Research in Developmental Disabilities 34 (2013) 1689–1699

Contents lists available at SciVerse ScienceDirect

Research in Developmental Disabilities

Gait stability in children with Cerebral Palsy

Sjoerd M. Bruijn [a,b,*], Matthew Millard [c], Leen van Gestel [d], Pieter Meyns [d], Ilse Jonkers [e], Kaat Desloovere [d,f]

[a] Research Center for Movement Control and Neuroplasticity, Department of Kinesiology, KU Leuven, Belgium
[b] Department of Orthopedics, First Affiliated Hospital of Fujian Medical University, Fuzhou, Fujian, PR China
[c] Bioengineering, Stanford University, Stanford, CA 94305, USA
[d] Department of Rehabilitation Sciences, Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Belgium
[e] Research Group in Human Movement Biomechanics, KU Leuven, Belgium
[f] Clinical Motion Analysis Laboratory, CERM, University Hospital Leuven, Leuven, Belgium

ARTICLE INFO

Article history:
Received 29 November 2012
Received in revised form 6 February 2013
Accepted 8 February 2013
Available online 15 March 2013

Keywords:
Gait stability
Angular momentum
Cerebral Palsy
Foot placement estimator

ABSTRACT

Children with unilateral Cerebral Palsy (CP) have several gait impairments, amongst which impaired gait stability may be one. We tested whether a newly developed stability measure (the foot placement estimator, FPE) which does not require long data series, can be used to asses gait stability in typically developing (TD) children as well as children with CP. In doing so, we tested the FPE's sensitivity to the assumptions needed to calculate this measure, as well as the ability of the FPE to detect differences in stability between children with CP and TD children, and differences in walking speed.

Participants were asked to walk at two different speeds, while gait kinematics were recorded. From these data, the FPE, as well as the error that violations of assumptions of the FPE could have caused were calculated.

The results showed that children with CP walked with marked instabilities in anterior–posterior and mediolateral directions. Furthermore, errors caused by violations of assumptions in calculation of FPE were only small (~1.5 cm), while effects of walking speed (~20 cm per m/s increase in walking speed) and group (~5 cm) were much larger. These results suggest that the FPE may be used to quantify gait stability in TD children and children with CP.

1. Introduction

Children with unilateral Cerebral Palsy (CP) have several gait impairments, amongst which impaired gait stability may be one (Hsue, Miller, & Su, 2009a, 2009b; Iosa, Marro, Paolucci, & Morelli, 2012; Kurz, Arpin, & Corr, 2012; Opheim, Jahnsen, Olsson, & Stanghelle, 2012).

Gait stability may be operationally defined as the ability to maintain gait in the presence of perturbations. In practice, people with lower gait stability are more likely to fall, making gait stability an important functional gait metric.

Recent studies have aimed at quantifying gait stability impairments in children with CP. For instance, Iosa et al. (2012) used variability measures and Kurz et al. (2012) used maximum Floquet multipliers (i.e., a measure derived from dynamical

* Corresponding author at: Motor Control Laboratory, Research Center for Movement Control and Neuroplasticity, Department of Kinesiology, KU Leuven, Tervuursevest 101 Box 1501, 3001 Leuven, Belgium. Tel.: +31618844777.
E-mail address: s.m.bruijn@gmail.com (S.M. Bruijn).

0891-4222/$ – see front matter
http://dx.doi.org/10.1016/j.ridd.2013.02.011

Abbreviation/symbol

(ϕ)	partial derivative of $X(\phi)$ with respect to changes in system energy
$\delta X(\phi)/\delta Ho$	partial derivative of $X(\phi)$ with respect to changes in total body angular momentum
$\delta X(\phi)/\delta J$	partial derivative of $X(\phi)$ with respect to changes in total body inertia
$\delta X(\phi)/\delta L$	partial derivative of $X(\phi)$ with respect to changes in leg length
$\dot{\theta}$	total body angular velocity
2D	two-dimensional
3D	three-dimensional
AP	antero-posterior
CoM	centre of mass position vector
CoP	centre of pressure vector
CP	Cerebral Palsy
D_{FPE}	distance between $X(\phi)$ and the foot at initial contact
D_{FPE}AP	AP distance between $X(\phi)_{AP}$ and toe marker at initial contact
D_{FPE}ML	ML distance between $X(\phi)_{ML}$ and the most lateral foot marker at initial contact
FPE	foot placement estimator method
g	gravitational constant
GEE	Generalized Estimation Equations
h	CoM height
H_{tot}	total body angular momentum vector
J_{CoM}	total body inertia tensor
m	mass of the subject
ML	medio-lateral
TD	typically developing
v_x	horizontal component of the velocity of the CoM
v_y	vertical component of the velocity of the CoM
$X(\phi)_{AP}$	AP position of $X(\phi)$ in lab coordinates
$X(\phi)_{ML}$	ML position of $X(\phi)$ in lab coordinates
$X(\phi)$	position of the foot placement estimator within plane of progression
$\Delta(T+V)$	change in system energy from initial contact to mid-stance
ΔHo	change in total body angular momentum from 50 ms before initial contact to 50 ms after initial contact
ΔJ	change in total body inertia from initial contact to mid-stance
ΔL	change in leg length from initial contact to mid-stance
$\varepsilon(T+V)$	potential error in $X(\phi)$ due to changes in system energy
εHo	potential error in $X(\phi)$ due to changes in total body angular momentum
εJ	potential error in $X(\phi)$ due to changes in total body inertia
εL	potential error in $X(\phi)$ due to changes in leg length
ϕ	leg angle

systems theory, that indicated the tendency of small, naturally occurring perturbations to grow or decay per gait cycle) to study gait stability in children with CP. In doing so, both found that children with CP are less stable than healthy controls. Still, accurate calculation of Floquet multipliers (Bruijn, van Dieën, Meijer, & Beek, 2009a) and variability measures (Owings & Grabiner, 2003) requires a substantial number of strides. For instance, for Floquet multipliers, 150 strides have been recommended (Bruijn et al., 2009a) and for variability measures 200 strides (Owings & Grabiner, 2003). Such long measurements may be infeasible in a clinical setting. Moreover, recent studies have criticized the relationship between both maximum Floquet multipliers and variability measures and gait stability (Bruijn, Bregman, Meijer, Beek, & van Dieen, 2011; Van Schooten et al., 2011). All in all, Floquet multipliers and variability measures may not be ideal to assess gait stability in a clinical population.

A gait stability measure that requires a minimum number of strides is ideal for clinical gait assessment. One such measure is the recently developed foot placement estimator ([FPE] Millard, McPhee, & Kubica, 2012; Millard, Wight, McPhee, Kubica,