $P < .004$, based on a Bonferroni correction for multiple comparisons (.05/13). Additionally, Pearson product-moment correlation coefficients were calculated between the different measures of postural sway for the infants with typical development, and again for the infants with delayed

development. For the correlation analyses, there were 156 total correlations calculated, so the significance level was set at $P < .000321$, based on the Bonferroni correction (.05/156). For independent t-tests and correlation analysis (described in detail below), all the data available was used.

3. Results

The age of the infants with typical development was 5.0 months (std 0.6 months). The age of the infants with delayed development was 13.3 months (std 3.4) months. Thus the infants with delayed development were older than those with typical development, as would be expected since all the infants entered the study when they were at a similar level of motor skill development (able to sit for about 10 s).

Results of independent t-tests showed significant differences between the typically developing and delayed developing infants only for the Lyapunov exponent (Table 2), both in the anterior-posterior direction and in the medial-lateral direction.

The correlation analysis showed that the linear measures of postural sway were often strongly positively correlated with each other, except for sway path, for both infants with typical development (Table 3) and infants with developmental delay (Table 4). The nonlinear measures tended to not be strongly correlated with each other, except for the approximate entropy in the anterior-posterior direction and the approximate entropy in the medial-lateral direction were positively correlated.

Approximate entropy and correlation dimension were strongly negatively correlated with many of the linear measures, but never with sway path. The Lyapunov exponent was not significantly correlated with any of the linear or other nonlinear measures. These trends were

seen in postural sway from both infants with typical development and infants with delayed development. There were more significant correlations of the postural sway measures for infants with typical development, which may be due to a somewhat larger sample size (n=33 for typical development group versus n=26 for delayed development group, over 25% more in the group with typical development).

4. Discussion

We hypothesized that the infants with developmental delay likely due to cerebral palsy will have more periodic postural sway than typically developing infants, and our data supported this hypothesis. In fact, the Lyapunov exponent was found to be significantly higher for sitting postural sway of typically developing infants than for delayed infants. Optimal variability theory (Stergiou, et al., 2006) does not require that the LyE be less for the pathologic condition. Instead, it suggests that there is an optimal value, and the pathology exists if the LyE is either too high or too low. However, for posture data, with a fixed point intrinsic dynamic, the tendency is for more regular postural sway to be associated with pathology (Vaillancourt & Newell, 2002a). The ApEn and the CorrDim were not sensitive to differences between the two groups in the present study, while the LyE was found to be more sensitive to the differences in postural sway dynamics between these two populations than ApEn or CorrDim.

We included a variety of different linear and nonlinear analytical techniques for analysis of postural sway data from sitting infants. The linear measures used in this study include range, root-mean-square, length of the sway path, and area covered by the sway path. These linear techniques were chosen from those considered by Chiari et al. (2002) for postural sway data as being relatively insensitive to body mass parameters, an important consideration for a

296 methodology to be applied to developing infants whose mass is changing rapidly with growth.
297 The other class of postural sway measures that we included was nonlinear analysis techniques,
298 which were taken from nonlinear dynamics (chaos theory) and information theory. The nonlinear
299 analysis techniques included ApEn, LyE and CorrDim.

300 From all these measures, the LyE measure of postural sway was the only one of these
301 measures that was significantly different between infants with typical versus delayed
302 development. The infants with delayed development were found to have postural sway with a
303 lower LyE than infants with typical development. The Lyapunov exponent is derived from chaos
304 theory, and is a measure of how rapidly trajectories diverge in phase space (Alligood, et al.,
305 1996). The LyE is a classic test of whether a system is chaotic or not, with a positive LyE being
306 consistent with the system being chaotic. We would like to understand the nature of the
307 difference in the LyE between these groups.

308 As mentioned in the introduction, there are a wide variety of differences to be expected
309 between infants with cerebral palsy and infants with typical development. Dynamic systems
310 theory has been used to describe infant sitting (Thelen & Spencer, 1998), and we expect the
311 postural control system dynamics to be altered in infants with developmental delay or cerebral
312 palsy, as compared to infants with typical development. A limitation of this study is that because
313 we enrolled infants just as they were able to sit upright, the developmentally delayed infants
314 were older than the infants with typical development. Thus it is possible that age is a contributing
315 factor to the observed differences. However, we find that none of the linear measures showed a
316 significant difference between the postural sway of infants with delayed versus typical
317 development. Instead, the difference between the two groups was seen in the LyE, a measure that
318 is sensitive to patterns in the movement.

Mathematically, the LyE indicates exponential divergence of trajectories in phase space. Embedding the postural sway data in a phase space means that, for example in a two dimensional phase space, velocity would be plotted versus position. Imagine that at some point in time, the postural COP data has a certain velocity and position. Then the infant sways around, but at a later time the infant has the same velocity and position as the previous time. These two points would be close to each other in the phase space plot. Does the infant's sway the second time follow a similar trajectory as the first time, or does it diverge from the first trajectory, and if so how much? The LyE quantifies this divergence. For our analysis, the data was embedded in a six dimensional phase space, using position, velocity, acceleration, etc. for six parameters (position plus 5 derivatives), but the concept is the same. A higher LyE indicates more divergence of the trajectories.

Our interpretation of the LyE relevant to clinical considerations, which is somewhat speculative, is that the COP from an infant with more diversity in motor control strategies will follow different trajectories, whereas the COP from an infant with limited diversity in motor control strategies will tend to follow a similar trajectory each time, with the result being less divergence in the trajectories, and a correspondingly lower LyE. Thus the infants with delayed development appear to have less diversity in their motor control strategies than infants with typical development, based on the lower LyE values seen in the COP from sitting postural sway. Our assumption is that the infants with typical development have better motor control, and thus we speculate that the diversity in motor control strategies has a benefit, perhaps that the infants with typical development are exploring a wider variety of solutions to postural control, and/or that infants with delayed development are freezing degrees of freedom in order to have fewer control parameters to have to manipulate as they maintain upright posture. This interpretation

supports the notion that the therapist should select activities that allow and encourage the infant to explore different strategies in motor control, rather than identical repetition of a single task.

In order to gain additional insight into the relationships between these various measures of postural sway, we looked at the correlations between the variables. If two variables are highly correlated, measuring one does not provide new ability to discriminate between two populations that the other has not already provided. Variables with low correlations to other variables are of interest because they potentially measure different aspects of the system. For example, the Lyapunov exponent and COP root-mean-square were two such variables with low correlation in this study. Of these, it was the Lyapunov exponent that was sensitive to whatever aspect of movement that was different about the sitting postural sway of infants with developmental delay and infants with typical development, where as root-mean-square was not. In fact, the LyE was not highly correlated with any of the other variables, consistent with it being a uniquely useful measure. A more in-depth analysis of the relationships between these variables using principle component analysis is published elsewhere (Harbourne et al., 2009).

5. Conclusions

The ability to discriminate between the typical and delayed development groups using nonlinear analysis of postural sway has the potential to add to the specificity of diagnosis in the early months of life, when most standardized tests of infant development have little predictive value. In addition, information from postural measures may aid the therapist in decision-making for therapeutic intervention and goal setting. Furthermore, it is desirable be able to objectively quantify progress being made by intervention in the developmentally delayed population, assuming that the therapeutic intervention moves the quality of their movement patterns towards

that of the typically developing population. Sensitive objective measures that can quantify changes in motor control of specific tasks would be useful in assessment of various interventions designed to assist developmentally delayed infants to achieve more typical movement patterns. An approach that includes nonlinear measures of postural sway, optimized for infant sitting posture data, may contribute to these goals in the future. More work is needed to determine if these potential benefits of nonlinear analysis can be realized in clinical work.

Conflict of interest statement

No authors listed in conjunction with this manuscript submission demonstrate any form of conflict of interest, be it financial or otherwise.

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Table 1

Subject information for infants included in the developmentally delayed group.

Subject	Diagnosis at 2 years old	Severity	GMFCS
1. C01	Spastic Quadriplegic CP	Severe	4
2. C02	Right Hemiplegic CP	Mild	1
3. C03	Right Hemiplegic CP	Mild	1
4. C04	Hypotonic, overall delays	Moderate	3
5. C05	Hypotonic, overall delays	Mild[a]	n/a
6. C06	Premature (28 weeks), BPD	Mild[a]	n/a
7. C07	Premature (28 weeks), BPD	Mild[a]	n/a
8. C08	Spastic lower extremities	Moderate	1
9. C09	Hypotonic, overall delays	Severe	3
10. C10	Athetoid CP	Moderate	2
11. C12	Mixed Quadriplegic CP	Moderate	3
12. C13	Spastic Quadriplegic CP	Severe	4
13. C14	Spastic Quadriplegic CP	Severe	4
14. C15	Right Hemiplegic CP	Mild	1
15. C17	Noonan’s Syndrome	Mild[a]	n/a
16. C18	Athetoid CP	Moderate	3
17. C19	Spastic Quad CP & MD	Moderate	3
18. C20	Spastic Quadriplegic CP	Severe	4
19. C21	Undiagnosed; motor delay	Moderate	2

20. C23	Spastic Quadriplegic CP	Severe	4
21. C24	Mental Retardation	Mild[a]	n/a
22. C25	Spastic Diplegia	Moderate	2
23. C26	Premature, hearing impaired	Mild[a]	n/a
24. C27	Premature	Mild[a]	n/a
25. C29	Premature, left side weakness	Mild	1
26. C30	Premature	Mild[a]	n/a

[a] Diagnosis of CP excluded, BPD = Brochial Pulmonary Dysplasia, MD = Muscular Dystrophy (Duchenne's), GMFCS = Gross Motor Function Classification Scale, n/a indicates GMFCS is not applicable unless infant is diagnosed with cerebral palsy. (Palisano et al., 1997)

Table 2

Independent t-tests comparing postural sway measures of infants with typical development with infants who have delayed development.

	DD [a]		TD[b]		*P*
	Mean	Std	Mean	Std	
Linear					
RMS AP	6.61	3.22	6.88	2.67	0.729
RMS ML	6.31	2.90	7.30	2.24	0.143
Range AP	32.63	12.96	37.86	11.70	0.110
Range ML	29.92	12.11	36.46	10.23	0.028
Sway Path	1024.26	222.31	1110.80	221.84	0.143
Circle	1037.32	834.03	1139.52	678.28	0.606
Ellipse	823.07	649.81	1017.00	661.95	0.265
*Nonlinea*r					
ApEn AP	0.613	0.245	0.695	0.213	0.171
ApEn ML	0.528	0.187	0.533	0.196	0.923
LyE AP	0.092	0.016	0.108	0.011	0.000
LyE ML	0.077	0.012	0.087	0.008	0.000
CorDim AP	4.262	0.306	4.357	0.261	0.204
CorDim ML	4.268	0.328	4.274	0.231	0.934

* Significant at $P < .004$
[a] $n = 26$
[b] $n = 33$

Table 3

Correlations between different measures of postural sway for infants with typical development.

	Linear						Nonlinear				
		Range					ApEn		LyE		CorrDim
	RMS ML	AP	ML	SwayPath	Circle	Ellipse	AP	ML	AP	ML	AP
Linear											
RMS AP	0.63*	0.94*	0.65*	0.10	0.93*	0.91*	-0.63*	-0.40	-0.04	0.10	-0.83*
RMS ML		0.58	0.96*	-0.04	0.82*	0.80*	-0.67*	-0.79*	0.15	-0.23	-0.59
Range AP			0.63*	0.26	0.86*	0.86*	-0.55	-0.37	0.02	0.20	-0.72*
Range ML				0.00	0.81*	0.78*	-0.64*	-0.74*	0.18	-0.13	-0.63*
SwayPath					0.01	0.04	0.14	0.10	0.29	0.33	0.12
Circle						0.99*	-0.66*	-0.56	0.05	-0.03	-0.79*
Ellipse							-0.65*	-0.54	0.04	-0.06	-0.76*
Nonlinear											
ApEn AP								0.82*	0.19	0.16	0.54
ApEn ML									-0.10	0.23	0.36
LyE AP										0.45	0.15
LyE ML											0.07
CorDim AP											

* Significant at $P < .000321$; $n = 33$.

Table 4

Correlations between different measures of postural sway for infants with delayed development.

	Linear						Nonlinear					
		Range					ApEn		LyE		CorrDim	
	RMS ML	AP	ML	SwayPath	Circle	Ellipse	AP	ML	AP	ML	AP	ML
Linear												
RMS AP	0.49	0.94*	0.52	0.23	0.85*	0.85*	-0.56	-0.44	-0.23	0.11	-0.81*	-0.30
RMS ML		0.50	0.97*	-0.20	0.80*	0.82*	-0.22	-0.73*	0.18	-0.14	-0.31	-0.44
Range AP			0.57	0.30	0.80*	0.81*	-0.50	-0.36	-0.17	0.24	-0.71*	-0.26
Range ML				-0.10	0.81*	0.84*	-0.16	-0.63	0.24	-0.01	-0.31	-0.44
SwayPath					0.08	0.03	0.05	0.44	-0.16	0.19	0.02	0.27
Circle						0.98*	-0.41	-0.58	-0.07	-0.08	-0.66*	-0.37
Ellipse							-0.44	-0.65	-0.02	0.00	-0.66*	-0.40
Nonlinear												
ApEn AP								0.63	0.53	0.21	0.63	0.19
ApEn ML									0.14	0.34	0.42	0.39
LyE AP										0.55	0.37	0.14
LyE ML											0.01	0.08
CorDim AP												0.40

* Significant at $P < .000321$; $n = 26$.

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493 **Fig. 1.** Infant sits on force plate for data collection, with researcher, parent and sibling nearby.

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