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

Anastasia Kyvelidou, MS, Regina T. Harbourne, MS, Wayne A. Stuberg, PhD, Junfeng Sun, PhD, Nicholas Stergiou, PhD


Objectives: To determine the reliability of linear and nonlinear tools, including intrasession and intersession reliabilities, 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: Typically developing infants (N=33; mean ± SD age at entry in the study, 15.2 ± 17.6 d).

Interventions: Not applicable.

Main Outcome Measures: Infants were tested twice in 1 week at each of the 4 months of the study. Sitting COP data were recorded for 3 trials at each session (2 each month within 1 week). The linear COP parameters of root mean square and range of sway for both the anterior-posterior and the medial-lateral directions, and the sway path, were calculated. The nonlinear parameters of approximate entropy, Lyapunov exponent, and correlation dimension for both directions were also calculated. Intrasession and intersession reliability was quantified by the intraclass correlation coefficient (ICC).

Results: The nonlinear tool of approximate entropy presented high intrasession and intersession ICC values compared with all other parameters evaluated. Generally, intrasession and intersession reliability increased in the last 2 months of the data collection and as sitting posture matured.

Conclusions: Our results showed that the evaluation of COP data is a reliable method of investigating the development of sitting postural control. 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; Nonlinear dynamics; Rehabilitation; Reproducibility of results.

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ent 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 (ie, predictable) manner, often across a range of time scales. Examples of nonlinear measures are the LyE and the ApEn. 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, 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 neurologic 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 used COP data from children, adults, and the 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 3-year-olds to 5-year-olds, was approximately the same in 5-year-olds and adult subjects, and then decreased again in elderly subjects. 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 emerge 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 dyskinesia, and it has been found that the patients exhibited decreased complexity in their sway patterns. The examples from these studies and several others indicate that nonlinear analysis can reveal the richness or shortage of behavioral control options or describe the strategies employed for the organization of the body’s degrees of freedom. 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 intrasession and intersession 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 here, 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 1 infant dropped out, 33 infants participated in this study (mean ± SD age at entry in the study, 152.4 ± 17.6d; sex, 14 boys 19 girls; mean ± SD weight at entry in the study, 7.37 ± 0.71kg; mean ± SD weight at end of the study, 8.53 ± 1.03kg). The infants were followed from the age of around 5 months to 8 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 0.5 SD of the mean, age of about 5 months at the time of initial data collection, the ability of the child to hold up the head when supported at the thorax, beginning ability to reach for objects dangled in front of the child in supported sitting or lying on the back, propping on the elbows when in prone for 30 seconds, and propping on both arms during sitting. The exclusion criteria were (1) a score on the Peabody Gross Motor Scale II of greater than 0.5 SD below the mean, (2) diagnosed visual deficits, and (3) diagnosed musculoskeletal problems.

Experimental Design

Each infant participated in 9 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-referenced and criterion-referenced test that examines gross motor function in children from birth to 83 months. The other 8 sessions were distributed over a period of 4 months. The infants were tested twice in 1 week at each of the 4 months of the study. Three trials at each session were used to determine intrasession reliability. The repeat testing within 1 week of each month’s testing was used for the estimation of the inter-session reliability. We were able to collect data for all 8 sessions over a period of 4 months for all infants, with the exception of 2 infants who did not come for the second session of the first month or for whom the data collected were not appropriate according to our criteria explained in the data analysis section.

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 was approximately 30 minutes to 1 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 and to be held by a parent for comforting, and by adjusting the temperature of the room to the infant’s comfort level. Infants were placed by their parent on the top of a forceplate that was covered with a special pad for warmth and securely adhered with tape on the forceplate. The baby was held in the sitting position in the middle of the plate...
when calm and happy (fig 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 3 trials that were acceptable for our criteria (see the data analysis section), 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 forceplate\(^a\) interfaced to a computer system running Vicon data acquisition software.\(^b\) The force platform simultaneously measures 3 force components, Fx, Fy, and Fz, and 3 moment components, Mx, My, and Mz. The forces and moments are measured by strain gauges attached to load cells at the 4 corners of the platform. The forceplate has a 4450N (1000lb) capacity for Fz and a 500lb capacity for Fx and Fy. The Fz channel has a natural frequency of 480Hz, and Fx and Fy have a natural frequency of 300Hz. COP data in both the AP and the ML directions were acquired through the Vicon software at 240Hz in order to be above a factor of 10 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 2 Panasonic Digital AV Mixers (Model WJ-MX30\(^c\)). The cameras were positioned to record a sagittal and a frontal view of the subject. Segments of acceptable (described in the data analysis section) data were analyzed using custom MatLab software.\(^d\)

Three acceptable trials (8.3s each) were selected from the videotape recording using the following criteria: (1) the infant did not move the arms (not reaching, holding an object, or flapping the arms), (2) the infant did not vocalize or cry, (3) the infant was not in the process of falling, (4) the trunk was not inclined more than 45\(^\circ\) to either side, (5) the infant was not touched, and (6) the arm position (propping or not propping) of the infant was noted during the entire trial, and only trials that had the infant using a consistent base of support were used. The COP data selected allowed for the examination of 1992 data points (8.3s×240Hz) 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 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 a possible confounding factor. These linear measures characterized the quantity or amount of variability present in the data.\(^27\)

In addition, 3 nonlinear measures of variability were calculated from the selected trials: the ApEn, the largest LyE, and the correlation dimension 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

### Table 1: Peabody Gross Motor Scale II Standard Scores for All Recruited Infants

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<th>Stationary</th>
<th>Locomotion</th>
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LyE and the correlation dimension was performed using the Chaos Data Analyzer Professional software. However, to calculate these measures accurately, a parameter must be chosen with extreme care and incorporated into the software. This parameter is the embedding dimension, and its calculation is conducted using a Global False Nearest Neighbor analysis. Global False Nearest Neighbor analysis of the COP time series is performed using the Tools for Dynamics software. The Global False Nearest Neighbor 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 dynamic system in space. For consistency in the analysis, the same embedding dimension (6) was used for all files, even if they had a dimension lower than 6. The ApEn was calculated using algorithms written by Pincus and implemented in MatLab. All the aforementioned 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.

### Statistical Analysis

Intrasession and intersession reliability was quantified by the ICC. Specifically, a 1-way ANOVA model with a random subject effect was used to estimate the intrasession reliability based on data from the first visit of the month for each child in the notation of Shrout and Fleiss. To estimate the intersession reliability, the averages of the 3 measurements during each session were analyzed using a 1-way ANOVA model with a random subject effect similar to the model for intrasession reliability. In the Results section, ICC findings are reported based on the work of Rosner. Specifically, an ICC less than .40 indicates poor reproducibility, while an ICC between .40 and .75 indicates fair to good reproducibility. Last, an ICC over .75 indicates excellent reproducibility.

### RESULTS

#### Linear Parameters

Intrasession ICCs for the linear parameters were between .07 and .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 the ML direction. However, the last 2 months of data collection presented consistently fair to good ICCs with the exception of the sway path parameter (fig 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.

Intrasession ICCs for linear parameters were between .19 and .76 (table 3). Range in the ML 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

![Table 2: Intersession (Within a Week per Month) Reliability, as
Expressed With the ICC, of Infant Sitting Posture for All
Linear Parameters](image)
across months was observed for range in AP direction. However, the last 3 data collections, which are included in the sessions for the third and fourth months, presented consistently fair to good ICCs (see Table 3, Fig 3). We can observe that RMS and range presented consistently increasing values in ICCs across data collections. However, sway path presented consistently decreasing values in ICCs across data collections. These findings are in agreement with the intersession reliability.

Nonlinear Parameters

Intersession ICCs for nonlinear parameters were between 0 and .74 (see Table 4). 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 the ML direction. However, the last 2 months of data collection presented alternating fair to good reproducibility (Table 4, Fig 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.

Intrasession ICCs for nonlinear parameters were between .18 and .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 intrasession reliability of linear parameters, the last 3 data collections, which are included in the sessions for the third and fourth months, presented fair to good ICCs (Fig 5).

DISCUSSION

The purpose of this study was to determine the reliability of linear and nonlinear tools, including intrasession and intersession 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 would have different reliability assessments because they were 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

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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 (ie, predictable) manner, often across a range of time scales.14

Our results showed that all linear parameters presented intersession and intrasession ICC values ranging from poor to good reproducibility. However, the last 2 months of data collection presented consistent fair to good ICCs. In contrast, the sway path parameter presented decreased values of intersession and intrasession ICCs across development. Similarly, all nonlinear parameters presented analogous intersession and intrasession ICC values ranging from poor to good reproducibility. In addition, the last 2 months of data collection presented consistently fair to good ICCs. Generally, ApEn presented the highest ICC values compared with 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 and elderly participants. Specifically, RMS in AP and ML directions showed fair to good intrasession reliability (.58) during standing of healthy elderly participants. Intraseason ICC values for the range of the sway area during standing in healthy adults were .43 and .71 for the AP and ML directions, while healthy elderly adults presented lower ICC values, .29 and .44, for the AP and ML directions, respectively. Intersession reliability of linear parameters during standing of healthy adults presented fair to poor reproducibility, with ICC values less than .55. Furthermore, the ICC values of linear parameters during infant sitting were similar to those of children without disabilities during standing balance tasks. Intrasession reproducibility of the Smart Balance Master System under different sensory conditions revealed ICC values that ranged between 0 and .79. Similarly, intersession reliability of the mean value of 3 repetitive tests ranged between .08 to .68. In addition, children standing on a forceplate between the ages of 2 and 4 years presented an ICC value for the sway index of .62. 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, because 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 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.
Fractal dimension intrasession reliability was found to be higher than linear tools, and most of the time it presented fair to good reproducibility. Similar to the results of the present study, ApEn, which is a measure of the regularity or predictability in the time series, showed fair to good intrasession reproducibility most of the time, consistently better than the linear parameters of COP during infant sitting.

The moderate intersession 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 .59 to .70. In addition, the 2-day intersession reliability of the Linfert-Hier- hoizer scales for infants 1 to 3 months old was –.24 to .69, while the Buher Baby test intersession reliability ranged from .40 to .96 depending on the age of the infants. Last, the 4-day to 10-day test-retest reliability of the Bayley motor scales for infants 9 and 15 months old ranged from .42 to .96 and increased with age. Interestingly, test-retest reliability of infant testing tends to become better with increasing age, and this was also the case in our results. Thus, it seems that higher variability in performance at a younger age is a result of the fact that infants are attempting many different sitting strategies, so less consistency/reliability is expected early on, whether linear or nonlinear tools are used to evaluate sitting performance.

An additional observation based on the findings of the present research was that intrasession and intersession reliability of infant sitting posture became better for the last 2 months of data collection. Similar to standing tasks in children, Baker et al 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 intrasession and intersession 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 uses. In the present study, when infants started participating in data collection, they were novices 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 in the same fashion in each trial or each session as well as they can perform it when they are older.
Study Limitations

We should also mention that intersubject variability may have affected our results. It can be hypothesized that when infants entered the study, they were at different levels of sitting development, which is why we observed differences in sitting behavior in the first 2 months. Therefore, an alternative could be to evaluate sitting postural development through stages of sitting instead of months. In addition, the fact that intersession reliability did not show consistently excellent reproducibility may be a result of the nature of the subjects. Infants between the ages of 4 and 8 months experience rapid physiologic, neuromuscular, and psychologic changes. These changes may be responsible for the diverse pattern that infants bring into play at each data collection session. Therefore, because 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.

CONCLUSIONS

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 for standing postural control. Regarding the nonlinear tools, ApEn presented the highest inrasession and intersession ICC values among all other parameters, while correlation dimension showed similar inrasession and intersession ICC values with the linear measures. In contrast, LyE presented the lowest inrasession and intersession ICC values compared with 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


Suppliers
a. Model OR6-7-1000; Advanced Mechanical Technology Inc, 176 Waltham St, Watertown, MA 02472.
b. Vicon, 9 Spectrum Pointe Dr, Lake Forest, CA 92630.
c. Panasonic Service and Technology Co, 20421 84th Ave S, Kent, WA 98032.
d. MathWorks, 3 Apple Hill Dr, Natick, MA 01760-2098.