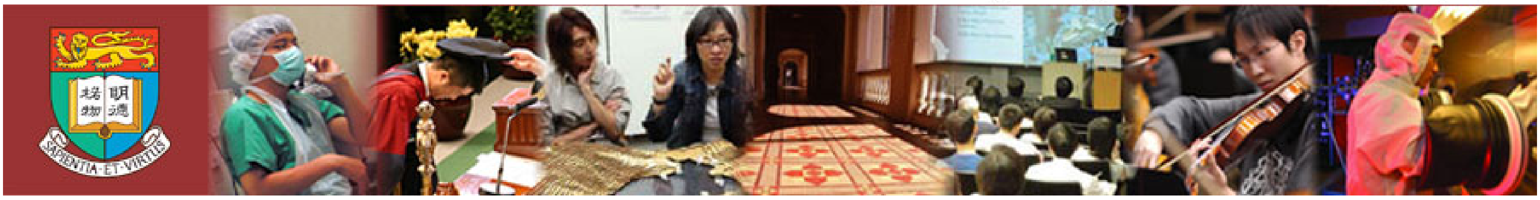

Title	Direction-specific impairment of stability limits and falls in children with developmental coordination disorder: Implications for rehabilitation
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Falls in children with developmental coordination disorder and direction-specific impairment of stability limits: Implications for rehabilitation

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Abstract

Limits of stability (LOS) is an important yet under-examined postural control ability in children with developmental coordination disorder (DCD). This study aimed to (1) compare the LOS and fall frequencies of children with and without DCD, and (2) explore the relationships between LOS parameters and falls in the DCD population. Thirty primary school-aged children with DCD and twenty age- and sex-matched typically-developing children participated in the study. Postural control ability, specifically LOS in standing, was evaluated using the LOS test. Reaction time, movement velocity, maximum excursion, end point excursion, and directional control were then calculated. Self-reported fall incidents in the previous week were also documented. Multivariate analysis of variance results revealed that children with DCD had shorter LOS maximum excursion in the backward direction compared to the control group (p = 0.003). This was associated with a higher number of falls in daily life (rho = -0.556, p = 0.001). No significant between-groups differences were found in other LOS-derived outcomes ($p > 0.05$). Children with DCD had direction-specific postural control impairment, specifically, diminished LOS in the backward direction. This is related to their falls in daily life. Therefore, improving LOS should be factored into rehabilitation treatment for children with DCD.

Keywords: Clumsy children; postural control; limits of stability; falls; rehabilitation

1. Introduction

Developmental coordination disorder (DCD) is one of the most common neurodevelopmental motor disorders, affecting about 6% of typically-developing children during the primary-school years. Classic features include clumsiness, poor coordination, slowness and inaccuracy of motor skills and poor postural control [1-3]. It has been reported that 73% to 87% of children with DCD suffer from balance problems [4] that interfere with participation in day-to-day activities and increase the risk of falls [2,5]. Suboptimal balance ability in children with DCD is therefore a concern of many parents and clinicians.

Balance (postural control) requires the ability to control the center of gravity (COG) within the base of support (BOS). The perimeter of the BOS is known as the limit of stability (LOS). During erect standing, the LOS defines the area in space through which a person can lean his or her body without altering the BOS. If the body sways beyond the LOS boundary, a corrective step will be elicited (stepping strategy) to re-establish a new BOS or else a fall will occur [6,7].

It is widely acknowledged that the LOS of an individual is affected by both mechanical (e.g., range of joint motion and postural alignment) and neural (e.g., muscle response latency and sensorimotor integration) factors [6-9]. Children with DCD exhibit neural deficits involving the central nervous system (e.g., parietal cortex and cerebellum) [10,11] and peripheral nervous system (e.g., muscle activation) [12,13] that may adversely affect their LOS. Previous studies have reported that children with DCD demonstrate poorer static [2,12,14], reactive [14] and anticipatory [13] postural control compared to their typically-developing peers. It is plausible that their LOS are affected as well. Examining LOS characteristics in children with DCD is very important, as stability is fundamental to many daily tasks such as reaching for objects, leaning back for hair washing, and walking. Movements exceeding the LOS will result in falls and injuries [6,15]. However, this specific, yet important aspect of balance performance is under-examined in the DCD population.

To the best of our knowledge, only Johnston et al. have examined the LOS characteristics of children with DCD. They reported that during a reaching forward task, some of the anterior trunk muscles in the DCD-affected children demonstrated delayed activation or even absent anticipatory muscle action [13]. We hypothesized that poor proximal trunk control may affect forward reaching distance and LOS in the antero-posterior directions. However, information about the actual LOS deficit in children with DCD remains elusive. Moreover, no information on comorbid conditions was provided in Johnston et al.'s study [13]. Because comorbidities (e.g., attention deficit hyperactivity disorder) can influence the nature and severity of sensorimotor deficits and possibly LOS performance [16], it is important to assess a homogeneous sample of children with DCD. The objectives of this cross-sectional, case-control and exploratory study were: (1) compare the LOS and fall frequencies of children with DCD (without comorbidities) and age- and sex-matched typically-developing children, and (2) explore the relationships between LOS parameters and falls in the DCD population.

2. Methods

2.1. Participants

Children with DCD were recruited from child assessment centers, non-government organizations, local primary schools, and parents' groups through flyer and website advertising. All child volunteers were screened and assessed by two physiotherapists to determine their eligibility to participate in the study. The inclusion criteria were: (1) a diagnosis of DCD based on the Diagnostic and Statistical Manual of Mental Disorders (DSM-IV-TR) [1]; (2) a total impairment score of < 5th percentile on the Movement Assessment Battery for Children (MABC) [17]; (3) a total score of < 46 (for children aged 5 years to 7 years 11 months), < 55 (for children aged 8 years to 9 years 11 months), or < 57 (for children aged 10 years) on the DCD questionnaire (2007 version) [18]; (4) aged between 6 and 10 years; and (5) studying in a mainstream primary school. Exclusion criteria were: (1) comorbid conditions such as attention deficit hyperactivity disorder or dyslexia; (2) diagnosis of cognitive, psychological, emotional, neurological or other motor disorders; (3) known significant congenital, musculoskeletal, visual, vestibular or other sensorimotor disorders that might affect balance; (4) receiving rehabilitation services; or (5) unable to follow the assessor's instructions.

Typically-developing children were recruited from mainstream primary schools as controls. The eligibility criteria were the same as those for the DCD group, except that eligible control children did not have a diagnosis of DCD; obtained a total impairment score of > 15th percentile on the MABC [17]; and had a total score of > 46 (for children aged 5 years to 7 years 11 months), > 55 (for children aged 8 years to 9 years 11 months), or > 57 (for children aged 10 years) on the DCD questionnaire (2007 version) [18]. Ethical approval was obtained from the Human Research Ethics Committee of the administering university. Each child and parent gave informed written consent before data collection. Data collection was performed by an experienced physiotherapist and a trained assistant. All experimental procedures were conducted in accordance with the Declaration of Helsinki for human experiments.

2.2. Outcome measurements

Participants' relevant personal information, medical history, and number of falls in the previous week were obtained by interviewing them and a parent. Physical activity level (in metabolic equivalent (MET) hours per week) was estimated based on the self-reported physical activity intensity (light, moderate or hard), duration (hours), frequency (times per week), and the assigned MET value of the specific activity according to the Compendium of Energy Expenditures for Youth [19]. Body height and weight of each child were measured using a mechanical scale equipped with a height rod. Body mass index (BMI, in kg/m^2) was then calculated using the equation: $weight/height^2$. In addition, each child was assessed on their motor proficiency using MABC [17] and the parent was invited to fill in the DCD questionnaire (2007 version) [18].

A computerized dynamic posturography (CDP) machine (Smart Equitest, NeuroCom International Inc., Oregon, USA) with dual force plates and a video screen was used to perform the LOS test. This test assesses the participant's ability to intentionally shift his or her weight (i.e., displace their COG) in eight spatial directions (four cardinal and four diagonal directions) within a fixed BOS, and to briefly maintain stability at these target positions (Fig. 1). Each participant was instructed to stand barefoot on the force platform of the CDP machine with standardized foot placement. A safety harness was used to prevent falls. During the test, the initial center of pressure (COP) was displayed on the screen of the CDP machine together with eight target positions – front, right-front, right, right-back, back, left-back, left and left-front (Fig. 1). These target positions represent the perimeter of the theoretical LOS, which is determined automatically by the machine based on the sway angle of the COG of the participant: 8° right side, 8° left side, 8° anteriorly, and 4.5° posteriorly. On command (a visual cue and an auditory cue), the participant moved his or her COP trace to hit one of the eight randomly selected spatial target positions located on the LOS perimeter as fast, accurately, and smoothly as possible and then briefly maintained this position (COP as close to the target as possible) (Fig. 1). To do this, each participant needed to lean his or her body as far as possible in a given direction without losing balance, stepping, or reaching for assistance. The displacements of COP were displayed on screen in real time (as visual feedback) (Fig. 1) and recorded automatically [15,20].

The LOS test measured the following parameters for each movement direction (note that only the four cardinal directions were included in the statistical analysis): (1) reaction time (in seconds), the time between the presentation of a visual-auditory cue and onset of voluntary shifting of the participant's COP toward the designated target; (2) movement velocity (in °/s), the average velocity of COP movement quantified for 5% to 95% of the distance from the initial position to the target position; (3) maximum excursion (in % LOS), the maximum distance traveled by the COP during a trial, including movements that passed beyond the designated target; (4) endpoint excursion (in % LOS), the distance of the COP movement at first attempt toward the target, which provides a measure of how far the participant is willing to move on the first attempt leaning toward the target and reflects the participant's perception of his or her own safety limits (endpoint is defined as the point at which the initial movement toward the designated target ceases); and (5) directional control (in % accuracy), which measures the smoothness of the displacement of the COP toward the target position. Its value, expressed as a percentage of the total on-target movement, was computed using the equation: [(Amount of on-target movement – amount of off-target movement)/Amount of on-target movement] × 100%. A value of 100% indicates a straight-line path from the starting position toward the target without any off-target movement [15,20].

Test-retest reliability of the LOS test was found to be moderate to good with intraclass correlation coefficients ranging from 0.69 to 0.88 in young people [21]. For the purpose of data recording, only one trial (lasting 8 seconds) was performed for each target position. However, one familiarization trial to each target position was given to ensure all participants understood how to weight shift to the target positions before the actual data recording [20].

2.3. Statistical analyses

Sample size calculations were based on statistical power of 80% and a two-tailed alpha level of 5%. In our previous study of children with DCD [3], the mean balance ability scores were 43.3 (SD = 12.8) and 57.1 (SD = 9.6) for the DCD group and control group, respectively. This translates into a large effect size of 1.23. Therefore, the minimum sample size required to detect a significant between-groups difference in LOS outcomes was 12 children per group.

All statistical analyses were performed using SPSS 20.0 software (IBM, Armonk, NY). Descriptive statistics (means and standard deviations) were used to describe all relevant demographic and outcome variables. Kolmogorov-Smirnov tests and/or histograms were used to check the normality of continuous data. Independent t-tests and chi-square tests were used to compare the continuous and categorical demographic variables, respectively, between the DCD and control groups. The Mann-Whitney U-test was used to compare the self-reported number of falls between groups. To compare LOS test outcomes between the two groups while accounting for a possible inflation of type I error due to multiple comparisons, multivariate analysis of variance was performed for each category of outcomes (i.e., reaction time, movement velocity, maximum excursion, end point excursion, and directional control). An alpha level of 5% (two-tailed) was set and Bonferroni adjusted, as appropriate. Effect sizes (partial eta-squared) were also calculated for all outcome variables. Values of 0.01, 0.06 and 0.14 indicate small, medium, and large effect sizes, respectively. Spearman's correlation coefficient (rho) was used to evaluate the bivariate association between selected LOS test scores and the number of falls among children with DCD (alpha = 0.05, two-tailed).

3. Results

Thirty children with DCD and twenty typically-developing children were eligible to participate in the study. No significant between-group differences in any of the participants' demographic characteristics were found ($p > 0.05$), except that the DCD group scored significantly lower on the MABC ($p < 0.001$) and the DCD questionnaire ($p < 0.001$) than the control group (inclusion criteria were fulfilled). In addition, they fell more frequently than the control participants (Mann-Whitney U = 80.500, $p < 0.001$) (Table 1).

Multivariate analysis results revealed an overall significant difference in LOS maximum excursion between the two groups (Hotelling's trace = 0.271; F(4,45) = 3.051; $p = 0.026$). No significant between-group differences were found in the LOS reaction time (Hotelling's trace = 0.137; F(4,45) = 1.540; $p = 0.207$), movement velocity (Hotelling's trace = 0.084; F(4,45) = 0.948; $p = 0.445$), end point excursions (Hotelling's trace = 0.151; F(4,45) = 1.703; $p = 0.166$) and directional control (Hotelling's trace = 0.095; F(4,45) = 1.069; $p = 0.383$). When each individual LOS maximum excursion outcome was considered, the between-group difference remained significant for the maximum excursion in the backward direction ($p = 0.003$), but not in other movement directions ($p > 0.0125$, Bonferroni adjusted). The DCD group had 22.4% less maximum excursion in the backward direction than the control group ($p = 0.003$) and the partial eta-squared value was 0.165, indicating a large effect size (Table 2). Moreover, there was a significant negative correlation between LOS maximum excursion in the backward direction and the number of falls among children with DCD (rho = -0.556, $p = 0.001$).

4. Discussion

This study is the first to show that children with DCD without comorbidities had impaired stability limits, specifically in the backward direction, compared to their typically-developing peers. It is known that in adults, an inability to reach a target at the back is due to biomechanical constraints (e.g., limited joint range of motion), sensorimotor deficits or fear of falling [9,15]. Although biomechanical factors [22] and balance confidence may not be adversely affected in children with DCD (as reflected by similar LOS endpoint excursion scores between the two groups), these children may exhibit various sensorimotor deficits, including impaired development of multisensory reweighting [23], inferior sensory organization of balance control (primarily visual and vestibular deficits) [2], less well developed internal models of body orientation and self-motion [24], atypical postural control strategies (excessive reliance on hip strategy to balance) [3], slow muscle force production [25], and delayed activation of anterior trunk muscles during reaching [13]. Therefore, it is not surprising to find that their ability to lean backward was compromised. We postulate that multi-sensory integration problems in children with DCD [2,23,24] might be the major cause of this LOS-related directional balance dysfunction. It is because the LOS test challenged the visuo-postural integration of the participants – participants had to move their COG to hit the visuospatial targets in response to visual and auditory cues [15,20]. Children with DCD probably had difficulty in integrating all these sensory signals so that their postural control, especially in the backward (most challenging) direction, was compromised. Further studies may establish the link between multi-sensory integration and directional balance performance in children with DCD and also explore the treatment strategies for remediating the sensory integration deficits and improving directional balance performance in this population.

LOS plays a significant role in indicating susceptibility to falls in adults [26]. Similarly, in children with DCD, we found that their limited COP maximum excursion in the backward direction was associated with more falls in daily life. Our findings thus inform rehabilitation treatments for this group of children: clinicians should pay special attention to restoring their ability to lean backward during balance and fall prevention training. Perhaps repeatedly practicing voluntary weight shifts in the sagittal plane may improve their LOS [20] and minimize the occurrence of falls. Further randomized controlled trials are necessary to explore effective interventions to remediate this direction-specific impairment of stability limits in children with DCD.

Apart from the maximum excursion and fall outcomes, we did not find any differences in other LOS parameters (i.e., reaction time, movement velocity, end point excursion and directional control) between children with and without DCD. This finding was surprising given that children with DCD may have numerous sensorimotor impairments that can affect reaction time, movement velocity, directional control, and balance performance [2,3,12,13,25]. We postulate that perhaps standing on both legs during the LOS test is not challenging enough to elicit their postural control deficits [14], or our DCD group might have developed compensatory strategies to remediate their LOS balance dysfunctions during the course of development [27]. Certainly, further studies are needed to confirm these hypotheses.

The present study has several limitations. First, the assessors were not blinded to group assignment, so bias might have been introduced during the measurements. Second, there could be a recall bias in reporting falls. A previous study suggested that subjects with injurious falls and better cognitive functions are more likely to recall their falls [28]. In addition, our participants did not report the direction of falls, which may not be always in the backward direction. Third, it is known that LOS is a significant predictor of functional performance [29]. We did not take this possible confounding factor (functional performance) into account in the correlation analysis. Further study is necessary to determine how impaired LOS, functional performance, and falls affect quality of life in children with DCD. Finally, some of our participants may have undiagnosed visual, vestibular or other sensorimotor disorders that might affect balance performances [30] because not all of them had received complete vestibular, auditory and visual assessments before the study. Further research should include a homogenous group of subjects to improve internal validity of the study.

In conclusion, children with DCD have direction-specific postural control impairment, specifically, diminished LOS in the backward direction. This is related to their higher fall incidents in daily lives. These new findings inform and optimize treatment strategies to rehabilitate children with DCD.

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Tables

Table 1. Participant characteristics

	DCD group (***n*** **= 30)**	**Control group** (***n*** **= 20)**	***p*** **value**
Age, year	7.7 ± 1.5	7.9 ± 1.6	0.652
Sex (boy/girl), n	23 / 7	11 / 9	0.108
Weight, kg	26.0 ± 9.2	24.0 ± 4.5	0.312
Height, cm	123.7 ± 11.5	125.8 ± 8.5	0.504
Body mass index, kg/m^2	16.5 ± 2.8	15.2 ± 2.4	0.087
Physical activity level, metabolic equivalent hours/week	13.1 ± 12.8	14.7 ± 8.6	0.632
Movement Assessment Battery for Children total impairment score percentile	4.5 ± 8.3	58.3 ± 13.1	< 0.001*
DCD questionnaire total score	46.4 ± 10.8	59.2 ± 8.2	< 0.001*
Cumulative number of falls in the previous week	71	6	< 0.001*
Average number of falls per person in the previous week	2	0	0.001*
Participants reporting falls, n (%)	27 (90%)	5 (25%)	< 0.001*

Note: Means ± standard deviations are presented unless specified otherwise.
*$p < 0.05$.

Table 2. Results from the Limits of Stability Test

	DCD group (*n* = 30)	**Control group (*n* = 20)**	***p* value**	**Effect size**
Reaction time, s				
Forward direction	0.92 ± 0.47	0.94 ± 0.31	0.838	0.001
Backward direction	0.61 ± 0.31	0.71 ± 0.31	0.277	0.025
Right direction	0.83 ± 0.36	0.68 ± 0.26	0.114	0.051
Left direction	0.77 ± 0.31	0.82 ± 0.26	0.606	0.006
Movement velocity, °/s				
Forward direction	4.92 ± 2.56	4.67 ± 2.00	0.715	0.003
Backward direction	4.29 ± 2.20	3.31 ± 1.85	0.108	0.053
Right direction	6.02 ± 2.68	6.61 ± 2.56	0.448	0.012
Left direction	6.35 ± 2.86	6.17 ± 2.65	0.820	0.001
Maximum excursions, %				
Forward direction	97.97 ± 12.89	94.60 ± 11.49	0.350	0.018
Backward direction	67.63 ± 22.81	87.15 ± 20.63	0.003*	0.165
Right direction	100.07 ± 11.60	97.60 ± 13.36	0.492	0.010
Left direction	95.17 ± 16.08	134.65 ± 179.81	0.235	0.029
End point excursions, %				
Forward direction	67.10 ± 28.67	80.50 ± 20.09	0.076	0.064
Backward direction	59.63 ± 25.62	46.20 ± 18.04	0.048	0.079
Right direction	77.53 ± 29.52	77.80 ± 21.04	0.972	< 0.001
Left direction	80.73 ± 25.51	78.00 ± 14.08	0.665	0.004
Directional control, %				
Forward direction	78.97 ± 16.44	81.70 ± 9.14	0.503	0.009
Backward direction	49.13 ± 23.95	58.95 ± 19.19	0.132	0.047
Right direction	99.00 ± 125.13	74.85 ± 8.55	0.395	0.015

Left direction	74.83 ± 13.32	79.50 ± 10.88	0.199	0.034

Note: Means ± standard deviations are presented.
*$p < 0.0125$ (Bonferroni adjusted).

Figure

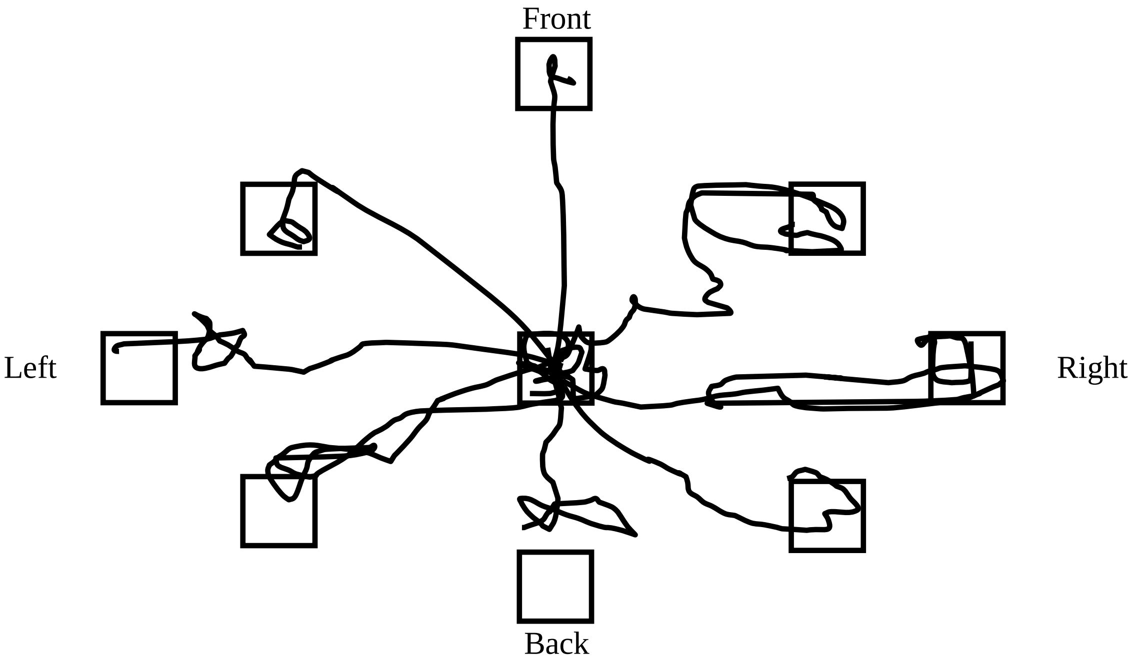

Figure 1. Trajectories of the center of pressure (COP) of a participant during the limits of stability test moving the COP from a central square (representing COP in erect standing) to target squares in eight different directions (representing 100% limits of stability).