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Joan E. Deffeyes

*University of Nebraska Medical Center*

Regina T. Harbourne

*University of Nebraska Medical Center*

Anastasia Kyvelidou

*University of Nebraska at Omaha, [akyvelidou@unomaha.edu](mailto:akyvelidou@unomaha.edu)*

Wayne A. Stuberg

*University of Nebraska Medical Center*

Nicholas Stergiou

*University of Nebraska at Omaha, [nstergiou@unomaha.edu](mailto:nstergiou@unomaha.edu)*

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# **Nonlinear analysis of sitting postural sway indicates developmental delay in infants**

Joan E. Deffeyes<sup>a</sup>, Regina T. Harbourne<sup>b</sup>, Anastasia Kyvelidou<sup>a</sup>, Wayne A. Stuberg<sup>b</sup>, Nicholas Stergiou<sup>a, c,\*</sup>

<sup>a</sup> Biomechanics Laboratory, University of Nebraska at Omaha, Omaha, NE, USA

<sup>b</sup> Munroe-Meyer Institute, University of Nebraska Medical Center, Omaha, NE, USA

<sup>c</sup> Department of Environmental, Agricultural and Occupational Health Sciences, College of Public Health, University of Nebraska Medical Center, 6001 West Dodge Street, Omaha, NE, 68182-0216 USA

\* Corresponding author. Address: Department of Environmental, Agricultural and Occupational Health Sciences, College of Public Health, University of Nebraska Medical Center, 6001 West Dodge Street, Omaha, NE 68182-0216, USA.

*E-mail address:* nstergiou@mail.unomaha.edu (N. Stergiou).

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**ABSTRACT**

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

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

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

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

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## 20 **1. Introduction**

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

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

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

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

66 (Stergiou, et al., 2004). Because these nonlinear analysis techniques are sensitive to patterns in  
67 the data, rather than the overall magnitude of the fluctuations, they could be ideal tools for  
68 quantifying the quality of postural sway, thus making them potentially clinically useful for  
69 studying both the typical and pathological development of motor control in infants. There are a  
70 number of different nonlinear analysis techniques, including ApEn, LyE, and CorrDim. ApEn is  
71 a measure of system complexity made by counting how often patterns of different lengths repeat  
72 in the time series (Pincus, 1991). The LyE is a measure of how rapidly trajectories diverge in  
73 phase space, and the CorrDim estimates the dimensionality of the system (Sprott & Rowlands,  
74 1998). See Stergiou, et al., (2004) for a more complete discussion of these nonlinear measures.

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

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

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

97         The actual assessment of chaos in experimental data is somewhat controversial due to  
98 limitations of the experimental data (Rapp, 1994), but despite the mathematical controversy,  
99 these algorithms have been successfully applied to many different biological and physiological  
100 systems, including postural sway data. In standing posture, nonlinear techniques have been used  
101 successfully to give insight into posture control. Nonlinear measures have been shown to be able  
102 to discriminate between pathologic and non-pathologic populations using standing COP data,  
103 and thus someday may be clinically useful measures. Patients with stroke (Roerdink, et al.,  
104 2006), traumatic brain injury (Cavanaugh, et al., 2006), and Parkinson's disease (Vaillancourt &  
105 Newell, 2000; Schmit, et al., 2006) have all been shown to differ from non-pathologic controls  
106 using nonlinear measures applied to standing COP data. Most encouraging for the present study  
107 is that COP data from standing posture in children with cerebral palsy has been found to differ  
108 from typically developing children, using both linear and nonlinear measures (Rose, et al., 2002;  
109 Donker, et al., 2008). Nonlinear measures of posture sway tend to decrease with pathology, when  
110 significant changes are observed. This might be interpreted as being more periodic, less complex,  
111 or less random.



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

120

## 121 **2. Methods**

### 122 *2.1. Participants*

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

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

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

## 140 *2.2. Inclusion and exclusion criteria*

141 Inclusion criteria for entry into the study for the typically developing infants were: a  
142 score on the Peabody Gross Motor Scale of greater than 0.5 SD below the mean, age of 5 months  
143 at the time of initial data collection, and sitting skills as described below in beginning sitting.  
144 Exclusion criteria for the sample of infants who are typically developing were: a score on the  
145 Peabody Gross Motor Scales less than 0.5 SD below the mean, diagnosed visual deficits, or  
146 diagnosed musculoskeletal problems. If a typically developing infant was found to be less than  
147 0.5 SD below the mean, and did not qualify for the study, the parents were informed of the score,  
148 the possibility of error in the measurement, and advised to have the infant re-evaluated within the  
149 next 3 months. Operational definitions of beginning sitting were used to determine the child's  
150 readiness for entry into the study. Beginning sitting was defined as (a) head control such that  
151 when trunk is supported at the mid-trunk, head is maintained for over one minute without  
152 bobbing; (b) infant can track an object across midline without losing head control; (c) infant may  
153 prop hands on floor or legs to lean on arms, but should not be able to reach and maintain balance  
154 in the prop sit position; (d) when supported in sitting can reach for toy; (e) can prop on elbows in  
155 the prone position for at least 30 s.

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

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

### 162 *2.3. Data collection*

163 For data acquisition (Fig. 1), infants sat on an AMTI force plate (Watertown, MA),  
164 interfaced to a computer system running Vicon data acquisition software (Lake Forest, CA).  
165 Markers can be seen on the infant in Fig. 1, and kinematic data was also collected, but is not  
166 discussed in this paper. COP data were acquired through the Vicon software at 240 Hz. A  
167 frequency analysis of both the medial-lateral and anterior-posterior components of all the COP  
168 time series from our preliminary data indicated that the range of signal frequencies that contain  
169 99.99% of the overall signal power is between 1 and 29 Hz. Therefore, the sampling frequency  
170 was set at 240 Hz in order to be above a factor of ten higher than the highest frequency that  
171 might contain relevant signal.

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

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

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

#### 200 *2.4. Data Analysis*

201         Linear measures of the variability present in postural sway were calculated using  
202 customized MatLab software from the COP time series, using the methodology of Prieto, et al.,  
203 (1996), and included root-mean-square (RMS), maximum minus minimum (range), length of the

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

211         Three nonlinear measures of variability were used, approximate entropy, largest  
212 Lyapunov exponent, and correlation dimension. Nonlinear measures of the variability present in  
213 postural sway were calculated from the COP time series as described by Harbourne and Stergiou  
214 (2003) and Stergiou, et al., (2004). Specifically, the nonlinear measures of largest Lyapunov  
215 Exponent (LyE) and the Correlation Dimension (CorrDim) were calculated using the Chaos Data  
216 Analyzer software (professional version, Physics Academic Software; Sprott & Rowlands, 1998)  
217 using an embedding dimension of six for all files, which had been determined as one higher than  
218 the highest value for a representative sample of data segments using the Tools for Dynamics  
219 software (Applied Nonlinear Sciences, LLC and Randle, Inc, Del Mar, CA). Using too low of an  
220 embedding dimension results in points being next to each other in the phase space that do not  
221 belong next to each other (i.e. too many false nearest neighbors); using too high of an embedding  
222 dimension can lead to too few nearby trajectories to do the analysis. For consistency in the  
223 analysis, the same embedding dimension was used for all files, even if they had a dimension  
224 lower than 6. The Approximate Entropy (ApEn) was calculated using MatLab code developed  
225 by Kaplan and Staffin (1996), implementing the methodology of Pincus (1991), using a lag value  
226 of 4, an  $r$  value of 0.2 times the standard deviation of the data file, and a vector length  $m$  of 2.

227 These  $r$  and  $m$  values are typically used in the calculation of ApEn for physiologic time series  
228 (Pincus and Goldberger, 1994), and the lag 4 values was used due to slight contamination of the  
229 240 Hz signal with a 60 Hz sinusoidal line noise. This noise was due to the electric power  
230 distribution in North America being at 60 Hz, which can result in contamination at this  
231 frequency, and at harmonics of this frequency. All the above mentioned nonlinear measures  
232 characterize the “quality” of movement variability present in the data by examining the patterns  
233 and the order that exist in the COP time series by evaluating point-by-point the entire data set  
234 (Stergiou, et al., 2006).

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

### 243 *2.5. Statistical Analysis*

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

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

254

### 255 **3. Results**

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

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

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

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

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

278

#### 279 **4. Discussion**

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

291 We included a variety of different linear and nonlinear analytical techniques for analysis  
292 of postural sway data from sitting infants. The linear measures used in this study include range,  
293 root-mean-square, length of the sway path, and area covered by the sway path. These linear  
294 techniques were chosen from those considered by Chiari et al. (2002) for postural sway data as  
295 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.

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

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

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

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

356

## 357 **5. Conclusions**

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

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

371

### 372 **Conflict of interest statement**

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

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385

386 **References**

- 387 Alligood, K.T., Sauer, T.D., Yorke, J.A., 1996. *Chaos: An Introduction to Dynamical Systems*.  
388 Springer-Verlag, New York.
- 389 Blauw-Hospers, C.H., Hadders-Algra, M., 2005. A systematic review of the effects of early  
390 intervention on motor development. *Dev. Med. Child Neurol.* 47 (6), 421-32.
- 391 Blauw-Hospers, C.H., de Graaf-Peters, V.B., Dirks, T., Bos, A.F., Hadders-Algra, M., 2007.  
392 Does early intervention in infants at high risk for a developmental motor disorder improve  
393 motor and cognitive development? *Neurosci. Biobehav. Rev.* 31 (8), 1201-1212.
- 394 Bleck, E.E., 1990. Management of the lower extremities in children who have cerebral palsy. *J.*  
395 *Bone Joint Surg.* 72A (1), 140-144.
- 396 Cavanaugh, J.T., Guskiewicz, K.M., Giuliani, C., Marshall S., Mercer V.S., Stergiou, N., 2006.  
397 Recovery of postural control after cerebral concussion: new insights using approximate  
398 entropy. *J. Athl. Training* 41 (3), 305-313.
- 399 Chen, J., Wollacott, M.H., 2007. Lower extremity kinetics for balance control in children with  
400 cerebral palsy. *J. Mot. Behav.* 39 (4), 306-316.
- 401 Chiari L., Rocchi L., Cappello A., 2002. Stabilometric parameters are affected by anthropometry  
402 and foot placement. *Clin. Biomech.* 17 (9-10), 666-677.
- 403 de Graaf-Peters, V.B., Blauw-Hospers, C.H., Dirks, T., Bakker, H., Bos, A.F., Hadders-Algra,  
404 M., 2007. Development of postural control in typically developing children and children  
405 with cerebral palsy: possibilities for intervention? *Neurosci. Biobehav. Rev.* 31 (8) 1191-  
406 1200.
- 407 Donker, S.F., Ledebt, A., Roerdink, M., Savelsbergh, G.J., Beek, P.J., 2008. Children with  
408 cerebral palsy exhibit greater and more regular postural sway than typically developing

- 409 children. *Exp. Brain. Res.* 184 (3), 363-370.
- 410 Donohue, P.K., Graham, E.M., 2007. Earlier markers for cerebral palsy and clinical research in  
411 premature infants. *J. Perinatol.* 27, 259–261.
- 412 Fedrizzi, E., Facchin, P., Marzaroli, M., Pagliano, E., Botteon, G., Percivalle, L., Fazzi, E., 2000.  
413 Predictors of independent walking in children with spastic diplegia. *J. Child Neurol.* 15 (4),  
414 228-234.
- 415 Folio, M.R., Fewell, R.R., 2000. *Peabody Developmental Motor Scales* second ed. Pro-ed, Inc.,  
416 Austin, TX.
- 417 Gardner, M.R., 2005. Outcomes in children experiencing neurologic insults as preterm neonates.  
418 *Pediatr. Nurs.* 31 (6), 448, 451-6.
- 419 Goldberger, A.L., Peng, C.K., Lipsitz, L.A., 2002. What is physiologic complexity and how does  
420 it change with aging and disease? *Neurobiol. Aging* 23 (1), 23-26.
- 421 Hadders-Algra, M., 2001. Evaluation of Motor Function in young infants by means of the  
422 assessment of general movements: a review. *Pediatr. Phys. Ther.* 13 (1), 27-36.
- 423 Harbourne, R.T., Stergiou, N., 2003. Nonlinear analysis of the development of sitting postural  
424 control. *Dev. Psychobiol.* 42, 368-377.
- 425 Harbourne, R.T., Deffeyes, J.E., Kyvelidou, A., Stergiou, N., 2009. Complexity of postural  
426 control in infants: linear and nonlinear features revealed by principal component analysis.  
427 *Nonlinear Dyn. Psychol. Life Sci.* 13 (1), 123-144.
- 428 Kaplan, D., Staffin, P., 1996. Software for heart rate variability. [Computer software]. <  
429 <http://www.macalester.edu/~kaplan/hrv/doc/>>.
- 430 Landsman, G.H., 2006. What evidence, whose evidence? physical therapy in New York State's  
431 clinical practice guideline and in the lives of mothers of disabled children. *Soc. Sci. Med.* 62

- 432 (11), 2670-2680.
- 433 Nelson, K.B., Ellenberg, J.H., 1982. Children who “outgrew” cerebral palsy. *Pediatrics* 69 (5),  
434 529-536.
- 435 Palisano, R., Rosenbaum, P., Walter, S., Russel, D., Wood, E., Galuppi, B., 1997. Development  
436 and reliability of a system to classify gross motor function in children with cerebral palsy.  
437 *Dev. Med. Child Neurol.* 39, 214–223.
- 438 Pincus, S.M., 1991. Approximate entropy as a measure of system complexity. *Proc. Natl. Acad.*  
439 *Sci. USA* 88, 2297-2301.
- 440 Pincus, S.M., Goldberger, A.L., 1994. Physiological time-series analysis: what does regularity  
441 quantify? *Am. J. Physiol. Heart Circ. Physiol.* 266 (4), H1643-H1656.
- 442 Prieto, T.E., Myklebust, J.B., Hoffmann, R.G., Lovett, E.G., Myklebust, B.M., 1996. Measures  
443 of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans.*  
444 *Biomed. Eng.* 43 (9), 956-966.
- 445 Rapp, P.E., 1994. A guide to dynamical analysis. *Integr. Psychol. Behav. Sci.* 29 (3), 311-327.
- 446 Rapp, P.E., Albano, A.M., Schmah, T.I., Farwell, L.A., 1993. Filtered noise can mimic low-  
447 dimensional chaotic attractors. *Phys. Rev. E*, 47 (4), 2289-2297.
- 448 Roerdink, M., De Haart, M., Daffertshofer, A., Donker, S.F., Geurts, A.C., Beek, P.J., 2006.  
449 Dynamical structure of center-of-pressure trajectories in patients recovering from stroke.  
450 *Exp. Brain Res.* 174 (2), 256-269.
- 451 Rose, J., Wolff, D.R., Jones, V.K., Bloch, D.A., Oehlert, J.W., Gamble, J.G., 2002. Postural  
452 balance in children with cerebral palsy. *Dev. Med. Child Neurol.* 44 (1), 58-63.
- 453 Schmit, J.M., Riley, M.A., Dalvi, A., Sahay, A., Shear, P.K., Shockley, K.D., Pun, R.Y., 2006.  
454 Deterministic center of pressure patterns characterize postural instability in Parkinson's

- 455 disease. *Exp. Brain Res.* 168 (3), 357-67.
- 456 Sprott, J.C., Rowlands, G., 1998. *Chaos Data Analyzer: The Professional Version*. Physics  
457 Academic Software, Raleigh, NC.
- 458 Stergiou, N., Buzzi, U.H., Kurz, M.J., Heidel, J., 2004. Nonlinear tools in human movement. In:  
459 Stergiou (Ed.), *Innovative Analysis of Human Movement: Analytical Tools for Human*  
460 *Movement Research* (pp. 63-90). Human Kinetics, Champaign, IL, pp. 63-90.
- 461 Stergiou, N., Harbourne, R.T., Cavanaugh, J.T., 2006. Optimal movement variability: a new  
462 theoretical perspective for neurologic physical therapy. *J. Neurol. Phys. Ther.* 30 (3), 120-  
463 129.
- 464 Thelen, E., Spencer, J.P., 1998. Posture control during reaching in young infants: a dynamic  
465 systems approach. *Neurosci. Biobehav. Rev.* (224), 507-514.
- 466 Vaillancourt, D.E., Newell, K.M., 2000. The dynamics of resting and postural tremor in  
467 Parkinson's disease. *Clin. Neurophysiol.* 111 (11), 2046-2056.
- 468 Vaillancourt, D.E., Newell, K.M., 2002a. Changing complexity in human behavior and  
469 physiology through aging and disease. *Neurobiol. Aging* 23, 1-11.
- 470 Vaillancourt, D.E., Newell, K.M., 2002b. Changing complexity in human behavior and  
471 physiology through aging and disease. *Neurobiol. Aging* 23, 27-29.
- 472 Wu, Y.W., Day, S.M., Strauss, D.J., Shavelle, R.M., 2004. Prognosis for ambulation in cerebral  
473 palsy: a population based study. *Pediatrics* 114 (5), 1264-1271.
- 474



475 **Table 1**

476 Subject information for infants included in the developmentally delayed group.

477

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 <sup>a</sup>	n/a
6. C06	Premature (28 weeks), BPD	Mild <sup>a</sup>	n/a
7. C07	Premature (28 weeks), BPD	Mild <sup>a</sup>	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 <sup>a</sup>	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 <sup>a</sup>	n/a
22. C25	Spastic Diplegia	Moderate	2
23. C26	Premature, hearing impaired	Mild <sup>a</sup>	n/a
24. C27	Premature	Mild <sup>a</sup>	n/a
25. C29	Premature, left side weakness	Mild	1
26. C30	Premature	Mild <sup>a</sup>	n/a

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

481

482 **Table 2**

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

	DD <sup>a</sup>		TD <sup>b</sup>		<i>P</i>
	Mean	Std	Mean	Std	
<i>Linear</i>					
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
<i>Nonlinear</i>					
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  $P < .004$

<sup>a</sup>  $n = 26$

<sup>b</sup>  $n = 33$

486 **Table 3**

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

	Linear						Nonlinear					
	RMS ML	Range		SwayPath	Circle	Ellipse	ApEn	LyE		CorrDim		
		AP	ML				AP	ML	AP	ML	AP	
<i>Linear</i>												
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*	
<i>Nonlinear</i>												
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  $P < .000321$ ;  $n = 33$ .

489 **Table 4**

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

	Linear						Nonlinear					
	RMS ML	Range		SwayPath	Circle	Ellipse	ApEn	LyE		CorrDim		
		AP	ML				AP	ML	AP	ML	AP	ML
<i>Linear</i>												
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
<i>Nonlinear</i>												
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  $P < .000321$ ;  $n = 26$ .

491

492

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

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