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Reliability of center of pressure measures for assessing the development of sitting postural control through the stages of sitting

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A B S T R A C T

Cerebral palsy (CP) impairs an individual's ability to move and control one's posture. Unfortunately, the signs and symptoms of CP may not be apparent before age two. Evaluating sitting posture is a potential way to assess the developing mechanisms that contribute to CP. The purpose of this project was to determine the reliability of linear and nonlinear measures, including inter- and intrastage reliability, when used to analyze the center of pressure (COP) time series during the stages of sitting development in children with typical development (TD) and with/at-risk for cerebral palsy (CP). We hypothesized that nonlinear tools would be more reliable than linear tools in assessing childrens' sitting development, and reliability would increase with development. COP data was recorded for three trials at eight sessions. Linear parameters used were root mean square, range of sway for the anterior-posterior (AP) and medial-lateral (ML) directions, and sway path. Nonlinear parameters used were Approximate Entropy, the largest Lyapunov Exponent, and Correlation Dimension for the AP and ML direction. Participants consisted of 33 children with TD and 26 children with/at-risk for CP. Our results determined that COP is a moderately reliable method for assessing the development of sitting postural control in stages in both groups. Thus, clinicians may be able to use measures from COP data across stages to assess the efficacy of therapeutic interventions that are intended to improve sitting postural abilities in children with/at-risk for CP.

1. Introduction

Cerebral palsy (CP) refers to a group of disorders caused by brain damage that impair an individual's ability to move and control one's muscles and posture [1,2]. CP is the most common motor disability in childhood, with one in 323 children currently

diagnosed [1]. Children with CP may experience difficulties in developmental benchmarks such as sitting, crawling, standing, or walking [3–5]. However, many signs of CP are not apparent before age two, making it difficult for clinicians to intervene early [1]. Evaluating sitting posture is a potential avenue for intervention in CP, as we can measure small changes that occur as children develop the ability to sit [6]. Early intervention for CP is crucial for long-term outcomes, so there is an urgent need to implement methods of intervention immediately [7,8]. Thus, it is necessary to identify a quantifiable method to assess the developing mechanisms of sitting postural control in children with early issues, recognize the problems to target through early intervention, and determine early intervention efficacy [9,10]. One quantifiable method for examining sitting postural control is evaluating center of pressure [7,11,12].

Center of pressure (COP) measurements, both linear and non-linear, have been used to quantify body sway in postural control [11,13–15]. COP refers to the point of application of the ground reaction force vector, and it describes the organization of posture [11]. Postural control can be measured through simple paradigms (e.g. sitting, standing) on a force platform [7,12]. Such paradigms have demonstrated that postural sway data in child sitting can separate children with developmental delays from children with typical development (TD). For example, Kyvelidou et al. [8] found that full-term typically developing infants explore more types of motor strategies at the onset of sitting, which suggests they have greater variability in their postural sway compared to those born pre-term and with developmental delays. Thus, variability in postural sway can be an indicator of health in movement [14,16].

We can measure variability in COP through the use of linear and nonlinear measures [11,13,14,17]. Linear measures have traditionally been used to quantify the amount of movement or change in COP during a particular task [13], as well as to quantify the amount of variation in a time series without considering order of distribution. On the contrary, nonlinear measures quantify the variation in COP with respect to how motor behavior emerges in time. Thus, the structure of the time series is quantified by the degree to which the values emerge in a predictable manner. Analyzing COP data with only linear measures is a problem because they cannot reveal the temporal organization of the data like nonlinear analyses can. By using both linear and nonlinear measures to quantify COP, we can analyze different aspects of the organization of posture.

The reliability of COP data during the acquisition of sitting posture has been previously evaluated in terms of age [7,12,18]. However, an alternative and more suitable strategy is to evaluate sitting postural development through the stages of sitting [7]. This will allow for children to be tested at the phase of sitting development regardless of age. For example, one child may develop the ability to sit at six months whereas another will at eight months of age. Rather than comparing these children on chronological age, we can compare them according to their stage of sitting. For instance, during stage 1 children use their hands to support their sitting whereas during

stage 2 they do not need to. The reliability of analyzing sitting by a child's stage of sitting has not been investigated prior to this study.

Therefore, the purpose of this study was to determine the reliability of linear and nonlinear measures, including inter- and intrastage reliability, when used to analyze the COP time series during the stages of sitting development in children with TD and with/at risk for CP. This is an ideal sample to study postural control because we can observe the development of independent sitting, which is the first time that children control their trunk in an upright position. We hypothesized that nonlinear tools would be more reliable than linear tools in assessing children's sitting development and that reliability measures would increase with development, similar to previous studies [7,12]. This is a re-analysis of previously published data. Analyzing the COP data with nonlinear and linear measures may give us insight into the manifold techniques that children with/at-risk for CP use to organize their movement and posture. We also hypothesized that the reliability across stages of sitting would be greater than the reliability across sessions, as in previous studies [7,12].

2. METHODSMethods

2.1. Participants

Thirty-three children with TD (mean ± SD age at study entry, 152.7 ± 17.7 days; 14 males) and 26 children with/at-risk for CP (425 ± 102.1 days; 10 males, 16 diagnosed with CP) participated in the study. A pediatrician who is an expert in neurodevelopmental disorders identified the children with or at risk for CP, and referred them to our study. Both groups of children were tracked for four months as they were learning to sit independently. Children were recruited from employee announcements from local universities. Prior to data collection, a parent provided informed consent approved by the university's Institutional Review Board. The inclusion and exclusion criteria are described in Table 1. Additionally, Gross Motor Function Classification System (GMFCS) Scores, which provide information regarding the severity and motor pattern of the children with CP, were as follows: Level 1 n = 13, Level 2 n = 3, Level 3 n = 5, and Level 4 n = 5.

2.2. Experimental design

All children participated in nine sessions. In session one, gross motor skills were assessed by the Peabody Gross Motor Scale II1 (45 min). This scale is validated for use in children from birth to 83 months. The remaining eight sessions (30–60 min) were spread across four months, with two sessions occurring within a single week of each month. A physical therapist identified the stage of sitting behavior at each session according to five stages (Table 2; adapted from previous use [19–21]). Three trials were required to estimate intrastage reliability from the same session for each child.

Table 1
Inclusion and Exclusion Criteria.

Inclusion and Exclusion Criteria of the Study
Inclusion criteria
-Age from 5 months to 2 years
-On the Peabody Gross Motor Scale II, a score less than 1.5 SD below the mean for their corrected age for infants with CP
-On the Peabody Gross Motor Scale II, a score within 0.5 SD from the mean for typically developing infants
-Head control when body is supported at the mid trunk; head is maintained for over 1 min without bobbing
-Infant can track an object across midline without losing head control
-Infant may prop hands on floor or legs to lean on arms but should not be able to reach and maintain balance in the prop sit position
-When supported in sitting can reach for toy
-Can prop on elbows in the prone position for at least 30 s
Exclusion criteria
-Diagnosed visual impairment
-Diagnosed hip dislocation or subluxation greater than 50%

2.3. Protocol

Children were given time to adjust to the testing environment. Once accustomed to the room, participants were placed in the center of the force plate. The parents sat in front of the child while the investigator remained at the child's side. Once the child was sitting independently, data collection began. After three successful trials were collected (see Data analysis) or the child indicated he/she was not able to complete the session (e.g. crying), data collection was ended.

We selected three acceptable trials (8.3 s each) from the videotapes based on: 1) no moving arms, 2) no crying/vocalizing, 3) no falling, 4) no leaning of the trunk to one side (45°), 5) no one touching the child, and 6) the use of a consistent base of support.

The force plate was an AMTI platform (Model OR6-7-1000) that was interfaced with a computer system running Vicon data-acquisition software. The Vicon software collected COP data at 240 Hz above a factor of 10, which was higher than the highest frequency found in the signal. This data was not filtered since nonlinear results can be skewed by this procedure [22–25]. Two Panasonic recorders (Model 5100 HS) interfaced with a Panasonic Digital AV Mixer (Model WJ-MX30) were used during each trial to record a sagittal and frontal view of the participants. Custom MatLab software was used to analyze acceptable segments of data (described later). This COP data contained 2000 data points (8.3sx240 Hz) for each COP direction in each trial since this number is considered appropriate for nonlinear analysis [25,26].

2.4. Data analysis

Customized MatLab software [27] was used to calculate the linear measures root mean square (RMS), range (max-min) for the AP and ML directions, and the sway path. These parameters are independent of the effect of biomechanical factors (e.g. weight) that change rapidly throughout development. These linear measures quantify the amount of variability in the data [28].

In addition, the nonlinear measures of variability [9] used were Approximate Entropy (ApEn), the largest Lyapunov Exponent (LyE), and the Correlation Dimension (CoD) for the AP and ML directions. Chaos Data Analyzer Professional Software was used to calculate the CoD and LyE. The same embedding dimension (6) was used for all files even if they had a lower dimension. Established algorithms were used to calculate ApEn [29], which were then analyzed in MatLab. For more details on the calculations of ApEn, CoD and LyE, refer to previous studies [7,12]. The nonlinear measures of variability characterize the structure of the variability in the data by examining point-by-point the time-evolving order and patterns present in the COP time series.

Table 2
Stages of Sitting Development.

Stage 1: Prop Sitting	Child can be placed in a sitting position and supported with assistance; the child is able to hold his/her head up when supported at the trunk
Stage 1.5: Transition	Child moves out of prop sit position for a short duration, and then returns to prop sitting
Stage 2: Variable	Child can sit for about 10 s without assistance from anyone; props oneself up by using the arms for support; not able to be left alone in the sitting position
Stage 2.5: Not Solid	Child can sit for longer than 10 s, but he/she is not completely balanced yet
Stage 3: Independent Sitting	Child can maintain sitting position all of the time without the use of his/her hands; not yet crawling or moving in and out of the sitting position

2.5. Statistical analysis

The Intraclass Correlation coefficient (ICC) was used to quantify inter- and intrastage reliability. A one-way analysis of variance model with a random subject effect was used to estimate the intrastage and interstage reliability. Intrastage reliability was calculated using averages of the measurements from the first session of a single stage. For interstage reliability, averages of the three measurements during each stage of sitting were compared. ICC findings are reported in the results section in the same manner as Rosner [30]. An ICC between 0.4 and 0.75 describes a fair to good reproducibility, whereas less than 0.4 indicates poor and greater than 0.75 indicates excellent reproducibility.

3. Results

3.1. Linear parameters

Interstage ICCs for the linear parameters (Fig. 1) were between 0 and 0.72 for TD children and 0 and 0.82 for children with/at-risk for CP. The highest ICC value was observed for AP range in TD children and for AP RMS in children with/at-risk for CP. All linear parameters presented ICC values ranging from poor to good reproducibility in TD

children and poor to excellent in children with/at-risk for CP. The highest mean ICC value across stages was ML RMS in TD children and sway path in children with/at-risk for CP. However, TD children displayed fair to good ICCs in stages 2, 2.5, and 3 (with the exception of sway path), whereas children with/at-risk for CP displayed fair to excellent ICCs in stage 3 (with the exception of AP range and AP RMS). AP Range had consistently increasing values in ICCs across stages in TD children.

For intrastage ICCs, linear parameters (Fig. 2) were between 0.06 and 0.74 for TD children and 0 and 0.84 for children with/at-risk for CP. The highest ICC value was ML range for TD children and AP RMS for children with/at-risk for CP. All linear parameters presented ICC values ranging from poor to good in TD children and poor to excellent in children with/at-risk for CP. The highest mean ICC value across stages was observed for ML range in TD children and AP RMS in children with/at-risk for CP. Sitting stage 3 presented fair to good ICCs in TD children.

3.2. Nonlinear parameters

Interstage ICCs for the nonlinear parameters (Fig. 1) were between 0 and 0.60 for TD children and between 0.04 and 0.87 for children with/at-risk for CP. The highest ICC values were observed for AP ApEn in TD children and for AP LyE in children with/at-risk for CP. All nonlinear parameters presented ICC values ranging from poor to good reproducibility in TD children and from poor to excellent in children with/at-risk for CP. The highest mean ICC value across stages was observed for ML ApEn in TD children and for AP LyE for children with/at-risk for CP. However, the last two stages (2.5 and 3) for TD children consisted of ata with fair to good reproducibility.

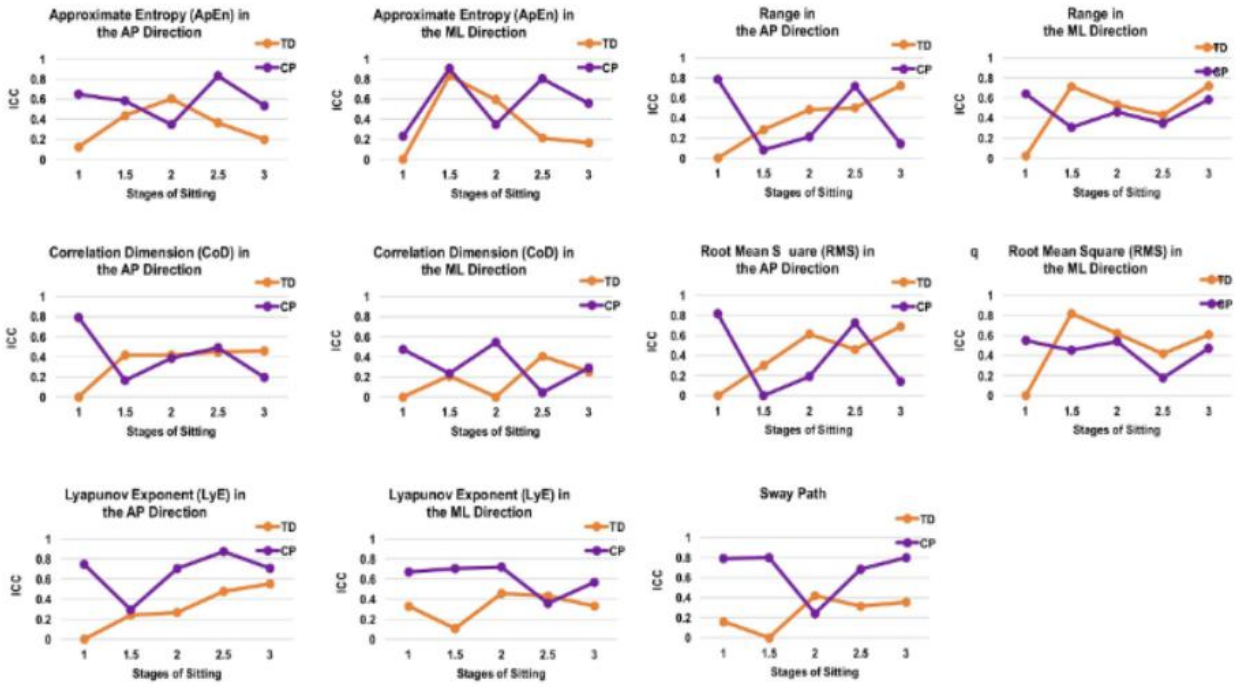

Fig. 1. Interstage ICCs for Linear and Nonlinear Parameters.

For intrastage ICCs, nonlinear parameters (Fig. 2) were between 0 and 0.66 for TD children and 0 and 0.79 for children with/at-risk for CP. The highest ICC value was ML ApEn for TD children and children with/at-risk for CP. All nonlinear parameters presented ICC values ranging from poor to good in the TD children and from poor to excellent in children with/at-risk for CP. The highest mean ICC value across stages was observed for ML ApEn in TD children and AP LyE in children with/at-risk for CP.

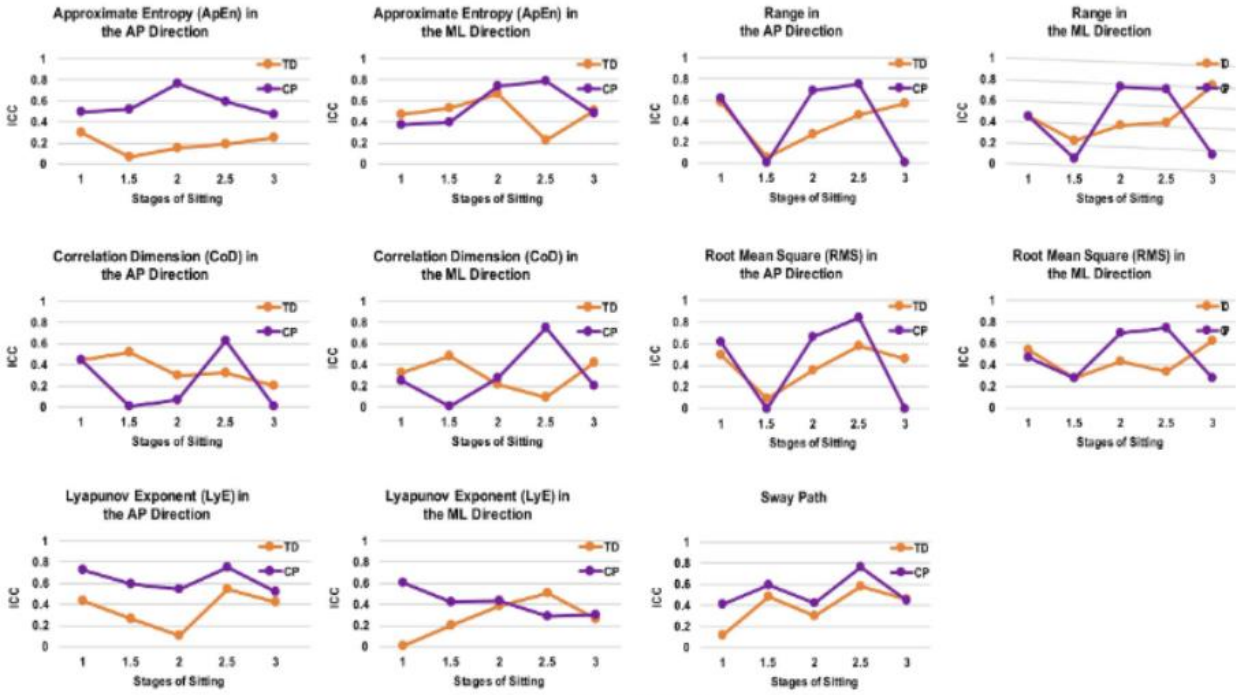

Fig. 2. Intrastage ICCs for Linear and Nonlinear Parameters.

4. Discussion

The purpose of this study was to establish the reliability of linear and nonlinear measures, including inter- and intrastage reliability, when analyzing COP time series during sitting postural control development in TD infants and infants with/at-risk for CP. We hypothesized that we would find different reliability values with the linear and nonlinear tools because they evaluate different features of the COP data (i.e. linear measures quantify the amount of variability present in the time series whereas nonlinear measures quantify the repeated or predictable patterns across the time series). We also anticipated that inter- and intrastage reliability would be better than inter- and intrasession reliability from previous studies [7,12].

For interstage reliability, the linear parameters were slightly more reliable in TD children than in children with/at-risk for CP. These results do not support past studies [7,12] of intersession reliability in which linear parameters averaged around 0.5, and there was an increasing trend in all linear parameters except sway path. Brouwer et al. [23] found intersession reliability to be poor to fair for linear measures during a standing

task in healthy adults. Our results support this in children with/at-risk for CP but not in TD children. The nonlinear parameters, however, increased with development in our TD children. Conversely, this was not true for AP and ML ApEn or ML LyE. In the children with/at-risk for CP, there were no apparent trends with development. Decreasing trends were found in AP and ML CoD, ML LyE, and AP range. This supports one result of past studies [7,12] as ML CoD decreased, but the other variables increased. Mazaheri et al. [32] assessed intersession reliability for the nonlinear analysis of COP provided by recurrence quantification analysis. The most reliable measures were percent determinism and entropy. Similarly, we found the highest ICC value for nonlinear measures to be ML ApEn for interstage reliability in TD children.

For intrastage reliability, all linear parameters increased in our TD children. For children with/at-risk for CP, sway path increased with development. Range and RMS fluctuated across development, with no apparent trends. These results support past studies [7,12] in that there was an increasing trend for all parameters. In addition, Zaino & McCoy [33] examined the intrasession reliability of COP measures in TD children and children with/at-risk for CP. Both groups of children had similar trends in test-retest reliability, but parameters were less reliable overall in children with/at-risk for CP. These results are opposite of our overall findings, as we found higher reliability in this group. Doyle, Newton, & Burnett [34] assessed the reliability of several COP measures in healthy young adults during quiet stance. They found that AP range of sway was the most reliable. Our results support this finding as we found that the highest ICC value was observed for AP range in TD children. In another study, Bauer et al. [35] examined COP variables in standing posture of healthy, older adults to investigate intrasession reliability. They found that AP sway was the most reliable COP variable. For our nonlinear parameters, most variables were stable across development for TD children, except for AP CoD which decreased. For children with/at-risk for CP, most variables were stable across development, except for AP and ML LyE which decreased. AP ApEn and AP CoD decreased with development. These results support past studies [7,12] in that there were was consistency across development, except for AP CoD which decreased. In addition, Cabellero, Barbado, & Moreno [36] collected quiet standing COP data on healthy, young adults. The most reliable variable in the stable condition was DFA and in the unstable condition were entropy measures. Cavanaugh et al. [37] found that in quiet standing in healthy adults, AP ApEn values ranged from moderate to good test-retest reliability between trials, where ML COP oscillations were more random and less stable. In our study, the highest ICC value was entropy (ML ApEn) for both groups.

5. Conclusions

There are few measurements of postural control in children which have acceptable reliability and validity documented [14]. Our results determined that COP methodology using linear and nonlinear measures is a moderately reliable method for

assessing the development of sitting postural control in stages in both TD children and children with/at-risk for CP. We acknowledge that our reliability values are not similar to other COP studies in adults, but this is expected due to the variability observed in child motor behavior. However, most parameters were more reliable in children with/at-risk for CP. Specifically, four out of the five linear parameters and four out of the six nonlinear parameters were more reliable in children with/at-risk for CP for the intrastage measures. Similarly, six out of the six nonlinear parameters were more reliable in the children with/at-risk for CP for interstage measures. We suspect that the reason for greater reliability in these measures in children with/at-risk for CP is because they are more rigid (i.e. less exploratory) in their sitting patterns, and they have reduced degrees of freedom compared to their typical-developing counterparts. Greater exploration of this finding is necessary, as this result is unexpected (i.e. one would expect greater reliability in children with typical development). Once these findings are verified, we can use this methodology to assess increments of change over time with respect to treatment in children with TD and with/at risk for CP. Moreover, examining the reliability within and across stages of sitting does not yield superior reliability values in comparison to within and across sessions of sitting development (from past studies [7,12]). In contrast, both methodologies produce similar results. Thus, we can conclude that clinicians may be able to use measures from COP data across stages of sitting or sessions based on chronological age to assess the efficacy of therapeutic interventions that are intended to improve sitting postural abilities in TD children and children with/at-risk for CP.

Conflict of interest statement

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We also confirm that any aspect of the work covered in this manuscript that has involved either experimental animals or human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

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