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Reliability of Center of Pressure Measures for Assessing the Development of Sitting Postural Control

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Running head: Reliability of COP in sitting infants

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Title: Reliability of center of pressure measures for assessing the development of sitting postural control.

Abstract

Objectives: To determine the reliability of linear and nonlinear tools, including intra- and inter-session reliability, when used to analyze the center of pressure (COP) time series during the development of infant sitting postural control.

Design: Longitudinal study

Setting: University hospital laboratory

Participants: Thirty three typically developing infants (mean age at entry in the study ± standard deviation, 152.4 ± 17.6 days).

Interventions: Not applicable

Main Outcome Measures: Infants were tested twice in one week at each of the four months of the study. Sitting COP data was recorded for three trials at each session (two each month within one week). The linear COP parameters of root mean square (RMS) and range of sway for both the anterior-posterior (AP) and the medial-lateral (ML) directions, and the sway path, were calculated. In addition, the nonlinear parameters of approximate entropy (ApEn), Lyapunov exponent (LyE), and correlation dimension (CoD) for both directions were also calculated. Intra-session and inter-session reliability was quantified by the intraclass correlation coefficient (ICC).

Results - Conclusions: Our results showed that the evaluation of COP data is a reliable method of investigating the development of sitting postural control. In particular, the nonlinear tool of ApEn presented high intra- and inter- session ICC values in comparison to all other parameters evaluated. Generally, intra- and inter- session reliability increased in the last two months of the data collections and as sitting posture matured. The present study emphasizes the need for establishing

COP reliability before using it as a method of examining intervention progress directed at improving the sitting postural abilities in infants with motor developmental delays.

Key Words: Posture, Reliability, Nonlinear, Infant Motor Development

Introduction

Children with posture and movement disorders struggle to attain the milestone of sitting, and independent sitting is often the first missed or delayed milestone indicating a posture or movement disorder[1]. Abnormal neurological signs generally identify these children along with high risk factors occurring around birth, scores obtained on developmental screening tests, or visual analysis of their movement quality. However, currently available tests even though being reliable in identifying delayed development, lack in quantifying progress as a result of small changes occurring during development[2,3]. Existing tests for measuring progress assess large changes in motor skills, and are not precise enough to provide information regarding rate of acquisition of skill on a short-term basis[2,3]. Moreover, the effect of intervention on motor development is an issue needing more research[4], but measurement tools that measure these effects are lacking. Thus, there is a need for a method of quantifying the mechanisms of postural control during the development of sitting, in order to be used eventually as a tool of measuring progress during treatment of an already identified motor delay or disorder.

A simple paradigm of evaluating postural control is the usage of a force platform and measuring the center of pressure (COP) which describes body sway. The COP is the point of application of the ground reaction force vector and it has traditionally been utilized to describe the organization of posture[5]. Researchers have employed the COP in investigations of postural control during standing in healthy[6] and non-healthy individuals[7], as well as healthy[8] and non-healthy older children[9]. The reproducibility of this methodology has been investigated extensively during standing for both populations. Reliability measures, such as the intraclass correlation coefficient (ICC), revealed that COP measures generally produced poor to fair reproducibility ranging from 0.3 to 0.75 under static and dynamic balance conditions[10,11,12,13]. Recently, this methodology has also been utilized to investigate sitting postural control[14,15,16,]. However, the reliability of COP measures for the evaluation of sitting postural control and specifically for infant motor development has not been identified.

Furthermore, COP data can also be evaluated not only with traditional linear measures, as those used in the previous studies for standing postural control, but also with nonlinear parameters. Such parameters can provide new insights in the ways that the nervous system controls the complexity of dynamic balance[14]. In addition, nonlinear measures evaluate different aspects of the COP data. Linear measures, such as the range and the length of path traced by the COP, quantify the amount of movement of the COP during a specific task or the quantity of variation present in a set of values independently of their order in the distribution. In contrast, nonlinear measures best capture variation in COP regarding how motor behavior emerges in time, for which the temporal organization in the distribution of values is of interest. Temporal organization, or "structure" is quantified by the degree to which values emerge in an orderly (i.e., predictable) manner, often across a range of time scales[14]. Examples of nonlinear measures are the Lyapunov Exponent (LyE) and the Approximate Entropy (ApEn)[14]. These nonlinear tools are being used increasingly to describe complex conditions for which linear techniques have been inadequate, confounding scientific study and the development of meaningful therapeutic options. For example, nonlinear analysis has recently appeared in research of heart rate irregularities, sudden cardiac death syndrome, blood pressure control, brain ischemia, epileptic seizures, and posture[17,18,19,20,21,22], to understand their complexity and eventually develop prognostic and diagnostic tools. Similarly, nonlinear analyses of the COP data as sitting develops can provide a window into the neurological status of the infant, and allow insight into the complex strategies infants use to control movement and posture. In standing posture, nonlinear analysis has provided insight into the type of characteristics/mechanisms of control used. For example, Newell[23] used COP data from children, adults and elderly by measuring standing postural sway and found that children had decreased complexity and dimensionality of the COP. Postural sway complexity and dimensionality increased from three year olds to five year olds, was approximately the same in five year olds and adult subjects, and then decreased again in elderly subjects[23]. These data suggested that as children grow and learn about their bodies, they can have more flexible control over the body's degrees of freedom, and greater complexity and dimensionality emerges in posture and movement. Nonlinear analysis of COP data has also been used to examine differences in standing posture between healthy controls and patients with tardive dykinesia and it has been found that the patients exhibited decreased complexity in their sway patterns[24]. The examples from these studies and several others[16,25,26], indicate that nonlinear analysis can reveal the richness or shortage of behavioral control options[27] or describe the strategies employed for the organization of the body's degrees of freedom[14]. However, the reliability of this methodology for evaluating COP data during sitting posture in infants has not been investigated.

Therefore, the purpose of this study was to determine the reliability of linear and nonlinear tools, including intra- and inter- session reliability, when used to analyze the COP time series during the development of infant sitting postural control. Independent sitting requires dynamic stabilization of all the linked segments of the body. Through learning and adaptation, an individual's nervous system anticipates any disturbance to posture, and links segments of the body to anticipate forces before the onset of movement. We can most readily study the learning of postural control in the infant population, and especially in the sitting position, which is the first time that the infant controls the trunk in an upright posture. This learning process in the normal infant provides important clues for developing treatment tools that enhance sitting and postural skills in children with movement disorders, and may also be valuable in treating adults with acquired central nervous system injury. Based on the previous research conducted in our laboratory and described above[14], we hypothesized that the nonlinear tools will be more reliable in assessing development of infant sitting postural control. The identification of the reliability of linear and nonlinear tools from COP data is the first but essential step for the study of therapeutic interventions directed at improving the sitting postural abilities in infants with motor developmental delays.

Methods

Participants

Thirty four typically developing infants were recruited for the present study. After one infant dropped out, 33 infants participated in this study (mean age at entry in the study ± standard deviation, 152.4 ± 17.6 days; gender, 14 male 19 female; weight at entry in the study ± standard deviation, 7.37 ± 0.71 kg, weight at end of the study ± standard deviation, 8.53 ± 1.03 kg). The infants were followed from the age of around five months to eight months, the time when infants are learning to sit independently. Infants were recruited from employee announcements at the campus of the University of Nebraska at Omaha and at the Munroe-Meyer Institute, University of Nebraska Medical Center. Before data collection commenced, the parents of the infants provided informed consent that was approved by the university human research ethics committee. The inclusion criteria for entry into the study for the infants were a score on the Peabody Gross Motor Scale II within 0.5SD of the mean, age of about five months at the time of initial data collection, the ability of the child to hold up their head when supported at the thorax, beginning ability to reach for objects dangled in front of them in supported sitting or lying on their back, propping on their elbows when in prone for thirty seconds and propping on both arms during sitting. The exclusion criteria were: a) a score on the Peabody Gross Motor Scale II of greater than 0.5 SD below the mean, b) diagnosed visual deficits, and c) diagnosed musculoskeletal problems.

Experimental design

Each infant participated in nine sessions. The first session lasted for 45 minutes and was used to perform the Peabody Gross Motor Scale (Table 1). The Peabody Gross Motor Scale II is a norm- and criterion-referenced test that examines gross motor function in children from birth to 83 months[28]. The other eight sessions were distributed over a period of four months. The infants were tested twice in one week at each of the four months of the study. Three trials at each session were used to determine intra-session reliability. The repeat testing within one week of each month's testing was used for the estimation of the inter-session reliability. We were able to collect data for all eight session over a period of four months for all infants, with the exception of two infants who either did not came for the second session of the first month or the data collected were not appropriate according to our criteria explained below.

Protocol

For all 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. The duration of the sessions took approximately 30 minutes to one hour. A standard set of infant toys was used for distraction and comfort, accompanied by a DVD player, which presented infant movies. 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. Infants were placed by their parent on the top of a force plate that was covered with a special pad for warmth which was securely adhered with tape on the force plate. The baby was held in the sitting position in the middle of the plate when calm and happy (Figure 1). 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 become insecure. The child was held at the thorax for support, and gradually the infant was guided into a sitting position while being distracted by toys presented by the parent or the investigator or a DVD movie. Once the examiner could completely let go of the infant, data were collected continuously while the child attempted to maintain postural control. Trials were performed until we had collected three trials that were acceptable for our criteria (see below), or until the infants were indicating that they were done. At any time the child became irritated; the session was halted for comforting by the parent, or a chance of feeding, and then resumed only when the child was again in a calm state.

Data analysis

For data acquisition, infants sat on an AMTI force plate (Advanced Mechanical Technology Inc., Model OR6-7-1000, Watertown, MA), interfaced to a computer system running Vicon data acquisition software (Lake Forest, CA). The force platform simultaneously measures three force components Fx, Fy, and Fz and three moment components Mx, My, and Mz. The forces and moments are measured by strain gauges attached to load cells at the four corners of the platform. The force plate has a 4450 N (1000 lb) capacity for Fz and a 2225 N (500 lb) capacity for Fx and Fy. The Fz channel has a natural frequency of 480 Hz and Fx and Fy have a natural frequency of 300 Hz. COP data in both the anterior-posterior (AP) and the medial-lateral (ML) directions were acquired through the Vicon software at 240 Hz, in order to be above a factor of ten higher than the highest frequency contained in the signal. No filtering was performed on the data because such a procedure can affect the nonlinear results. Furthermore, video of each trial was collected using two Panasonic recorders (Model 5100 HS) interfaced with a Panasonic Digital AV Mixer (Model WJ-MX30). The cameras were positioned to record a sagittal and a frontal view of the subject. Segments of acceptable (described below) data were analyzed using custom MatLab software (MathWorks, Nantick, MA).

Three acceptable trials (8.3 seconds each) were selected from the videotape record using the following criteria: a) infant did not move the arms (not reaching, holding an object, or flapping their arms), b) infant did not vocalize or cry, c) infant was not in the process of falling, d) trunk was not inclined more than 45 degrees to either side, e) not being touched, f) the arm position (propping or not propping) of the infants was noted during the entire trial and only trials that have the infant using consistent base of support was used. The COP data selected allowed for the examination of 1992 data points (8.3 sec X 240 Hz) for each COP direction for each trial. This number is considered adequate for nonlinear analysis[29,30].

Linear measures were calculated from the selected trials using customized MatLab software from the COP data, using the methodology of Prieto et al[31], and included root-mean-square (RMS), maximum minus minimum (range) and length of the path traced by the COP (sway path) for the AP and the ML directions. These parameters were selected according to Chiari et al.[32] and they are all independent of the effect of biomechanical factors such as weight. Weight changes dramatically during development so it is possible confounding factor. These linear measures characterized the quantity or amount of variability present in the data[27].

In addition, three nonlinear measures of variability were calculated from the selected trials: the approximate entropy (ApEn), the largest Lyapunov exponent (LyE), and the correlation dimension (CoD) for both the AP and the ML directions. Rather than quantifying the amount of variability as the linear measures do, the nonlinear measures are sensitive to patterns in the data. Nonlinear measures of the variability present in postural sway were calculated from the COP data as described by Harbourne and Stergiou[14]. The calculation of the Lyapunov Exponent and the Correlation Dimension was performed using the Chaos Data Analyzer Professional software[33]. However, to accurately calculate these measures, a parameter must be chosen with extreme care and incorporated in the software. This parameter is the embedding dimension and its calculation is conducted using a Global False Nearest Neighbor (GFNN) analysis[34]. GFNN analysis of the COP time series is performed using the Tools for Dynamics software. The GFNN analysis describes the minimum number of variables that is required to form a valid state space from a given time series. The embedded dimension is a description of the number of dimensions needed to unfold the structure of a given dynamical system in space[35]. For consistency in the analysis, the same embedding dimension (6) was used for all files, even if they had a dimension lower than six. The ApEn was calculated using algorithms written by Pincus[36] implemented in MATLAB. All the above mentioned nonlinear measures characterize the structure of the variability present in the data by examining the patterns and the time evolving order that exist in the COP time series by evaluating point-by-point the entire data set[27].

Statistical Analysis

Intra-session and inter-session reliability was quantified by the intraclass correlation coefficient[37] (ICC). Specifically, a one-way ANOVA model with a random subject effect was used to estimate the intra-session reliability based on data from the first visit of the month for each child (ICC[1,1] in the notation of Shrout and Fleiss[37]). To estimate the inter-session reliability, the averages of the three measurements during each session are analyzed using a one-way ANOVA model with a random subject effect similar to the model for intra-session reliability. In the results section ICC findings are reported based on Rosner[38]. Specifically, an ICC of less than 0.4 indicates poor reproducibility while an ICC between 0.4 and 0.75 indicates fair to good reproducibility. Lastly, an ICC over 0.75 indicates excellent reproducibility.

Results

Linear Parameters

Inter-session ICCs for the linear parameters were between 0.07 and 0.72 (Table 2). The Range in the AP direction presented the highest ICC value. All linear parameters presented ICC values ranging from poor to fair to good reproducibility. The highest mean ICC value across months was observed for Range in ML direction. However, the last two months of data collections presented consistently fair to good ICCs with the exception of the sway path parameter (Figure 2). We can observe that mean RMS and mean Range showed consistently increasing values in ICCs across months of sitting postural development. However, sway path presented consistently decreasing values in ICCs across months of sitting postural development.

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Intra-session ICCs for linear parameters were between 0.19 and 0.76 (Table 3). Range in the ML direction presented the highest ICC value, which suggests excellent reproducibility. All linear parameters presented ICC values ranging from poor to fair to good reproducibility. The highest mean ICC value across months was observed for Range in AP direction. However, the last three data collections, which are included in the third and fourth month sessions, presented consistently fair to good ICCs (Table 3, Figure 3). We can observe that RMS and Range presented consistently increasing values in ICC's across data collections. However, sway path presented consistently decreasing values in ICCs across data collections. The above findings are in agreement with the inter-session reliability.

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Nonlinear Parameters

Inter-session ICCs for nonlinear parameters were between 0 and 0.74 (Table 3). ApEn in the AP direction presented the highest ICC value. All nonlinear parameters presented ICC values ranging from poor to fair to good reproducibility. The highest mean ICC value across months was observed for LyE in ML direction. However, the last two months of data collections presented alternating fair to good reproducibility (Table 4, Figure 4). We can observe that the mean values of all nonlinear parameters presented consistently increasing values in ICCs across months of sitting postural development with the exception of ApEn in the AP direction.

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Intra-session ICCs for nonlinear parameters were between 0.18 and 0.75 (Table 5). ApEn in the ML direction presented the highest ICC value, which suggests excellent reproducibility. All nonlinear parameters presented ICC values ranging from poor to fair to good reproducibility. The highest mean ICC value across months was observed by ApEn in the ML direction. Furthermore, as seen in the intra-session reliability of linear parameters, the last three data collections, which are included in the third and fourth month sessions, presented fair to good ICCs (Figure 5).

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Discussion

The purpose of this study was to determine the reliability of linear and nonlinear tools, including intra- and inter- session reliability, when used to analyze the COP time series during the development of infant sitting postural control. We hypothesized that the linear and nonlinear tools will have different reliability assessments since they are evaluating different aspects of the COP data. This assumption was based on the fact that linear measures, such as the range and the length of path traced by the COP, quantify the amount of movement of the COP during a specific task or the quantity of variation present in a set of values independently of their order in the distribution. In contrast, nonlinear measures best capture variation in COP regarding how motor behavior emerges in time, for which the temporal organization in the distribution of values is of interest. Temporal organization, or "structure" is quantified by the degree to which values emerge in an orderly (i.e., predictable) manner, often across a range of time scales[14].

Our results showed that all linear parameters presented inter- and intra- session ICC values ranging from poor to good reproducibility. However, the last two months of data collections presented consistently fair to good ICCs. In contrast the sway path parameter presented decreased values of inter- and intra- session ICCs across development. Similarly, all nonlinear parameters presented analogous inter- and intra- session ICC values ranging from poor to good reproducibility. In addition, the last two months of data collections presented consistently fair to good ICCs. Generally, ApEn presented the highest ICC values compared to all other parameters examined, while the rest of the linear and nonlinear parameters presented similar values with the exception of LyE which showed the lowest ICC values.

Reproducibility of linear parameters during infant sitting posture showed similar results to those from standing posture studies in healthy adults[10] and elderly individuals[11,39]. Specifically, RMS in AP and ML directions showed fair to good intra-session reliability (0.58) during standing of healthy elderly participants[39]. Intra-session ICC values for the range of the sway area during standing in healthy adults were 0.43 and 0.71 for AP and ML directions[10], while healthy elderly presented lower ICC values, 0.29 and 0.44, for AP and ML directions respectively[39]. Inter-session reliability of linear parameters during standing of healthy adults presented fair to poor reproducibility, with ICC values less than 0.55[10]. Furthermore, the ICC values of linear parameters during infant sitting were similar to those of children without disabilities during standing balance tasks[12]. Intra-session reproducibility of the Smart Balance Master System under different sensory conditions revealed ICC values that ranged between 0 and 0.79[12]. Similarly, inter-session reliability of the mean value of three repetitive tests ranged between 0.08 to 0.68[12]. In addition, children standing on a force plate between the age of two and four presented an ICC value for the sway index of 0.62[13]. Therefore, our results are similar to those reported in the literature from standing posture studies.

Regarding the reproducibility of the specific nonlinear parameters presented here, no direct comparisons can be made, since the reliability of the nonlinear analysis of COP data has not yet been explored under sitting or standing tasks. In a recent study, Doyle et al.[40] investigated a different nonlinear parameter, fractal dimension, from COP data during standing in young healthy people. This parameter allows the measure of the degree of complexity by evaluating how fast the data increase or decrease as the scale becomes larger or smaller. Fractal dimension intra-session reliability was found to be higher than linear tools and most of the time it presented fair to good to excellent reproducibility[38]. Similar to the results of the present study, ApEn, which is a measure of the regularity or predictability in the time series, showed most of the time fair to good intra-session (>0.50) reproducibility and consistently better than the linear parameters of COP during infant sitting.

The moderate inter-session reliability results of the COP of infant sitting are consistent not only with COP studies of other populations and different paradigms, but also with other infant motor tests. The test-retest reliability of a neurobehavioral assessment for preterm infants ranged from 0.59 to 0.70[41]. In addition, the two day inter-session reliability of the Linfert–Hierhoizer scales for one up to three month old infants was -0.24 up to 0.69, while the Buher Baby test inter-session reliability ranged from 0.40 to 0.96 depending on the age of the infants[42]. Lastly, the four to ten day test-retest reliability of the Bayley motor scales for nine and 15 month old infants ranged from 0.42 to 0.96 and increasing with age[41]. Interestingly, test-retest reliability of infant testing tends to become better with increasing age as it was also the case in our results. Thus, it seems that higher variability in performance at a younger age is due to the fact that infants are attempting many different sitting strategies, so it is expected to have less consistency/reliability early on, whether you use linear or nonlinear tools to evaluate sitting performance.

An additional observation, based on the findings of the present research, was that intra- and inter- session reliability of infant sitting posture became better on the last two months of data collections. Similar for standing tasks in children, Baker et al.[13] found that younger children were not as reliable as older children regarding their COP sway index as expressed by ICC values. This apparent similarity in intra- and inter- session reliability of COP parameters during standing and sitting can be explained by examining the previous experience of the child in the specific skill as well as the different patterns of sitting and standing that the child utilizes. In the present study when infants started participating in data collections they were novice and inexperienced in the sitting skill. However, as development occurred and sitting became everyday practice, infants became more capable in sitting independently without falling. At the onset of sitting infants cannot perform the sitting skill at the same fashion in each trial or each session as well as they can perform it when they are older.

We should also mention that inter-subject variability may have affected our results. It can be hypothesized, that when infants entered the study, were at different levels of sitting development, which is why we observed differences in the sitting behavior of the first two months. Therefore, an alternative could be to evaluate sitting postural development through stages of sitting instead of months. In addition, the fact that inter-session reliability did not show consistently excellent reproducibility may be due to the nature of the subjects. Infants, between the age of four and eight months old, experience rapid physiological, neuromuscular and psychological changes. These changes may be responsible for the diverse pattern that infants bring into play at each data collection session. Therefore, since infants are going through a period of rapid growth and change along many interwoven lines of development it is important to take multiple measures and then take the mean of the parameter studied. This step will actually allow us to characterize more accurately the construct that we are measuring.

In conclusion, our results determined that linear and nonlinear investigation of COP data is a reliable method for investigating the development of sitting postural control. Our results from our linear parameters were similar to those reported in the literature from standing postural control. Regarding the nonlinear tools, ApEn presented the highest intra- and inter- session ICC values among all other parameters, while CoD showed similar intra- and inter- session ICC values with the linear measures. In contrast, LyE presented the lowest intra- and inter- session ICC values in comparison to all other parameters examined. Therefore, the evaluation of sitting postural control using linear and nonlinear tools of COP time series is a reliable method for quantifying incremental change through the development of sitting postural control. It is fundamental to know precisely how reliable an experimental paradigm is in order to evaluate therapeutic protocols that target the acquisition of infant sitting postural control. Our results provided the first and essential step for the development of appropriate methodology using measures from COP data to assess the efficacy of therapeutic interventions directed at improving the sitting postural abilities in infants with motor developmental delays.

References

1. Wu YW, Day SM, Strauss DJ, Shavelle RM. Prognosis for ambulation in CP: a population-based study, Pediatrics, 2004; 114:1264-1271.
2. Campbell SK. The infant at risk for developmental disability. In: Campbell SK (Ed.) Decision Making in Pediatric Neurologic Physical Therapy, pp. 260-332. Philadelphia, PA: Churchhill Livingstone; 1999.
3. Prechtl HFR, Einspieler C, Cioni G, Bos F, Ferrari F, Sontheimer D. An early marker for neurological deficits after perinatal brain lesions. Lancet, 1997; 347:1361-1363.
4. Hadders-Algra M. Evaluation of motor function in young infants by means of the assessment of general movements: a review. Pediatr Phys Ther 2001; 13: 27-36.
5. Massion J. Movement, posture, and equilibrium: interaction and coordination. Prog Neurobiol 1992; 38:35-56.
6. Donker FS, Roerdink M, Greven AJ, Beek PJ. Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. Exp Brain Res 2007; 181:1-11.
7. Rocchi L, Chiari L, Horak FB. Effects of deep brain stimulation and levodopa on postural sway in Parkinson's disease. J Neurol Neurosurg Psychiatry 2002; 73:267-74.
8. Riach CL, Hayes KC. Maturation of postural sway in young children. Dev Med Child Neurol 1987; 29:650-8.
9. Cherng RJ, Su FC, Chen JJ, Kuan TS. Performance of static standing balance in children with spastic diplegic cerebral palsy under altered sensory environments. Am J Phys Med Rehabil 2007; 78:336-43.

10. Brouwer B, Culham EG, Liston RAL, Grant T. Normal variability of postural measure: implications for the reliability of relative balance performance outcomes. Scand J Rehab Med 1998; 30:131-7.

11. Lafond L, Corriveau H, He´bert R, Prince MF. Intrasession Reliability of Center of Pressure Measures of Postural Steadiness in Healthy Elderly People. Arch Phys Med Rehabil 2004; 85:896-901.

12. Liao H, Mao P, Hwang A. Test-retest reliability of balance tests in children with cerebral palsy. Dev Med Child Neurol 2001; 43:180-6.

13. Baker CP, Newstead AH, Mossberg KA, Nicodemus CL. Reliability of static standing balance in nondisabled children: comparison of two methods of measurement. Pediatr Rehabil 1998; 2:15-20.

14. Harbourne RT, Stergiou N. Nonlinear analysis of the development of sitting postural control. Dev Psychobiol 2003; 42:368-77.

15. Bertenthal BI, Rose JL, Bai DL. Perception-action coupling in the development of visual control of posture. J Exp Psychol 1997; 23:1631-1643.

16. Boker SM, Schreiber T, Pompe B, and Bertenthal BI. "Nonlinear analysis of perceptual-motor coupling in the development of postural control," in Nonlinear Techniques in Physiological Time Series Analysis, H. Kantz, J. Kurths, and G. Mayer-Kress, Eds. Heidelberg, Germany: Springer, 1998.

17. Buchman TG, Cobb JP, Lapedes AS, Kepler TB. Complex systems analysis: a tool for shock research. Shock, 2001; 16:248-251.

18. Goldberger AL, Rigney DR, Mietus J, Antman EM, Greenwald S. Nonlinear dynamics in sudden cardiac death syndrome: Heartrate oscillations and bifurcations. Experientia 1988;

44:983-97.

19. Goldstein B, Toweill D, Lai S, Sonnenthal K, Kimberly B. (). Uncoupling of the automatic and cardiovascular systems in acute brain injury. Am J Physiol, 1998; 275 (Regulatory Integrative Com. Physiol., 44): R1287-R1292.

20. Lanza GA, Guido V, Galeazzi M, Mustilli M, Natali R, Ierardi C, Milici C, Burzotta F, Pasceri V, Tomassini F, Lupi A, Meseri A. Prognostic role of heart rate variability in patients with a recent acute myocardial infarction. Am J Cardiol 1998; 82: 1323-1328.

21. Slutzky MW, Cvitanovic P, Mogul DJ. Deterministic chaos and noise in three in vitro hippocampal models of epilepsy. Ann Biomed Eng 2001; 29:607-618.

22. Wagner CD, Nafz B, Persson PB. Chaos in blood pressure control. Cardiovasc Res 1996; 31: 380-387.

23. Newell KM. Degrees of freedom and the development of center of pressure profiles. In Newell KM and Molenaar PMC (Eds) Applications of nonlinear dynamics to developmental process modeling, pp. 63-84, Hillsdale, NJ: Erlbaum, 1997.

24. Newell KM, Van Emmerik REA, Lee D, Sprague RL. On postural stability and variability. Gait Posture, 1993; 1:225-230.

25. Yamada N (1995). Chaotic swaying of the upright posture. Human Movement Science 1995, 14:711-726.

26. Delignières D, Deschamps T, Legros A, Caillou N. A methodological note on non-linear time series analysis: Is Collins and De Luca (1993)'s open- and closed-loop model a statistical artifact? J Motor Behav 2003; 35:86-96

27. Stergiou N, Harbourne RT, Cavanaugh JT. Optimal movement variability: a new theoretical perspective for neurologic physical therapy. J Neurol Phys Ther 2006; 30:120-

9.

28. Folio MR, Fewell RR. Peabody Developmental Motor Scales, 2nd Edition. Pro-ed, Inc., Austin, TX, 2000.

29. Grassberger P, Procaccia I. Measuring the strangeness of strange attractors. Physica D 1983; 9:189–208.

30. Pincus SM, Gladstone IM, Ehrenkranz RA. A regularity statistic for medical data analysis. Journal of Clinical Monitoring 1991; 7:335–345.

31. Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: Differences between healthy young and elderly adults. IEEE Trans Biomed Eng 1996; 43:956-66.

32. Chiari, L., Rocchi, L., & Capello, A. Stabilometric parameters are affected by anthropometry and foot placement. Clin Biomech 2002; 17, 666-677.

33. Sprott JC, Rowlands G.Chaos datas analyzer: the professional version. Raleigh, NC: Physics Academic Software 1998.

34. Stergiou N, Buzzi UH, Kurz MJ, Heidel J. Nonlinear Tools in Human Movement. In: Stergiou, N. (Ed.) Innovative Analyses for Human Movement, pp. 63-90. Champaign, IL: Human Kinetics Publishers; 2004.

35. Mitra S, Riley MA, Turvey MT. Chaos in human rhythmic movement. J Mot Behav 1997; 29:195-198.

36. Pincus, S.M. Approximate entropy as a measure of system complexity. Proc Natl Acad Sci U S A, 1991; 88: 2297-2301.

37. Shrout PE, Fleiss JL. Intraclass Correlations: Uses in assessing rater reliability. Psychol Bull 1979; 86:420-8.

38. Rosner B. Fundamentals of biostatistics. 5th edition. Duxbury Thomsom Learning. 2000. Page 563.

39. Hughes MA, Duncan PW, Rose DK, Chandler JM, Studenski SA. The relationship of postural sway to sensorimotor function, functional performance, and disability in the elderly. Arch Phys Med Rehabil 1996; 77:567-72.

40. Doyle TL, Newton RU, Burnett AF. Reliability of traditional and fractal dimension measures of quiet stance center of pressure in young, healthy people. Arc Phys Med Rehabil 2005; 86:2034-40

41. Horner TM. Test-retest and home clinic characteristics of the Bayley Scales if infant development in nine and fifteen month old infants. Child Development 1980; 51:758-761

42. Werner EE, Bayley N. The reliability of Bayley's revised scale of mental and motor development during the first year of life. Child Development 1966; 37:39-50

Legends

Table 1. Peabody Gross Motor Scale II standard scores for all recruited infants.

Table 2. Inter-session (within a week per month) reliability, as expressed with the Intra-class correlation coefficient (ICC), of infant sitting posture for all linear parameters.

Table 3. Intra-session (within each session) reliability, as expressed with the Intra-class correlation coefficient (ICC), of infant sitting posture for all linear parameters.

Table 4. Inter-session (within a week per month) reliability, as expressed with the Intra-class correlation coefficient (ICC), of infant sitting posture for all nonlinear parameters

Table 5. Intra-session (within each session) reliability, as expressed with the Intra-class correlation coefficient (ICC), of infant sitting posture for all nonlinear parameters.

Figure 1. Position of infant during data collection. The infant is sitting on the top of a force plate while a DVD player is in front of the infant for maintaining a calm and relaxed state.

Figure 2. Inter-session reliability (ICC) for linear parameters of COP across months. Most linear parameters ICCs are averaging around 0.5 and there is an increasing trend as the infant develops. This is not true for Mean Sway Path where ICC are lower than 0.5 and there is a decreasing trend across development.

Figure 3. Intra-session reliability (ICC) for linear parameters of COP across data collection sessions. All linear parameters ICCs are averaging around 0.5 and there is an increasing trend as the infant develops except for Mean Sway Path ICCs, which present a decreasing trend across development.

Figure 4. Inter-session reliability (ICC) for nonlinear parameters of COP across months. All nonlinear parameters ICCs are averaging lower than 0.5 and there is an increasing trend as the infant develops.

Figure 5. Intra-session reliability (ICC) for nonlinear parameters of COP across data collection

sessions. All nonlinear parameters ICCs are averaging around 0.5.

Tables

Table 1.

	PDMS-II Standard Scores		
Subjects	*Reflexes*	*Stationary*	*Locomotion*
T01	10	10	10
T02	10	11	10
T03	9	10	9
T04	10	12	10
T05	10	11	10
T06	10	11	10
T07	10	11	10
T08	9	9	9
T09	10	11	10
T10	9	10	9
T11	10	10	10
T12	10	10	10
T13	10	9	10
T14	9	10	9
T15	10	11	10
T16	10	11	10
T17	11	11	10
T18	8	10	9
T19	10	11	10
T20	10	10	10
T21	9	10	9
T22	10	11	10
T23	10	10	10
T24	10	11	10
T25	10	10	10
T26	10	10	10
T27	10	11	10
T28	10	11	9
T29	11	10	9
T30	9	10	9
T31	10	10	10
T32	10	11	9
T33	10	10	10

Table 2.

Variables	ICC's				
	1st Month	2nd Month	3rd Month	4th Month	Mean
RMS AP	0.24	0.31	0.68	0.52	0.44
RMS ML	0.11	0.55	0.48	0.50	0.41
Range AP	0.07	0.23	0.72	0.54	0.39
Range ML	0.18	0.46	0.53	0.64	0.45
Sway Path	0.48	0.40	0.08	0.32	0.32

Abbreviations: RMS = root mean square, AP = anterior-posterior, ML = medial-lateral

Table 3.

Variables	ICC's								
	1st Month		2nd Month		3rd Month		4th Month		
Sessions	1st	2nd	1st	2nd	1st	2nd	1st	2nd	Mean
RMS AP	0.52	0.59	0.30	0.53	0.42	0.50	0.58	0.66	0.51
RMS ML	0.42	0.57	0.36	0.46	0.30	0.57	0.70	0.51	0.49
Range AP	0.57	0.52	0.19	0.49	0.47	0.62	0.57	0.72	0.52
Range ML	0.37	0.52	0.33	0.39	0.38	0.58	0.76	0.47	0.48
Sway Path	0.46	0.48	0.58	0.61	0.44	0.53	0.48	0.35	0.49

Abbreviations: RMS = root mean square, AP = anterior-posterior, ML = medial-lateral

Table 4.

Variables	ICC's				
	1st Month	2nd Month	3rd Month	4th Month	Mean
ApEn AP	0.17	0.33	0.74	0.07	0.33
ApEn ML	0	0.52	0.32	0.29	0.28
LyE AP	0.07	0.30	0.50	0.14	0.25
LyE ML	0.28	0.35	0.34	0.56	0.38
CoD AP	0.32	0.10	0.72	0.28	0.36
CoD ML	0	0.03	0.40	0.34	0.19

Abbreviations: ApEn = approximate entropy, LyE = luapunov exponent, CoD = correlation dimension, AP = anterior-posterior, ML = medial-lateral

Table 5.

Variables	ICC's								
	1st Month		2nd Month		3rd Month		4th Month		
Sessions	1st	2nd	1st	2nd	1st	2nd	1st	2nd	Mean
ApEn AP	0.54	0.66	0.39	0.65	0.62	0.67	0.59	0.64	0.60
ApEn ML	0.66	0.60	0.75	0.73	0.72	0.56	0.69	0.59	0.66
LyE AP	0.53	0.26	0.31	0.29	0.45	0.52	0.14	0.21	0.34
LyE ML	0.18	0.30	0.31	0.47	0.33	0.41	0.43	0.39	0.35
CoD AP	0.52	0.43	0.25	0.36	0.51	0.44	0.29	0.41	0.40
CoD ML	0.23	0.52	0.31	0.32	0.34	0.36	0.57	0.16	0.35

Abbreviations: ApEn = approximate entropy, LyE = luapunov exponent, CoD = correlation dimension, AP = anterior-posterior, ML = medial-lateral

Figure 1.

Figure 2

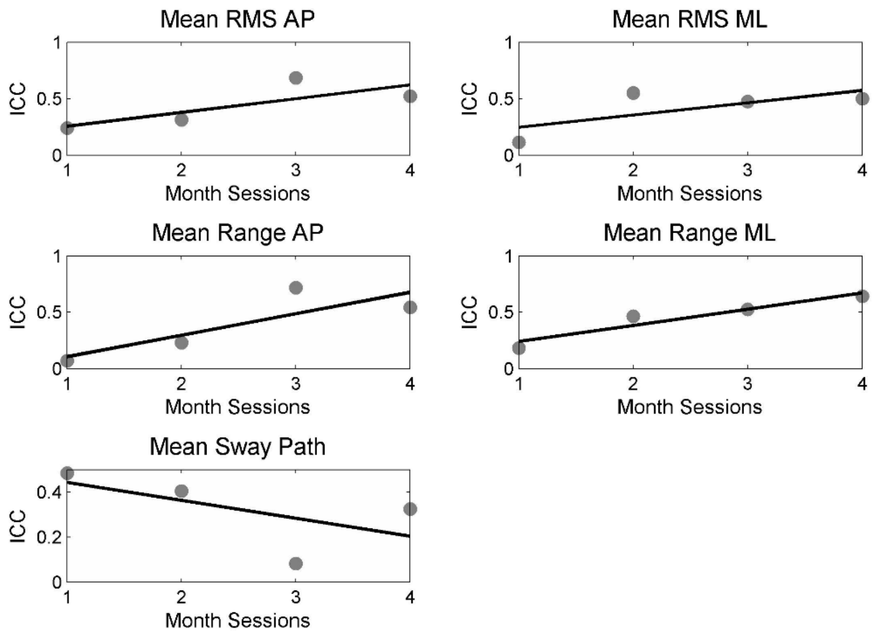

Figure 3

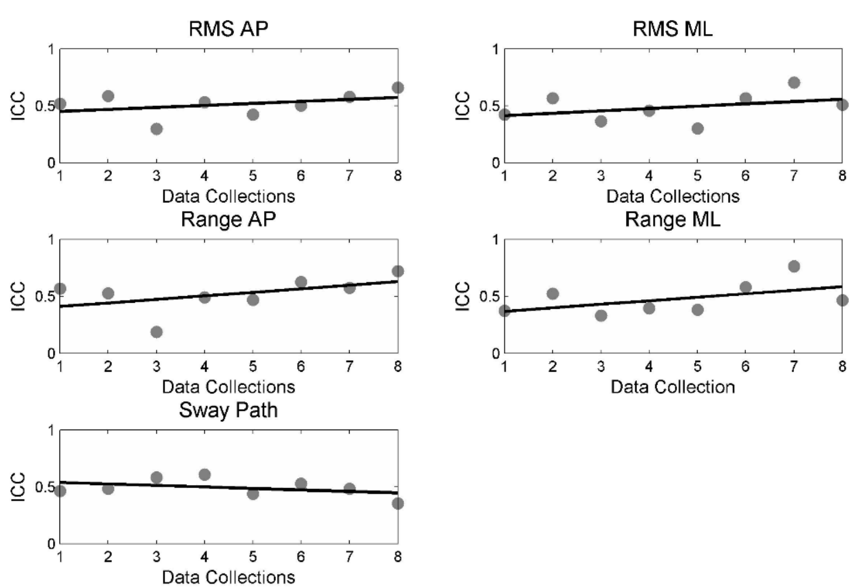

Figure 4

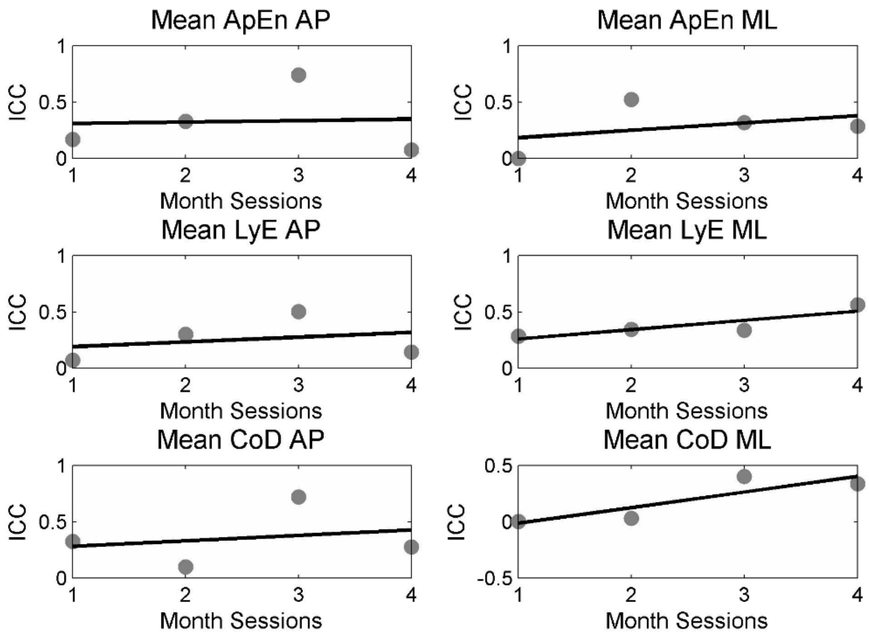

Figure 5