Full length article

Local dynamic stability during treadmill walking can detect children with developmental coordination disorder

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ARTICLE INFO

ABSTRACT

Objective: Developmental coordination disorder (DCD) is an innate impairment of motor coordination that affects basic locomotion and balance. This study investigated local dynamic stability of trunk accelerations during treadmill walking as an objective evaluation of gait stability and the sensitivity and specificity of this measure to discriminate children with DCD from typically developing children.

Method: Eight children with DCD and ten age- and gender-matched typically developing children (TD) walked four minutes on a treadmill. Trunk accelerations in vertical, medio-lateral and anterior-posterior directions were recorded with a sternum mounted accelerometer at 256 Hz. Short term local dynamic stability (λs), root mean square (RMS) and relative root mean square (RMSR) were calculated from measures of orthogonal trunk accelerations. Receiver operating characteristic curve (ROC) analysis was performed to discriminate between groups based on short term local dynamic stability.

Results: λs was significantly greater in children with DCD in the main movement direction (AP) (DCD: $1.69 \pm 0.17 \lambda s$; TD: $1.41 \pm 0.17 \lambda s$; $p = 0.005$), indicating reduced local dynamic stability. RMS and RMSR accelerations showed no difference between children with DCD and TD children in any direction. The ROC analysis of λs in separate directions and in two dimensions showed an excellent accuracy of discriminating between children with DCD and TD children. Anterior-posterior direction in combination with medio-lateral or vertical showed best performance with an area under the curve (AUC) of 0.91.

Conclusion: We have shown that children with developmental coordination disorder have general reduced local dynamic stability and that the short term Lyapunov exponent has good power of discrimination between DCD and TD.

1. Introduction

Developmental coordination disorder (DCD) is an innate impairment of motor coordination that may affect basic locomotion, balance and acquisition of motor skills. Due to great variability of motor performance between children with DCD [1] and diagnostic criteria that leave room for clinical interpretation [2], DCD is under-recognised and difficult to diagnose by health care professionals [3]. Standardised norm-referenced tests are available to assess motor function (e.g. mABC-2 & BOTMP), but they are mainly skill-based and may be influenced by experience in the specific task [4]. In summary, there could be

a need for objective measures to identify children with DCD based on deficits in basic locomotion. Gait is a basic, highly automatised motor function and less affected by experience, gender and movement culture. As instability in gait may play an important role in the motor impairments associated with DCD [5], objective evaluation of gait stability could be a relevant addition to the diagnostic toolbox and an important method to evaluate improvements in proprioception and functional motor control.

Prior research on gait function in children with DCD has mainly been focused on identifying characteristics and variability in discrete spatiotemporal parameters and kinematics. Even though children with

DCD exhibit a more asymmetrical and variable kinematic gait pattern [6], and a greater stride-to-stride variability [7] (normally interpreted as an expression of impaired gait control), Woodruff and colleagues concluded in their study on classification of gait patterns in children with DCD, that there was no solid systematic gait pattern explaining the gait deviation from typically developing children [8]. It remains unclear, however, how the previously reported discrete measures of variability relate to time-dependent measures of stability [9] in children with DCD.

In the present study we decided to investigate local dynamic stability of trunk accelerations during treadmill walking. Local dynamic stability is a method of quantifying the body's resilience to small perturbations naturally inherent during walking [10,11]. It is quantified over numerous sequential steps, and is a measure of how well a person responds to their internal variability and the environment's external variability (e.g., a slippery or uneven walking surface). If small perturbations are not appropriately attenuated, the deviations from the normal gait pattern will accumulate. During gait, proprioceptive, vestibular and visuo-motor feedback contribute to an online control to attenuate the natural kinematic and kinetic variability [12,13]. This continuous processing and response requires an efficient, online motor adjustment, sensory organization and efficient neuromuscular response. These are mechanisms that are commonly reported to be impaired in children with DCD [5]. If children with DCD respond less efficiently to their naturally occurring, but increased variability, their local dynamic stability will be reduced. This may be reflected in reduced stability during gait or even increased risk of falling [9,10].

We therefore hypothesised that children with DCD have lower local dynamic stability during gait than typically developing children (TD). To establish clinical relevance, we further explored whether local dynamic stability has the sensitivity and specificity to discriminate between children with DCD and TD children.

2. Method

2.1. Participants

Eight children with DCD and ten age-, gender- and anthropometrically matched TD children with normal motor proficiency were recruited (Table 1). The DCD group was recruited through paediatric physiotherapists, occupational therapists and the Danish Parents Association for DCD. Motor performance was assessed using the Movement Assessment Battery for children (MABC-2), which is a norm-referenced basic motor abilities assessment tool containing fine motor, ball handling, and balance tasks [14].

Inclusion criteria for children with DCD were a score below the 15th percentile in the MABC-2 and to meet the official criteria for DCD according to the DSM-V [15] based on evaluation by a qualified health care professional. To avoid confounding factors, we did not include children with co-morbidities. Inclusion criteria for the TD-children were a score above the 16th percentile in the MABC-2, and no diagnosed or suspected neurodevelopment disorders. Informed written consent was obtained from a legal guardian. The experimental protocol was approved by the Capital Region Committee on Health Research Ethics, Denmark (ref.: H-4-2013-144).

Table 1
Participant Characteristics (mean ± SD).

	DCD group (*n* = 8)	TD group (*n* = 10)	*p*-value
Age, years	8.8 ± 1.5	9.1 ± 1.4	0.885
MABC-2 percentile	2.6 ± 3.93	73.3 ± 5.2	< 0.001
Gender (♂/♀), n	6/2	7/3	0.658
Height, cm	139.5 ± 8.1	141.1 ± 3.0	0.763
Body mass, kg	33.6 ± 7.3	33.7 ± 1.8	0.839

2.2. Procedure and data acquisition

Trunk accelerations were recorded with a sternum mounted accelerometer (MQ16, MarqMedical, Denmark) during four minutes walking at preferred walking speed. The test was performed on treadmill to control for walking speed, and each participant was accustomed to treadmill walking for maximum five minutes at different speeds comfortable to the child. Familiarisation ended at four min. if the child felt comfortable. Relatively short familiarisation was chosen to ensure full attentional focus during testing. Preferred walking speed was determined according to the recognised protocol by Dingwell and Marin [11,16], in which preferred walking speed is selected 6 times by the subject while alternating between increasing and decreasing speeds from 0.42 m/s above or below the previously selected speed. The preferred walking speed is subsequently calculated as the average of the six self-selected speeds. The participants were instructed, to walk without support from treadmill handles and were informed of time progress every minute. Upper body accelerations in vertical (VT), medio-lateral (ML) and anteror-posterior (AP) directions were sampled at 256 Hz (MQ16, Marq Medical, Denmark). Recordings began when the treadmill reached a constant speed and the participant was comfortable with the selected speed.

2.3. Data analysis

All data processing and calculations were performed using customised MATLAB (The MathWorks, Inc., Natick, MA, USA) scripts [11]. Accelerometer based assessment of gait parameters has been validated in children [17]. The primary outcome was short term local dynamic stability in each VT, ML and AP directions. Root mean square was calculated for each direction of acceleration as a measure of variability.

The method for calculating local dynamic stability has been described extensively in the literature [10,11,16]. Local dynamic stability was quantified using nonlinear time-series methods, and expressed as the short term Lyapunov exponent (λs) which has shown good reliability, good intrasession and fair intersession repeatability and a correlation to falls risk [10,18–20]. The first 195 strides were identified from the vertical accelerations, and the unfiltered time-series were time-normalised to 19,500 data points using cubic spline interpolation. Five-dimensional state spaces were reconstructed from each acceleration direction using the method of delays [21]. From the reconstructed state spaces Euclidean distances between nearest neighbours in state space were calculated as a function of time and averaged over all nearest neighbours. λs was calculated as the average rate of logarithmic divergence of the distance between nearest neighbours in state space from 0 to 0.5 stride (ln(div) > /stride-time from 0–0.5 stride) [11,22]. A higher λs expresses lower local dynamic stability as the rate of divergence in state space is faster.

Acceleration Root Mean Square (RMS) was calculated as the dispersion of the acceleration data relative to zero and quantifies the average magnitude of accelerations in each direction during a complete walking trial [23]. To normalise RMS for effect of walking speed, the ratios between RMS accelleration in each direction and the RMS vector magnitude (RMSR) were calculated [24].

2.4. Statistical analysis

The distribution of the data was analysed for normality using the Shapiro-Wilk test and Q-Q plots in IBM SPSS statistics 22 (IBM Corp. Released 2013. IBM SPSS Statistics for Windows). Non-parametric (Mann–Whitney U) tests were used to test for group differences in age, height, body mass and MABC-2 percentile. A chi-squared test was used to evaluate sex differences between groups. Non-parametric (Mann–Whitney U) tests were performed to compare the short term λs, RMS and RMSR between children with DCD and TD children in separate directions of acceleration. The discriminative power of λs to