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Approximate entropy used to assess sitting postural sway of infants with developmental delay

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ABSTRACT

Infant sitting postural sway provides a window into motor development at an early age. The approximate entropy, a measure of randomness, in the postural sway was used to assess developmental delay, as occurs in cerebral palsy. Parameters used for the calculation of approximate entropy were investigated, and approximate entropy of postural sway in early sitting was found to be lower for infants with developmental delay in the anterior–posterior axis, but not in the medial–lateral axis. Spectral analysis showed higher frequency features in the postural sway of early sitting of infants with typical development, suggesting a faster control mechanism is active in infants with typical development as compared to infants with delayed development, perhaps activated by near-fall events.

1. Introduction

Cerebral palsy occurs because of brain injury sustained very early in life, either before, during, or shortly after birth, and is characterized by motor dysfunction. Identifying affected infants when they are very young allows for physical therapy to be started early when brain plasticity is maximal (Ballantyne, Spilkin, Hesselink, & Trauner, 2008), with the goal of improving the long-term outcome for these infants (Blauw-Hospers & Hadders-Algra, 2005; Blauw-Hospers, de Graaf-Peters, Dirks, Bos, & Hadders-Algra, 2007; de Graaf-Peters et al., 2007). Sitting is a motor skill acquired early in life, typically at about age 4–9 months, and thus can serve as a window into the development of motor skills in very young infants (Harbourne & Stergiou, 2003). Studying sitting dynamics affords the possibility of objectively quantifying motor coordination in order to identify infants who might benefit from physical therapy, and to assess improvements as therapy progresses, even in infants who cannot yet stand. Because cerebral palsy is difficult to diagnose in young infants, we have described the infants in our study as “developmentally delayed” since we can confirm they were developmentally delayed. However, the developmentally delayed infants in our study were either diagnosed with cerebral palsy or at risk for cerebral palsy, and not a general sampling of infants with all types of developmental delay.

Lack of general movement complexity in young infants may be a useful indicator of cerebral palsy and that therapeutic intervention is appropriate (Hadders-Algra, 2004), but it is not yet clear how best to objectively quantify movement complexity in very young infants. Hadders-Algra’s (2004) discussion of complexity is focused on the quality of general movements, which are the frequent and varied movements of all parts of the body, and that the healthy infant produces highly varied

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movement patterns. Conversely, infants with cerebral palsy display less complex movement patterns, perhaps as a result of damage to the cortical subplate (Hadders-Algra, 2007). Hadders-Algra's (2004) method of quantifying general movement complexity from video recordings requires two days of training, and requires further practice to become a skilled observer. Another way to quantify body movements is to record time series data from a force plate. However, to quantify the dynamics of infant sitting postural sway using force plate data, a measure of time series dynamics is needed that is sensitive to differences between affected and unaffected infants. This measure needs to be robust to experimental noise and robust to shorter time series segments since many infants cannot sit for extended periods of time. The long term goal of this work is to develop a measure that can assess developmental delay early in life, is sensitive enough that it can be used to monitor the effectiveness of a course of therapy, and is robust enough to real-world data limitations such as noise and limited time for analysis, that it could someday be applied in a clinical setting.

Approximate entropy was developed by Pincus (1991) as a measure of "complexity" for time series data, where "complexity" is defined as being low for time series with a repetitive pattern such as a sine function, high for a random variable, and intermediate for systems with chaotic dynamics. Alternatively, it can be described as a measure of "regularity" where time series data with repeated patterns have low approximate entropy and high regularity (Pincus & Goldberger, 1994), i.e. approximate entropy is a measure of lack of regularity. Because approximate entropy is sensitive to the system dynamics, it is a potentially useful measure for a wide range of medical conditions that alter physiological or motor control dynamics. There are a number of medical fields where the use of approximate entropy has been investigated, including cardiology (Kaplan et al., 1991; Pincus & Goldberger, 1994), endocrinology (Liu, Iranmanesh, Keenan, Pincus, & Veldhuis, 2007; Veldhuis, Keenan, & Pincus, 2008), anesthesiology (Kumar, Anand, Chari, Yaddanapudi, & Srivastava, 2007), traumatic brain injury (Cavanaugh et al., 2005, 2006), Parkinson's disease (Morrison, Kerr, Newell, & Silburn, 2008), and orthopedics (Georgoulis, Moraiti, Ristanis, & Stergiou, 2006). Two hypotheses that have been advanced to explain the impact of pathology on control dynamics in humans, the loss of complexity hypothesis, which suggests that complexity will decrease with pathology (Goldberger, Peng, & Lipsitz, 2002), and the optimal movement variability hypothesis, which suggests that complexity may either increase or decrease from an intermediate optimal value (Stergiou, Harbourne, & Cavanaugh, 2006). Both the loss of complexity hypothesis (Goldberger et al., 2002) and the optimal movement variability hypothesis (Stergiou et al., 2006) suggest that approximate entropy of time series data from physiological systems may be clinically useful, as pathology can shift the regularity of system dynamics away from the optimal values. A measure like approximate entropy, with the ability to quantify regularity of system dynamics, may someday be used clinically to discriminate typically developing children from those with pathology, help assess severity of pathology, and assess efficacy of treatment.

One interpretation of approximate entropy as applied to postural sway is as an indication of the level of attention directed at postural control, with low attention automatic control having higher entropy (Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008). If attention is diverted to another task, then postural control becomes more automatic and entropy increases (Cavanaugh, Mercer, & Stergiou, 2007; Donker, Roerdink, Greven, & Beek, 2007). Conversely if neurological injury makes postural control more difficult, then more attention is required to be focused on control and postural sway becomes more regular, as in stroke (Roerdink et al., 2006) or in mild traumatic brain injury (Cavanaugh et al., 2005, 2006). Based on this precedence, we hypothesize that cerebral palsy, being a neurological injury, would result in less automatic control of posture, and thus a lower entropy.

Despite the wide range of research applications of approximate entropy, the methodology of application of the approximate entropy algorithm to experimental data has yet to be fully optimized for widespread clinical implementation. Experimentally measured time series data is necessarily of limited length, and often, if not always, corrupted by experimental noise of unknown dynamics. Experimental noise is often assumed to be white noise, or independent and identically distributed error, allowing for statistical treatment based on these assumptions. The reality is that the measurement noise is generated by physical processes that have certain dynamics associated with them, which may lead to noise dynamics being something other than the statistical ideal of white noise. For example, time series data acquired at high enough frequency will often have a 60 Hz noise component due to electrical power distribution using 60 Hz frequency (or 50 Hz in Europe). The 60 Hz noise is certainly not well represented as white noise. The dynamics of the noise may not be important if the measure used on the time series data is range or standard deviation, but in using measures of the dynamics of the time series, including approximate entropy, the dynamics of the noise may interfere with the measurement of the dynamics of the system under study. One way the impact of noise can be studied is to add in computer generated white noise to time series data, and investigate the impact that the added white noise has on the approximate entropy analysis. However, this method leaves open the possibility that real experimental noise, which is not pure white noise, may have a different effect on the analysis.

Another approach to understanding the impact of experimental noise on measures of system dynamics is to use a model system that has known dynamics, and see if the dynamical analysis gives a result in reasonable agreement with the known dynamics. For example, a mechanical single pendulum has limit cycle dynamics, and thus would be expected to have a low value for the approximate entropy. Higher values of approximate entropy from experimental measurements of the dynamics of a single pendulum are likely a result of contamination of the measured signal with experimental noise with more complex dynamics. Data acquired from the single pendulum with the same experimental equipment as the infant sitting data would be contaminated with noise having the same dynamics as noise contaminating the infant sitting data. Thus it is possible to select analysis parameters for the approximate entropy analysis using pendulum data that minimize the impact of experimental noise on the analysis. A double pendulum is a pendulum with two linked segments that are each free