Gait & Posture 36 (2012) 600–604

Contents lists available at SciVerse ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Differences in the dynamic gait stability of children with cerebral palsy and typically developing children

Max J. Kurz *, David J. Arpin, Brad Corr

Department of Physical Therapy, Munroe-Meyer Institute for Genetics and Rehabilitation, University of Nebraska Medical Center, Omaha, NE, United States

ARTICLE INFO

Article history:
Received 16 November 2011
Received in revised form 25 May 2012
Accepted 30 May 2012

Keywords:
Walking
Orbital stability
Nonlinear dynamics
Stability
Balance

ABSTRACT

The aim of this investigation was to evaluate the differences in the dynamic gait stability of children with cerebral palsy (CP) and typically developing (TD) children. The participants walked on a treadmill for 2 min as a motion capture system assessed the walking kinematics. Floquet analysis was used to quantify the rate of dissipation of disturbances that were present in the walking kinematics, and the variability measures were used to assess the magnitude of the disturbances present in the step length and width. The Floquet multipliers, step width and length values were correlated with Sections D and E of the Gross Motor Function Measure (GMFM). The children with CP had a larger Floquet multiplier and used a wider step width than the TD children. The magnitude of the maximum Floquet multiplier was positively correlated with the step width. Furthermore, the magnitude of the maximum Floquet multiplier and the step width were negatively correlated with the score on Section E of the GMFM. Lastly, the children with CP used a more variable step length than the TD children. These results suggest that children with CP have poor dynamic gait stability because they require more strides to dissipate the disturbances that are present in their walking pattern. In effort to stabilize these disturbances, the children with CP appear to utilize a wider step width and modulate their step length. Overall the inability to effectively dissipate the gait disturbances may be correlated with the child's ability to perform a wide range of gross motor skills (e.g., step over obstacles, jump, walk up stairs).

1. Introduction

Cerebral palsy (CP) is a neurologic disorder that results from a defect or insult to the immature brain. Although the brain insult does not progressively worsen, there is often an accumulation of musculoskeletal impairments that result in slower walking speed, a shorter-stride length, and more time spent in double support [1,2]. It has been speculated that these gait changes reflect the unstable walking pattern seen in these children. Although it is well recognized that children with CP have poor balance and a higher incidence of falls [3], few efforts have been made to quantify the dynamic walking stability of these children. Rather, the majority of the scientific literature in this area has focused on using standing posture measurements to assess the balance instabilities seen in these children [4,5]. The problem with this approach is that static balance tests do not correlate well with measures of dynamic gait stability or the prediction of falls [6,7]. Hence, standing balance measures may not be the best metric for assessing the dynamic gait stability of children with CP.

In general, bipedal walking is inherently unstable because the center of mass (COM) is in a constant state of fluctuation, and may exceed the base of support during single support [8,9]. In spite of this, the walking pattern remains dynamically stable because the COM is decelerated and redirected to remain within the base of support during the double support period [8,9]. In typically developing children, the COM has the largest amount of displacement and acceleration in the forward direction [8,10], and is stabilized by adjusting the step length [11]. In a similar fashion, the step width is also actively modulated to redirect the COM in the frontal plane to remain within the base of support [11,12].

A considerable amount of experimental evidence has shown that the variability present in the step length and width is related to the balance impairments seen in adults with neurological impairments [13–16]. In these studies, a greater amount of variability is thought to reflect larger foot placement errors that may result in the loss of balance. Only recently have the variability concepts begun to infiltrate the current CP literature where it has been shown that children with CP have a more variable step length [17]. However, these initial results should be interpreted with caution because variability metrics do not provide direct information on how the neuromuscular system recovers from

* Corresponding author at: Department of Physical Therapy, Munroe-Meyer Institute for Genetics, and Rehabilitation, University of Nebraska Medical Center, 985450 Nebraska Medical Center, Omaha, NE 68198-5450, United States.
Tel.: +1 402 559 6415; fax: +1 402 559 9263.
E-mail address: mkurz@unmc.edu (M.J. Kurz).

0966-6362/$ – see front matter
http://dx.doi.org/10.1016/j.gaitpost.2012.05.029

disturbances that are present in the walking pattern [18]. Rather variability measures only provide an indication of the overall magnitude of the disturbances present in the walking pattern. Furthermore, variations in the walking pattern may not always be related to poor gait stability. It is alternatively possible that an increased amount of variation in the step length and width may also indicate that the child has greater adaptability for overcoming disturbances in the gait pattern [11,12]. This paradox remains as a limitation for the application of variability measures, such as standard deviation and coefficient of variation, for effectively quantifying the dynamic walking gait stability of children with CP.

Floquet analysis is a well-established technique that has been successfully used to quantify the dynamic stability of the unperturbed walking patterns of humans [19–23]. The stability of the movement pattern can be assessed based on the rate of change of a set of state variables that quantify the behavior of the joint kinematics. Experimental data has shown that the state variables that define the walking kinematics oscillate in a rhythmic pattern and form a closed loop trajectory or limit cycle (Fig. 1) [19,20]. Floquet analysis quantifies the rate that the walking pattern returns back to the limit cycle trajectory after experiencing a disturbance. A walking pattern is less stable if it takes more strides to return back to the limit cycle trajectory [19–23]. The Floquet multipliers are used to quantify the rate that the gait pattern returns back to the limit cycle trajectory. The maximum Floquet multiplier dominates the behavioral change in the gait pattern and is used to define the rate of change in the gait pattern. A maximum Floquet multiplier that is closer to one indicates that it takes more strides to dissipate the disturbances [19–23].

The purpose of this investigation was (1) to determine if there are differences in the maximum Floquet multipliers calculated from the walking patterns of children with CP and typically developing (TD) children, (2) to determine if the largest Floquet multiplier is related to the standing and walking clinical Gross Motor Function Measure (GMFM) scores for children with CP, (3) to determine if children with CP have greater variations in their step width and length than TD children, (4) to determine if the amount of variability in the step width and length is related to the clinical GMFM scores for children with CP.

2. Methods

The University Institutional Review Board approved all experimental procedures, and the parents consented and the children assented to participating in the experiment. Nine children with spastic diplegic CP (age = 7.8 ± 2.8 yrs), and six typically developing (TD) children (age = 8.0 ± 2.4 yrs) 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. Sections D (standing) and E (i.e., walking, running, jumping) of the Gross Motor Function Measure (GMFM) were used to assess the motor abilities of the children with CP [24]. The GMFM was not performed for the TD children because they would score the maximum points on the test.

The participants walked on a treadmill for 2 min at a speed that was based on the Froude number for children with spastic diplegic CP who are community ambulators (Froude = 0.31) [1]. The Froude number was calculated from the walking speed and leg lengths of children with CP that have been previously reported in the literature [1]. By having all of the participants walk at the same Froude velocity we assumed that the children with CP and TD children were moving in a dynamically similar fashion. A three-dimensional motion capture system (120 Hz) was used to track a modified Helen Hayes reflective marker set that was placed on the participant's lower extremities. A knee alignment device (KAD) was used during the standing calibration to ensure that the markers were correctly positioned. The position data for all markers were filtered using a zero-lag Butterworth filter with a 6 Hz cut-off, and the Vicon plug-in gait software (Vicon, Centennial, CO) was used to calculate the sagittal plane lower extremity joint angles. The respective derivatives of the joint angles were determined using the first-central difference method.

A state vector (**S**) was created to define the walking attractor dynamic (Eq. (1))

$$\mathbf{S}(t) = [\theta_1, \ldots, \theta_6, \dot{\theta}_1, \ldots \dot{\theta}_6]^T \quad (1)$$

where θ_i represent the respective bilateral lower extremity sagittal plane joint angles (e.g., hip, knee and ankle), and $\dot{\theta}_i$ was the respective derivatives. We evaluated the bilateral sagittal plane joint kinematics because they represent the dominant plane of motion during walking.

The state space data were partitioned into their respective strides and were normalized to 101 samples using a cubic spline routine. Susbsequently, Poincare maps were created for every sample of the normalized stride. Poincare maps were defined for each point of the normalized gait cycle as (Eq. (2))

$$\mathbf{S}_{n+1} = \mathbf{F}(\mathbf{S}_n) \quad (2)$$

where **S** is the state vector of the system, **F** is the function that describes the change in the location of the state vector in the Poincare map from one stride (n) to the next ($n+1$). Ideally, if the walking pattern was completely periodic (i.e., no deviation from the preferred joint kinematics), the function would map to the same point in Poincaré map. However, this is not the case because the joint kinematics fluctuate slightly from stride-to-stride.

It was assumed that the mean ensemble ($\mathbf{S}^*$) represented the preferred joint kinematics, and deviations away from the mean from one stride ($\mathbf{S}_n$) to the next ($\mathbf{S}_{n+1}$) represented disturbances (Eq. (3)).

$$[\mathbf{S}_{n+1} - \mathbf{S}^*] = J(\mathbf{S}^*)[\mathbf{S}_n - \mathbf{S}^*] \quad (3)$$

The rate of change in the state vector from one stride (n) to the next ($n+1$) was quantified by the Jacobian ($J(\mathbf{S}^*)$). A least squares algorithm was used to solve for the Jacobian, and the Floquet multipliers were the eigenvalues of the Jacobian [19]. For each subject, the largest maximum Floquet multiplier was calculated for each point of the normalized stride. The largest maximum Floquet multiplier from all the points of the normalized stride was used to quantify the dissipation rate of the disturbances present in the walking pattern. A maximum Floquet multiplier that was further away from zero signified that it took more strides to dissipate the disturbances.

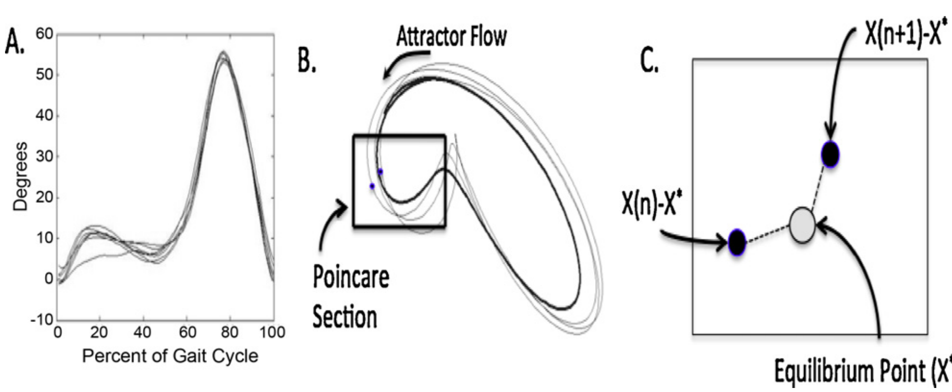

Fig. 1. Floquet analysis. (A) The respective joint kinematic time series are separated into the respective strides and normalized to 101 points, (B) the state variables of the walking kinematics are used to construct the attractor, which has a limit cycle shape. The attractor is constructed by plotting the angular position on the abscissa and the angular velocity on the ordinate. The bold trajectory in the limit cycle represents the mean of the trajectories, which is assumed to be the preferred walking pattern. Disturbances in the walking pattern promote the trajectories to diverge away from the mean limit cycle trajectory, (C) Poincare sections are taken of the attractor, and are used to evaluate the amount of divergence or convergence from one stride ($X(n)-X^*$) to the next ($X(n+1)-X^*$). X^* is the equilibrium point, which is the position of the mean limit cycle trajectory in the Poincare section [18–20].