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Children with cerebral palsy have greater stochastic features present in the variability of their gait kinematics

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ABSTRACT

Children with CP have a more variable gait pattern. However, it is currently unknown if these variations arise from deterministic variations that are a result of a change in the motor command or stochastic features that are present in the nervous system. The aim of this investigation was to use a Langevin equation methodology to evaluate the deterministic and stochastic features that are present in the variability of the gait kinematics of children with cerebral palsy (CP). Ten children with spastic diplegic CP and nine typically developing (TD) children participated in this investigation. All of the children walked on a treadmill for 2 min while a three-dimensional motion capture system recorded the step kinematics. Our major findings for this investigation were: (1) children with CP had greater variability in their gait patterns than TD children, (2) the variability of the children with CP and TD children had similar deterministic features, (3) the variability had greater stochastic features for the children with CP, and (4) the increase in the amount of variability was strongly correlated with the increase in stochastic features. These results indicate that the variability seen in the gait patterns of children with CP may be due to the inability to suppress the noise that is present in the neuromuscular system.

1. Introduction

It has previously been shown that children with cerebral palsy (CP) have an increased amount of variability in their gait patterns (Katz-Leurer, Rotem, Keren, & Meyer, 2009; Kurz, Arpin, & Corr, 2012). These variations are presumed to be related to an inability of children with CP to adequately adjust the stepping kinematics to accommodate internal and external perturbations that are encountered. These intentional and specific adjustments in the step kinematics are defined as deterministic because they are related to the execution of the motor command. It is alternatively possible that the increased gait variability is due to noise or stochastic processes that occur at every level of the neuromuscular system. For example, it has been shown that there are random errors in the release of neurotransmitters at the neuromuscular junction and in the recruitment of the motor units (Faisal, Selen, & Wolpert, 1998). These subtle changes create stochastic changes in the timing and force production of the muscle (Chu & Sanger, 2009; Hamilton, Jones, & Wolpert, 2004; Jones, Hamilton, & Wolpert, 2002). Furthermore, it has been demonstrated that there is noise in the transduction of the sensory feedback, which can be problematic if the noise is equal to or greater than the sensory information (Faisal et al., 2008). Hence, it is possible that the

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increased variability in the gait patterns of children with CP may be due to the inability to suppress the stochastic features that permeate every level of the nervous system.

The separation of the deterministic and stochastic features that promote variability in human movement has historically been a challenge. However, several investigations have demonstrated that the Langevin equation methodology can be used to successfully separate the deterministic and stochastic sources that govern the variability present in a wide variety of human movements (e.g., postural sway, tremor, rhythmic joint movements, isometric finger forces) (Bonnet et al., 2010; Bosek, Grzegorzewski, & Kowalczyk, 2004; Bosek, Grzegorzewski, Kowalczyk, & Lubiński, 2005; Frank, Friedrich, & Beek, 2006; Friedrich et al., 2000; Gottschall, Peinke, Lippens, & Nagel, 2009; Kurz, Arpin, Davies, & Harbourne, 2013; van Mourik, Daffertshofer, & Beek, 2006, 2008). The methodology for this approach is well established and assumes that variability in the behavior can be described by a first-order stochastic differential equation

$$\dot{x}(t) = D^{(1)}(x) + \sqrt{2D^{(2)}(x)}\Gamma(t) \quad (1)$$

where $\dot{x}$ is the rate of change of the system, $D^{(1)}(x)$ is the drift coefficient, $D^{(2)}(x)$ is the diffusion coefficient and $\Gamma(t)$ is the Langevin force (Frank et al., 2006; Friedrich & Peinke, 1997; Gottschall et al., 2009). The Langevin force is modeled as Gaussian white noise whose amplitude is dependent upon the magnitude of the diffusion coefficient. Effectively, the drift coefficient represents the deterministic changes in the state of the system, while the diffusion coefficient represents the stochastic features.

The purpose of this investigation was to examine whether the heightened variability seen in the gait kinematics of children with CP is due to an increase in stochastic features present in the stepping kinematics and/or are a result of inconsistencies of deterministic features that are related to the selection and alteration of the steps. To this end, we used a Langevin equation methodological approach to evaluate the differences in the deterministic and stochastic features that may contribute to the variability present in the stepping pattern of children with CP.

2. Methods

Ten children with spastic diplegic CP (age = 7.8 ± 2.8 years) and nine typically developing (TD) children (age = 8.0 ± 2.4 years) participated in this investigation. The children with CP had a Gross Motor Function Classification System level between I and II, and wore their prescribed ankle–foot orthosis during the experiment. The Institutional Review Board at the University of Nebraska Medical Center approved all the experimental procedures. The parents of each child consented for their child to participate and each child assented to participate.

Children walked on a treadmill for 2 min at 0.8 m/s. The 0.8 m/s speed was selected based on previously recorded average walking speeds for children with cerebral palsy (Abel & Damiano, 1996; Kurz et al., 2012). A three-dimensional motion capture system (120 Hz; Vicon, Centennial, CO) was used to track reflective markers placed on the heel, toe, ankle and sacrum of each participant. The positional data for all the markers were filtered using a zero-lag Butterworth filter with a 6 Hz cut-off. Due to the fact that the position of the children on the treadmill may drift, the difference in the horizontal position of the sacrum and the right ankle marker at foot-contact was used to quantify the stepping kinematics. The maximum forward position of the ankle marker relative to the sacrum marker was identified for each step and was used to generate a time series that represented the stepping kinematics. The stepping kinematic time series was subsequently differenced (e.g., $X_{i+1} - X_i$) to ensure that the data was stationary and that the mean of the stepping pattern was zero. The standard deviation of the differenced stepping kinematic time series was calculated to determine the amount of gait variability present in the respective groups.

The Langevin equation methodology was used to reconstruct the drift and diffusion features of the stepping kinematic time series. The drift coefficient represented the deterministic changes in the gait pattern from one step to the next, while the diffusion coefficient represented the stochastic features present in the stepping kinematics. Reconstruction of the drift ($D^{(1)}(x)$) and diffusion coefficients ($D^{(2)}(x)$) was based on a conditional probability distribution that represented the probability of the system to be in state x' at time $t + \tau$ given a previous state x at time t. The amount of drift and diffusion from the respective states was calculated as follows

$$D_i^{(n)}(x) = \frac{1}{n!\tau}\langle [x_i(t+\tau) - x_i(t)]^n \rangle \quad (2)$$

where x_i represents the ith step, t represents time, τ represents a change in time from the current step, n is the nth order coefficient to be reconstructed, and $\langle\,\rangle$ is the mean divergence (Frank et al., 2006; Gottschall et al., 2009). This computation was carried out for all neighboring pairs across the kinematic time series such that the amount of average divergence from the initial kinematic data point was computed as time evolved.

An exemplary drift plot reconstructed from the stepping kinematics is shown in Fig. 1A. The drift coefficient was estimated from the plot by fitting a first order polynomial ($y = a_0 + a_1x$) to x_i and $D^{(1)}(x)$. The a_0 constant of the polynomial represents the preferred fixed point of the stepping kinematics. The fixed point was zero for this experiment since the data was differentiated. The a_1 linear coefficient depicted the deterministic features that comprise the kinematic variations. A larger a_1 indicates a more rapid deterministic change in the kinematics (Gottschall et al., 2009). For this investigation changes in a_1 were evaluated.