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Review article

Quality and structure of variability in children during motor development: A systematic review

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Variability has been perceived to be beneficial to movement organization and execution, being essential to selection of movement patterns during motor development, to obtain flexible patterns and adaptability to different task demands. Human movement variability can be measured by linear and nonlinear tools. Recently, nonlinear techniques have been used successfully to give insight into motor skills control in children, and be able to discriminate pathologic and non-pathologic children. For that, this paper is the first to review systematically studies that used nonlinear measures in children. We intend to describe which mathematical tools are utilized to analyze quality and structure of variability, the factors that influence this variability and methodological procedures which are considered for its analysis, and how they are interpreted in child motor development field. A search was performed by one reviewer in relevant databases and the quality appraisal was conducted independently by two reviewers. In all, 27 articles were identified and 20 were selected for the present review. It was detected a large variation in sample characteristics and methodological issues among studies. In fact, the main importance of this review was due to the attempt to define some parameters and standardize some values for typical children and children with disabilities. It is noted that the results from nonlinear techniques depend on the task being analyzed, the age and the type of mathematical technique chosen. The presence of disability is associated to decreases in complexity and nonlinear tools were considered sensible to investigate the effectiveness of practice and intervention in typical children and children with cerebral palsy. Furthermore, future studies should be more careful in standardizing selection, recruitment and explaining missing data. Future reports also should present details of their results and limitations to favor comparisons and helping in formulating new research questions.

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1. Introduction

Variability is one of the most common features of human movement, and can be described as the normal variation that occurs during motor performance across many repetitions of a task (Stergiou, Harbourne, & Cavanaugh, 2006). Variability has been perceived to be beneficial to movement organization and execution, being essential for selecting movement patterns during motor development and obtaining flexible patterns and adaptability to different task demands (Manoel & Connolly, 1995; Tseng, Scholz, & Schoner, 2002).

Human movement variability can be measured by linear and non-linear tools. Traditional linear measures provide a description of the amount or magnitude of the variability around a central point (Cavanaugh, Guskiewicz, & Stergiou, 2005; Harbourne & Stergiou, 2009; Newell & Corcos, 1993). Linear techniques such as path length range, coefficient of variation, excursion, and standard deviations can be used to describe the quantity of movement, but these techniques do not give any information about the quality of movement and how the movement is controlled over time (Lomax, 2007; Stergiou, Harbourne, & Cavanaugh, 2006). However, in studies on postural control there are conflicting interpretations of the linear measures of center of pressure (COP), since some authors described increases in COP area and excursion such as a better controlled posture (Cignetti, Kyvelidou, Harbourne, & Stergiou, 2011; Hughes, Duncan, Rose, Chandler, & Studenski, 1996), whereas other studies with similar results interpreted them as decreased postural control (Prado, Stoffrengen, & Duarte, 2007). Although the results from variability can have conflicting interpretations depending on the theoretical assumption taken, it would be relevant to analyze other aspects of variability. Therefore, it is important to analyze these data with other mathematical tools to observe not only the amount of variability through linear measures, but also structure and quality of the variability.

Recent studies on variability considered that the structure of variation is better obtained by measuring the temporal organization (Vaillancourt & Newell, 2002; Vaillancourt, Sosnoff, & Newell, 2004). In this case, temporal organization of variability is quantified by the way the movement patterns emerge over time and how each point in the movement trajectory influences the next one in an orderly manner (Donker, Roerdink, Greven, & Beek, 2007; Stergiou, Buzzi, Kurz, & Heidel, 2004; Stegiou & Decker, 2011).

By showing both structure and quality of the variability, non-linear methods can provide insight into the neuromotor control of the movement. These tools being used in the literature for this purpose include approximate entropy (ApEn), sample entropy (SEn), complexity index (CI), correlation dimension (CoD), largest Lyapunov exponent (LyE), and detrended fluctuation analysis (DFA) (Bruijn, van Dieën, Meijer, & Beek, 2009; Cavanaugh, Kochi, & Stergiou, 2010; Donker et al., 2007; Gates & Dingwell, 2007, 2008; Kurz & Hou, 2010; Kurz, Markopoulou, & Stergiou, 2010; Sosnoff & Voudrie, 2009; Sosnoff, Valantine, & Newell, 2006; Stegiou & Decker, 2011; Stins, Michielsen, Roerdink, & Beek, 2009; Vaillancourt et al., 2004; Yang & Wu, 2010).

Non-linear measurement of variability are based on dynamic system principles (Vaillancourt et al., 2004). It has been demonstrated that temporal variations in movement trajectories exhibit deterministic patterns, which have been defined as chaotic (Harbourne & Stergiou, 2009). In this sense, chaotic regimes allowing a healthy system to have a wide range of potential behaviors and an optimal state of variability renders the system more flexible and adaptable (Miller, Stergiou, & Kurz, 2006; Vaillancourt et al., 2004). Alternatively, abnormal development may be characterized by a narrow range of behaviors, some of which may be rigid, inflexible and highly predictable or, on the contrary, random, unfocused and unpredictable (Harbourne & Stergiou, 2009; Stergiou et al., 2006, 2004).

Recently, non-linear techniques have been successfully used to give insight into motor skill control in children, such as standing and sitting postural control (Gruber, Busa, Gorton, & Emmerick, 2011), spontaneous movements of upper and lower extremities (Ohgi et al., 2008; Smith, Teulier, Samson, Stergious, & Ulrich, 2011), and quality of prehension force (Deutsch & Newel, 2004).

Non-linear measurements have been shown to be able to discriminate pathologic and non-pathologic children. COP data from standing and sitting posture in children with cerebral palsy have been found to differ from typically developing children (Cignetti et al., 2011; Deffeyes, Harbourne, DeJong, et al., 2009). Children with myelomeningocele (Smith et al., 2011), premature infants with brain injury (Ohgi et al., 2008), and infants with Down syndrome (Smith, Stergiou, & Ulrich, 2010) have all been shown to be less adaptable and flexible than typical children by using non-linear measurement applied to movement trajectories. Furthermore, structure of variability is influenced by extrinsic factors such as load carriage tasks (Pau, Kim, & Nussbaum, 2012), vision and cognitive demand tasks on standing postural control (Stins et al., 2009), and velocity changes in walking activity (Buzzi & Ulrich, 2004).

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