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Anticipatory postural adjustment deficits in children with developmental coordination disorder during a self-induced prehension task while standing on one leg

Ludvík Valtr[1]✉, Lucia Bizovská[1], Reza Abdollahipour[1], Dorothee Jelsma[2], Peter Wilson[1,3] & Bouwien Smits-Engelsman[4,5]

Effective postural control is essential for motor skill development, yet the specific nature of anticipatory control in children with Developmental Coordination Disorder (DCD) remains poorly understood for complex or dynamic stability tasks. This study investigated *anticipatory postural adjustments* (APA) during a self-initiated dynamic stability task. The Can Placement Task (CPT)—a self-initiated dynamic stability task—was performed by 23 children with DCD and 30 typically developing (TD) children aged 9–12 years. The task involved standing on one leg while also repositioning a can on the floor. Center of pressure (COP) movement was recorded by two force platforms during the five phases of the movement. The ground reaction force measured external support during both descent to pick up the can and ascent after replacing the can. The study used a mixed-design approach with group (DCD, TD) as a between-subject factor and condition (can position close or far) and phase of movement as within-subject. Distinct movement control characteristics were shown for children with DCD including a greater range of COP movement and higher COP velocity in the anterior-posterior direction prior to movement initiation compared with TD. The DCD group also relied more on external support during both the downward and upward phases of the CPT and needed more trials to complete the task. Only two significant interaction effects involving Group and the within-subject factors emerged. Children with DCD swayed significantly more at specific phases of the task, especially when coming up and restoring balance, and did not adapt COP velocity as a function of reaching distance. Dynamic control of posture in children with DCD is impaired as they struggle to generate the effective APAs necessary to maintain dynamic stability which leads to greater reliance on external support and more corrective movements. The CPT provides a valuable assessment of posture and dynamic balance control during a complex prehension movement performed on one leg; the task highlights distinct movement patterns between children with and without DCD.

Keywords Children, Developmental coordination disorder, Force-plate, One-leg stance, APA

Abbreviations

ADHD	Attention deficit/hyperactivity disorder
ANOVA	Analysis of variance
AP	Anterior–posterior

[1]Department of Natural Sciences in Kinanthropology, Faculty of Physical Culture, Palacký University Olomouc, Olomouc, Czech Republic. [2]Clinical and Developmental Neuropsychology, University of Groningen, Groningen, The Netherlands. [3]Healthy Brain and Mind Research Centre, Australian Catholic University, Melbourne, VIC, Australia. [4]Division of Physiotherapy, Department of Health and Rehabilitation Sciences, Faculty of Health Sciences, University of Cape Town, Cape Town, South Africa. [5]Physical Activity, Sport and Recreation, Faculty Health Sciences, North-West University, Potchefstroom, South Africa. ✉email: ludvik.valtr@upol.cz

APA	Anticipatory postural adjustments
COP	Center of pressure
CPT	Can placement task
DCD	Developmental coordination disorder
GRF	Ground reaction force
MABC-2	Movement assessment battery for children, second edition
ML	Medio lateral
TD	Typically developing
TTS	Total test score

Developmental coordination disorder (DCD) is defined by characteristic differences in motor control that diverge substantially from typical development[1] and tend to co-occur with other neurodevelopmental disorders. When these behaviours interfere with the performance of everyday activities, academic achievement or participation in sport and leisure, a diagnosis of DCD is given[1]. DCD is also often called a motor learning disorder because the acquisition of new skills seems to be either impaired or delayed. While the precise specification of underlying deficits remains an issue of ongoing investigation, poor postural control is commonly reported in DCD, with reduced anticipatory (or feedforward) control a likely cause[2].

It has been hypothesised that the performance difficulties that characterise children with DCD may be explained in motor control terms by disruptions to the forward modeling process resulting in heightened dependence on delayed visual feedback[3–5]. This is termed the internal modeling deficit (IMD) hypothesis[5]. A forward model relies on two core processes: prediction and error processing[6]. Feedforward loops predict the effect of motor commands on the moving body and use these forward models as a template for rapid error correction via feedback loops[7]. Proprioceptive feedback is processed more rapidly by the central nervous system than visual but has been reported to be less optimal in children with DCD. For sensory afference to be processed, there is always a lag between the actual state of the motor effectors and how this state is perceived by the central nervous system[6,8,9]. If corrective responses are delayed when a performer reaches the limits of stability, the neuromuscular correction signal will have to be larger or may arrive too late to correct the on-going movement to restore balance. This can manifest as stumbles, falls and trips, all characteristics of movement clumsiness seen in children with DCD.

It is well accepted that maintenance of balance and posture during voluntary movement requires anticipatory motor control[10,11]. Underlying these anticipatory postural adjustments (APA) are feedforward commands designed to minimize the balance disturbances caused by ensuing movement[12,13]. As such, APA occur before any disruption to posture/equilibrium from the movement itself[11]—i.e., APA arise from internal commands rather than external inputs. Importantly, when one attempts to maintain balance during voluntary movement or in response to predictable perturbations (like an imminent external force), APA are initiated which, in turn, displace the center of pressure (COP) so as to position the body more optimally over the course of movement. Better anticipatory control will lead to smoother movements with reduced COP oscillations[14]. However, with less efficient anticipatory control, COP path length increases. In such cases, the person either loses balance and falls, or must execute reactive corrective movements to avoid a fall. These compensatory movements are typically associated with increased COP velocity in order to regain stability. In short, the presence of larger COP path lengths and increased COP velocity indicate poorer anticipatory control, reflecting an inability to adequately prepare for or stabilize against movement-related balance challenges.

While children with DCD are known to have difficulties in postural control, current clinical tests lack precision and do not allow researchers nor clinicians to make informed inferences about underlying mechanisms that may be impaired. Indeed, standing on one leg remains the most common clinical balance test in motor test batteries[15–17]. More specifically, simple measures of this type do not discriminate between the main forms of neuromuscular control - reactive, anticipatory, and online, for instance. Postural adjustments can be studied more systematically by using external perturbations, reactive balance, and self-induced movements that enlist predictive adjustments. Of the latter, by anticipating the expected perturbation, self-induced movements bypass perceptual delays, enabling adaptation before the perturbation occurs[18]. A growing body of evidence suggests that the motor organization of reactive responses[19] and APA are dysfunctional in children with DCD[2,20–22]. Anticipatory control mechanisms are critical in preparing the body for upcoming perturbations[17,23], highlighting the necessity for a balance assessment that measures both functional performance and anticipatory postural control in response to perturbations.

Self-initiated perturbation tasks are very well suited to test the hypothesis that children with DCD are less able to predict their movements and associated postural adjustments. Previous research has relied mainly on EMG methods to identify APA by analysing muscle activity patterns and their timing relative to movement initiation. The few studies that have explored anticipatory postural control in DCD have revealed delayed APA in a number of tasks contexts: self-induced arm movements from a standing position[23], kicking a ball[21], stepping onto a step[21], and standing on one foot[21]. For more information, see also the meta-analytic reviews by Wilson et al.[24], Smits-Engelsman et al.[25] and Subara-Zukic et al.[26].

COP displacements have been also used to infer the presence and effectiveness of APA during gait initiation and, therefore, the integrity of feedforward (or predictive) motor control[27,28]. Effective predictive control is evidenced by smooth and minimal COP deviations, showing that (fast) internal feedback is being used to maintain balance via ongoing postural adjustments. Larger or erratic COP deviations during movement execution suggest that the performer is relying more on slower forms of feedback to correct balance disturbances as they occur—this mode of control shows poor predictive control, known as IMD[24].

One intriguing hypothesis is that reduced postural control and stability in DCD may arise as a consequence of impaired utilization of vestibular feedback[29]. Unlike standing upright and stationary on one leg, where vestibular feedback would play a negligible role, stooping tasks require integration of somatosensory and visual with additional vestibular feedback in order to maintain postural stability. Indeed, performance of this task, given its complexity, will involve multiple levels of control. While muscular strength is an obvious constraint when performing a single-leg stance, multi-sensory integration, and anticipatory motor control are critical to the maintenance of dynamic stability—where the centre of mass is moving—over a single base of support. Therefore, a precise assessment of dynamic stability during a self-induced perturbation task can provide vital information about the way the task is controlled and factors that influence performance.

In a newly developed test for motor skill-related fitness (PERF-FIT), we introduced the Can Placement Task (CPT) to test dynamic stability (see Fig. 1). The task consists of a self-timed movement that induces large shifts in COP and loss of balance if not performed under finely-tuned anticipatory control. In the original PERF-FIT CPT, subjects are asked to stoop forward, pick up a can positioned in front of the foot and move it either away or closer to their front foot while standing on one leg. The stability limits encountered during a stooping movement are very different from one leg standing which makes the former more resistant to ceiling effects seen on many clinical balance tests[30,31]. When a forward trunk movement is performed by a standing child, the geometry of the body is changed and, with it, the center of gravity is displaced on the force plate. Because this movement is initiated by internal forces resulting from muscle contraction, children learn to anticipate the magnitude of the forces after many repetitions—a process of (learned) internal modeling. That is, displacement of the center of gravity is gradually reduced as the performer learns to generate "anticipatory" forces in the direction opposite to the reaction forces associated with forward trunk movement; this serves to minimize the postural disturbance caused by the movement, especially when anticipatory movements are initiated earlier[32–34].

The purpose of our study was to investigate APA in DCD during a self-initiated dynamic stability task. More specifically, our primary aim was to use a novel one-leg dynamic stability task to examine the COP profiles of children with DCD compared with TD using the CPT, tested under different reach distance conditions and examined over five phases of movement. We hypothesized larger oscillations in COP in the DCD group, specifically larger displacement (COP path length and movement range) and more corrections (COP velocity) when performing the placement action. Our secondary (and related) aim was to explore group differences in the control of forces on the can during relocation, focusing on external support during both the descent and ascent. We predicted that children with DCD would exert greater leaning forces on the can while picking it up and putting it down, suggesting poor anticipatory control during the final phase of the stooping movement and initial relocation of the can.

Methods

Subjects

Participants were 59 children aged 9–12 years of age from four elementary schools, 53 of whom were included in the analysis (see Fig. 2). Informed consent was signed by the parents or legal guardians of the children and oral assent was provided by each child. Demographic and clinical descriptions of the TD and DCD groups are shown in Table 1. Purposive sampling was used to select participants who met specific criteria relevant to the study. Children were classified as DCD according to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5-TR)[1]. Children were screened using the Movement Assessment Battery for Children, Second Edition (MABC-2)[35] and a cut-off score of below the 16th percentile (Criterion A). The test was administered by six examiners who were certificated and experienced users of this method. The impact of motor coordination difficulties on daily activities and academic performance (Criterion B) was evaluated by teachers using the MABC-2 checklist[35] with the 16th percentile as cut-off scores. School psychologists provided an evaluation of Criterion C and D. Among the 23 children diagnosed with DCD, three of them also had Attention Deficit / Hyperactivity Disorder (ADHD), and in two cases, ADHD co-occurred with a comorbid Learning Disability.

Experimental procedure

For the purpose of this study, we used an adaptation of the PERF-FIT[36] item where a single can was moved instead of four on the clinical test. The PERF-FIT test battery (including CPT) has shown good-to-excellent inter-rater reliability and test-retest reliability when testing children[37]. Each movement trial had five phases: (I)

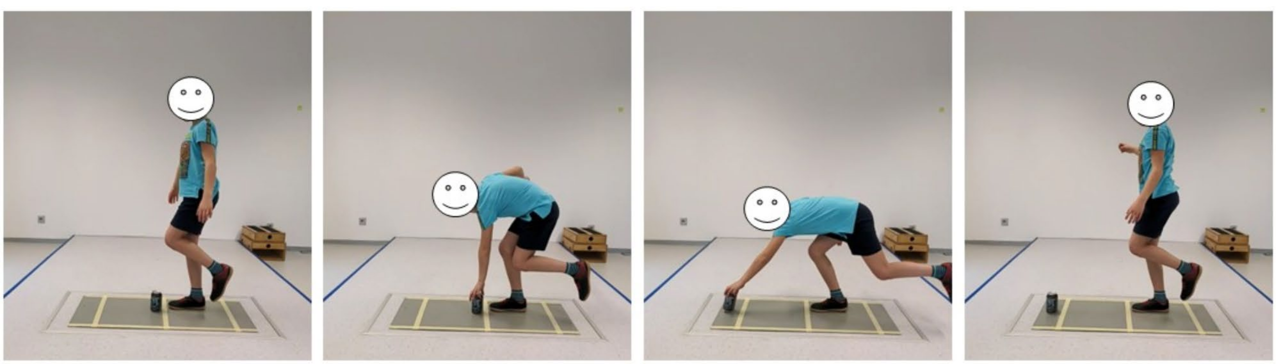

Fig. 1. Performance of the can task in "further" condition.

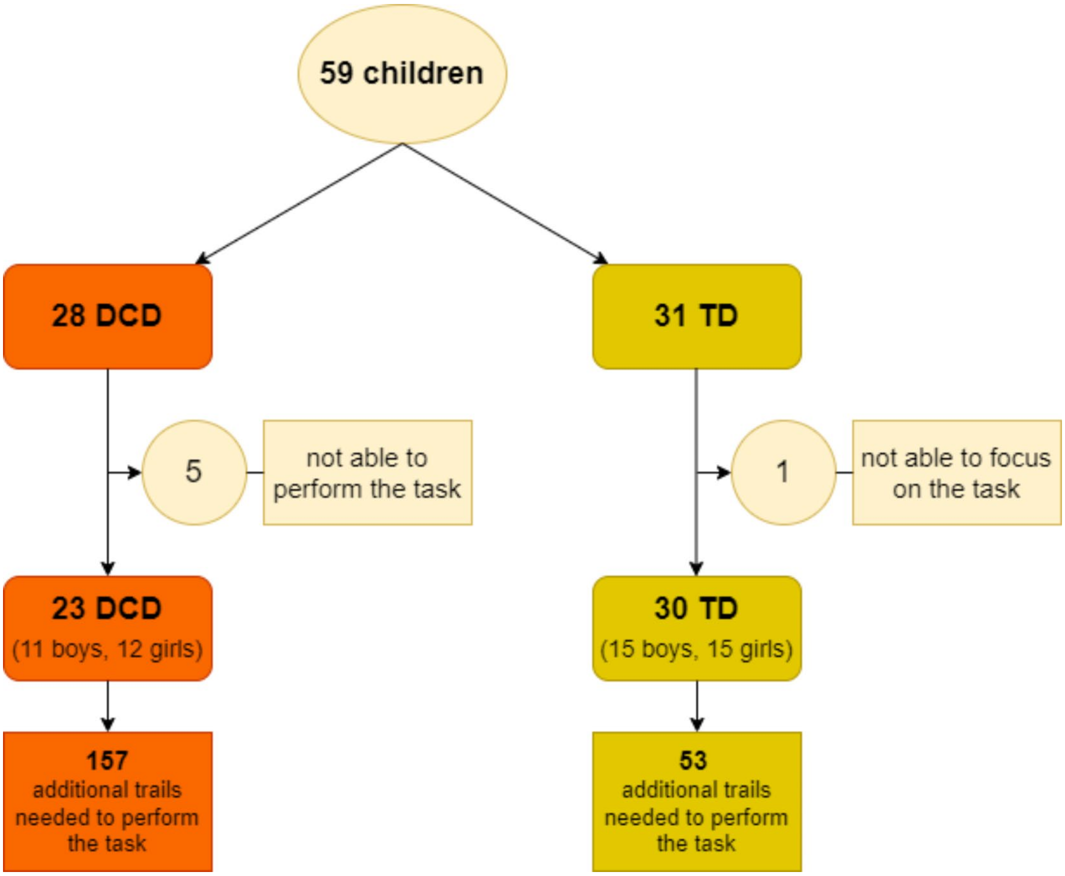

Fig. 2. Flow chart of experimental design.

	TD	DCD	p
n participants (boys)	30 (15)	23 (11)	
Age (years)	10.2 ± 1.0	9.8 ± 1.4	0.163
Weight (kg)	39.4 ± 10.4	37.4 ± 11.8	0.254
Height (cm)	147.0 ± 8.1	143.8 ± 11.2	0.236
MABC-2 TTS	83.3 ± 7.3	61.5 ± 8.4	< 0.0001
Balance score	30.5 ± 2.4	24.0 ± 5.0	< 0.001
Extra trials	1.6 ± 1.9	6.8 ± 5.8	< 0.001

Table 1. Participants data. $p = p$ value of Mann-Whitney U test for Age, Weight, MABC-2 Total Test Score, Balance score and Extra trials. For Height t-test was used.

initial quiet stance (fixed time interval of 3 s), (II) stooping down and taking the can off the platform, (III) the can being moved (no contact of a can with the force platform), (IV) putting the can down and straightening up, (V) final quiet stance (fixed time interval of 3 s) (see example in Fig. 1). No instruction was given about the swinging lower limb, except that it was not allowed to touch the floor or the other lower limb. The upper limbs were free and relaxed. Participants were provided with a number of familiarization trials until they successfully completed one trial for each leg. Two types of can movement were used: (a) with initial position of the can in front of the standing line with the instruction to move the can behind a second line positioned parallel 35 cm ahead of the standing line ("further" condition) (Fig. 1) and (b) with initial position of the can on the far side of the second line with the instruction to move the can back in front of the standing line ("close" condition). Three successful repetitions of each type of can movement were performed for each supporting leg (left or right), resulting in a total of 12 trials. The order of starting leg was randomized.

Data acquisition and analysis

Two force platforms (AMTI OR6-5, Advanced Mechanical Technology, Inc., Watertown, MA, USA, sampling rate 200 Hz) were used for the recording of the ground reaction force (GRF) and COP movement. GRF and COP data were filtered using a 4th order bidirectional low-pass Butterworth filter with the cut-off frequency of 10 Hz.

For precise detection of phases of movement, participants stood on one platform, a can was placed on the other one (Fig. 1, yellow line in the middle represents the border between platforms). Five abovementioned phases of movement were recognised based on the behaviour of the vertical component of GRF recorded with the platform a can was placed on (Fig. 3). Phase III was identified as a period during which a force value less than 0 N was observed. Total path length of the COP movement, COP movement range in anterior-posterior (AP) and mediolateral (ML) directions and mean COP velocity in both directions were computed for the COP movement recorded by the platform the child was standing on[38,39] during all five phases of movement. Furthermore, in phases II and IV, maximum values of vertical component of GRF of the plate with can, which measured external support during both descent to pick up the can and ascent after replacing the can, were computed. Duration of each phase was also recorded. Phase identification and computation of resulting variables was performed in Matlab (R2022b, MathWorks, Inc., Natick, MA, USA).

Statistical analysis

Firstly, the normality and homogeneity of the data were verified by the Shapiro-Wilk test and the Levene test, respectively. To test possible differences between groups, the *t*-test was performed on age, weight, MABC-2 Total test score (TTS), Balance standard scores, and number of extra trials needed to perform the task (Gaussian distribution of data, Shapiro-Wilk test, $p > 0.05$). Mann-Whitney *U* tests were performed on height (no Gaussian distribution of data, Shapiro-Wilk test, $p < 0.05$). Statistical analysis was performed using a mixed-design analysis of variance (ANOVA) with groups (TD vs. DCD) as a between-subject factor and conditions (far vs. close) and phase of movement as within-subjects factors. For GRF data, a mixed-design ANOVA with Group (TD vs. DCD) as a between-subject factor and condition (far vs. close) and phase of movement (II vs. IV) as within-subjects factors. Mauchly's test was used to check the sphericity assumption. Greenhouse-Geisser corrections were applied to adjust the degrees of freedom, when needed. Bonferroni adjustments were employed for all pairwise post hoc comparisons. Effect size values for ANOVA were quantified using partial eta squared ($\eta 2$), where $\eta 2$ = 0.01, 0.06, and 0.14 corresponded to a small, moderate, and large effect, respectively[40]. To estimate the effect sizes for post hoc comparisons Cohen's *d* was utilized. The evaluation of Cohen's *d* corresponded to a low ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) effect[40]. The significance level was set at 0.05. In a preliminary analysis not included in this manuscript, a mixed ANOVA was performed that included gender and leg as between-subjects factors. This analysis failed to show significant main or interaction effects that involved gender or leg; therefore, the results of this analysis are not presented here. In the presented analysis, average values of both lower limbs were included.

Results

Diagnostic overview

Of the 23 children diagnosed with DCD, 8 had MABC-2 TTS below the fifth percentile, and 6 with a Balance score below the 5th percentile. Among the 5 DCD children who were unable to perform the task, all showed

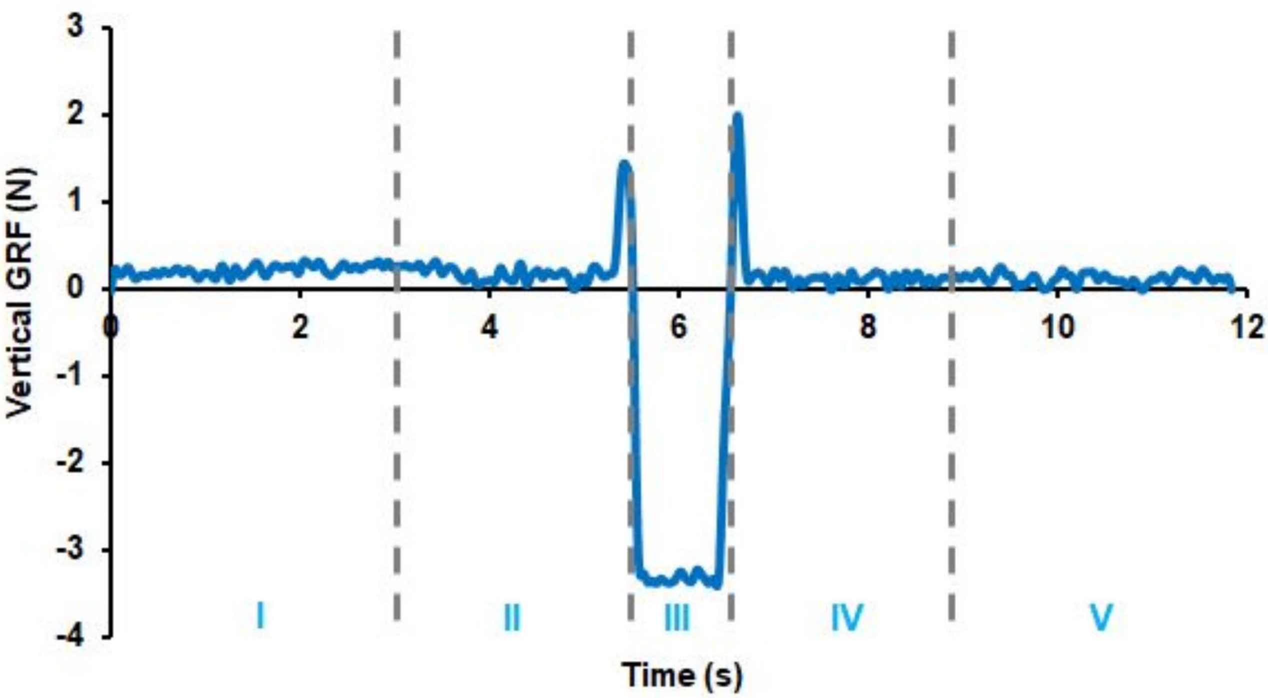

Fig. 3. Definition of the phases of participants' movement (phases I–V) based on the behavior of the vertical component of the ground reaction force (GRF) recorded with the platform a can was placed on.

MABC-2 TTS and Balance scores below the 5th percentile. DCD children also needed significantly more trials to complete the task (Table 1).

The first aim of our study was to examine group differences in COP profiles between children with DCD and TD over the five phases of movement and two conditions of the CPT. It was hypothesized to see larger displacement (COP path length and movement range) and more corrections are needed (COP velocity) for the disturbance by the large trunk movement. The secondary aim of our study was to explore maximum values of vertical component of GRF applied on the can, which measured external descent to pick up the can and ascent after replacing the can.

Mixed-design ANOVA results

Descriptive data and the results of factorial ANOVA are described in Tables 2 and 3.

Group main effect

Individuals with DCD had significantly longer movement paths (Table 3), covering an average distance of 250.4 ± 137.7 mm compared with 219.5 ± 104.8 mm for the TD group. This was also shown by larger movements for DCD in both AP and ML directions: DCD (51.6 ± 22.2 mm and 30.8 ± 8.5 mm in AP and ML respectively) compared with TD (47.8 ± 22.7 mm and 28.8 ± 7.4 mm in AP and ML respectively). Velocity in the AP direction was also significantly larger in DCD (Table 3), with an average of 63.5 ± 28.8 mm s^{-1} compared with 53.9 ± 20.8 mm s^{-1} for TD; the comparison for ML direction was not significantly different. There were no significant effects involving group for movement time of the different phases (Phase II, III, IV). For GRF it was found that children with DCD leaned significantly more on the can both when stooping down to contact the can and then rising off the floor (Table 3): an average GRF of 4.34 ± 4.43 N for DCD children compared with 2.48 ± 2.22 N for TD showing greater reliance on external support during the task.

Interaction effects

Of the seven mixed model analyses, only two that involved group were significant (Table 3). The first, phase x group, was found in the AP range of motion. Simple effects showed that this effect was explained by significant group differences for phase I ($p = 0.049$, d = 0.479), IV ($p = 0.045$, d = 0.365), and V ($p = 0.002$, d = 0.795), indicating that children with DCD did not make larger AP movements compared to TD children when going down (phase II) and leaning (phase III), but swayed more during initial standing (phase I), when coming up (phase IV) and restoring balance to again standing still (phase V). The second was a 3-way interaction (phase x distance x group) on velocity in AP direction. This finding indicated that individuals with DCD used higher velocity than TD in phases I ($p = 0.029$, d = 0.621), III ($p = 0.022$, d = 0.654), IV ($p = 0.012$, d = 0.723) and V ($p = 0.019$, d = 0.673). In TD children velocity in AP direction in close condition was lower (69.30 ± 20.07 mm s^{-1}) relative to further condition (80.20 ± 20.53 mm s^{-1}) during phase III ($p = 0.003$, d = 0.537) indicating that they needed less corrective movements during the movement away from the stance leg. On the other hand, in DCD, the velocity remained consistently high (86.95 ± 20.08 mm s^{-1} in close condition and 86.07 ± 20.54 mm s^{-1} in further condition, $p = 0.823$, d = 0.043) and was not adapted based on the distance to move.

Discussion

Smooth and efficient postural control and balance are the cornerstone of gross-motor skills and their development with age and practice. While balance is often regarded as a general motor ability, recent meta-analyses have revealed that, contrary to previous assumptions, correlations between tasks requiring different control aspects (such as static, dynamic, anticipatory, and reactive) are surprisingly low, indicating that balance control may be task-specific[17,41]. Despite the common use of the one-leg stance test as a standard measure of balance, real-life scenarios seldom involve the maintenance of static one-legged postures, but rather demand seamless transitions between different stances. It is well established that children with DCD perform poorly on balance tasks, but less is known about the impact of self-induced movements requiring APAs and whether expected CoP shifts differ when standing on one leg. If unilateral balance is not well developed, demand on both the anticipatory and reactive control system increases[42]. This assertion was confirmed in our study by group differences in AP movement during phases I and V, indicating significant difficulties for children with DCD in maintaining stability at the beginning and completion of the movement (Table 3). Particularly in phase I, which involves preparation for stooping down and primarily engages APA, group differences in range of motion and COP velocity in AP direction show that children with DCD have difficulty generating effective APA[14], which are crucial for initiating the stooping movement. Another indication of deficient control of APAs in DCD was observed in the GRF results that revealed that the DCD children leaned more heavily on the can during descent and ascent compared with TD (DCD 4.34 ± 4.43 N; TD 2.48 ± 2.22 N; $p = 0.002$). This suggests that by leaning on the can, children with DCD either extend the base of support, compensating for poor counter movements in the rest of the body, or do not slow down adequately in descent. Furthermore, extending their base of support can complicate the process of regaining an optimal posture, particularly if their COP is not correctly aligned over their foot area of support[43]. This poorly controlled stooping movement –further away from the optimal "minimal movement of COP"—may result in a posture from which it is much harder to recover and initiate subsequent movements effectively. Finally, the challenges of the CPT for children with DCD were also shown by a higher number of additional trials to complete the task compared with TD children (DCD 6.8 ± 5.8; TD 1.6 ± 1.9; $p < 0.001$). Indeed, five of our original sample of 28 children with DCD were unable to complete the task at all.

Leaning forward and returning to an upright posture while maintaining balance on one-leg requires not only adequate postural control and dynamic stability but also strength. While the child maintains equilibrium before and after stooping, they must actively counterbalance any tendency to topple during forward or upward

Variable	Group	"Close" condition					"Further" condition				
		Phase					Phase				
		I	II	III	IV	V	I	II	III	IV	V
Duration (s)*	DCD		3.55 ± 1.14	1.21 ± 0.47	3.84 ± 0.60			3.24 ± 1.04	1.21 ± 0.31	4.02 ± 0.49	
	TD		3.26 ± 0.70	1.31 ± 0.32	4.01 ± 0.62			2.90 ± 0.55	1.21 ± 0.29	4.01 ± 0.43	
Path length (mm)	DCD	176.63 ± 58.86	353.96 ± 97.13	148.14 ± 60.01	404.74 ± 130.87	178.33 ± 73.58	191.42 ± 67.82	304.77 ± 96.49	140.40 ± 25.84	428.12 ± 79.85	177.76 ± 73.47
	TD	152.37 ± 31.30	298.25 ± 69.26	136.31 ± 29.20	352.76 ± 75.71	147.51 ± 34.71	161.37 ± 30.36	269.64 ± 51.19	141.36 ± 28.27	388.29 ± 68.66	146.90 ± 30.73
Range AP (mm)	DCD	29.27 ± 7.58	75.29 ± 14.29	46.90 ± 12.68	65.07 ± 18.79	34.37 ± 10.99	33.71 ± 11.33	56.94 ± 7.96	50.69 ± 11.38	87.26 ± 13.49	36.43 ± 12.95
	TD	28.07 ± 6.38	79.79 ± 14.20	43.27 ± 10.60	57.71 ± 10.91	28.38 ± 10.28	27.18 ± 5.88	60.03 ± 12.79	46.16 ± 10.17	81.05 ± 15.42	26.22 ± 5.71
Range ML (mm)	DCD	24.43 ± 4.35	34.84 ± 4.02	29.70 ± 5.44	42.04 ± 12.44	26.34 ± 5.95	24.60 ± 4.73	33.10 ± 5.36	28.53 ± 4.27	39.46 ± 3.97	24.62 ± 5.92
	TD	21.82 ± 4.02	32.87 ± 4.28	29.11 ± 4.63	37.08 ± 5.28	23.19 ± 4.13	21.86 ± 4.33	31.55 ± 4.29	28.78 ± 3.97	38.63 ± 5.35	22.89 ± 4.18
Velocity AP (mm s^{-1})	DCD	38.35 ± 13.55	73.45 ± 13.39	86.95 ± 26.92	77.25 ± 34.22	41.31 ± 21.84	43.12 ± 17.89	67.75 ± 10.66	86.07 ± 23.21	78.72 ± 28.38	42.04 ± 20.34
	TD	33.02 ± 7.43	66.56 ± 13.11	69.27 ± 12.61	60.66 ± 9.16	32.43 ± 9.94	34.66 ± 6.59	64.59 ± 11.62	80.21 ± 18.25	65.58 ± 9.43	32.22 ± 7.48
Velocity ML (mm s^{-1})	DCD	35.70 ± 11.11	56.85 ± 9.40	70.07 ± 11.69	57.20 ± 8.79	32.73 ± 7.69	37.75 ± 9.15	54.76 ± 9.30	69.99 ± 12.36	58.35 ± 8.81	33.38 ± 9.98
	TD	31.41 ± 6.52	51.70 ± 8.04	67.57 ± 13.07	52.58 ± 7.35	29.38 ± 5.88	33.65 ± 8.15	51.81 ± 8.86	72.30 ± 14.44	57.80 ± 8.20	29.65 ± 6.62
Max GRF absolute (N)	DCD		4.28 ± 3.86		4.02 ± 5.34			4.70 ± 4.27		4.38 ± 4.51	
	TD		2.29 ± 1.85		2.14 ± 2.10			3.29 ± 3.13		2.19 ± 1.38	

Table 2. Descriptive statistics (presented as a mean ± standard deviation) of the force plate variables in the close and further condition. *AP* anterior-posterior, *ML* = Mediolateral, *GRF* ground reaction force. *Time in phase I and V was always 3 s.

Variable	Group	Phase	Condition	Phase × group	Condition × group	Phase × condition	Phase × condition × group
Time	$F(1, 53)=0.331$, $p=0.568$, η2 = 0.006	**$F(2, 53)=368.57$, $p<0.001$, η2 = 0.878**	**$F(1, 53)=6.996$, $p=0.011$, η2 = 0.121**	$F(2, 53)=2.234$, $p=0.112$, η2 = 0.042	$F(1, 53)=2.309$, $p=0.135$, η2 = 0.043	**$F(2, 53)=15.415$, $p<0.001$, η2 = 0.232**	$F(2, 53)=0.337$, $p=0.715$, η2 = 0.007
Path length	**$F(1, 53)=9.133$, $p=.004$, η2 = 0.152**	**$F(4, 53)=278.885$, $p<0.001$, η2 = 0.845**	$F(1, 53)=0.001$, $p=0.981$, η2 = 0.000	$F(4, 53)=1.583$, $p=0.180$, η2 = 0.030	$F(1, 53)=0.880$, $p=0.353$, η2 = 0.017	**$F(4, 53)=8.401$, $p<0.001$, η2 = 0.141**	$F(4, 53)=0.377$, $p=0.825$, η2 = 0.007
Range AP	**$F(1, 53)=4.742$, $p=0.034$, η2 = 0.085**	**$F(4, 53)=332.842$, $p<0.001$, η2 = 0.867**	**$F(1, 53)=4.982$, $p=0.030$, η2 = 0.089**	**$F(4, 53)=4.378$, $p=0.002$, η2 = 0.079**	$F(1, 53)=1.851$, $p=0.180$, η2 = 0.035	**$F(4, 53)=66.254$, $p<0.001$, η2 = 0.565**	$F(4, 53)=0.517$, $p=0.723$, η2 = 0.010
Range ML	**$F(1, 53)=7.140$, $p=0.010$, η2 = 0.123**	**$F(4, 53)=167.929$, $p<0.001$, η2 = 0.767**	$F(1, 53)=3.017$, $p=0.088$, η2 = 0.056	$F(4, 53)=1.152$, $p=0.333$, η2 = 0.022	$F(1, 53)=2.445$, $p=0.124$, η2 = 0.046	$F(4, 53)=0.546$, $p=0.702$, η2 = 0.011	$F(4, 53)=1.021$, $p=0.397$, η2 = 0.020
Velocity AP	**$F(1, 53)=8.158$, $p=0.006$, η2 = 0.138**	**$F(4, 53)=185.537$, $p<0.001$, η2 = 0.784**	$F(1, 53)=3.291$, $p=0.076$, η2 = 0.061	$F(4, 53)=1.721$, $p=0.147$, η2 = 0.033	$F(1, 53)=2.967$, $p=0.091$, η2 = 0.055	**$F(4, 53)=3.693$, $p=0.006$, η2 = 0.068**	**$F(4, 53)=2.525$, $p=0.042$, η2 = 0.047**
Velocity ML	$F(1, 53)=2.761$, $p=0.103$, η2 = 0.051	**$F(4, 53)=359.016$, $p<0.001$, η2 = 0.876**	**$F(1, 53)=4.361$, $p=0.042$, η2 = 0.079**	$F(4, 53)=0.982$, $p=0.418$, η2 = 0.019	$F(1, 53)=2.559$, $p=0.116$, η2 = 0.048	$F(4, 53)=2.071$, $p=0.086$, η2 = 0.039	$F(4, 53)=0.972$, $p=0.424$, η2 = 0.019
Max GRF absolute	**$F(1, 53)=7.955$, $p=0.007$, η2 = 0.135**	$F(1, 53)=1.357$, $p<0.249$, η2 = 0.026	$F(1, 53)=1.430$, $p=0.237$, η2 = 0.027	$F(1, 53)=0.194$, $p=0.661$, η2 = 0.004	$F(1, 53)=0.032$, $p=0.858$, η2 = 0.001	$F(1, 53)=0.426$, $p=0.517$, η2 = 0.008	$F(4, 53)=0.325$, $p=0.571$, η2 = 0.006

Table 3. Results of mixed ANOVA. *AP* anterior-posterior, *ML* mediolateral, *GRF* ground reaction force. Significant results with p values smaller than 0.05 are in boldface.

movements. Moving forward primarily involves an eccentric contraction of the extensor chain, whereas returning up requires the application of greater force due to gravity, making the timing of the contraction crucial[44].

The increased dependence on (slower) external forms of sensory feedback can be attributed to several underlying factors related to atypical neuromuscular processes that have been documented in DCD. Specifically, children with DCD show atypical central nervous system structures and functions[2,45], multisensory integration difficulties, poor predictive control, and inefficient recruitment of postural muscles[46]. Furthermore, they often experience slower muscle force generation[47] and have lower maximum muscle strength in their lower extremities[48,49]. The combination of these factors appear to necessitate greater reliance on slower forms of feedback control which result in higher COP velocity and more frequent corrections in the AP direction. In essence, this aberrant pattern of performance is a consequence of poor predictive motor control, combined with reduced and less fine-tuned force generation[50].

A specific neuromuscular factor that may contribute to reduced control of the body during stooping is low muscle force production of the hip extensors. In instances where the hamstring muscles, the main hip extensors, fail to generate sufficient eccentric force to control the forward movement of the trunk during stooping, excessive force may be applied to the can, as seen in DCD. Other neuromuscular factors include less stability in muscle force production by the legs[51,52], lower knee muscle peak force[53], increased knee flexor and extensor coactivation[54], and prolonged activation or co-contraction of ankle muscles during standing[15].

In cases where muscles do not generate adequate force during return to an upright position, or when the COP is too far forwards, children with DCD push against the can to initiate take-off. This compensatory action would be necessary to help overcome lower propulsive muscle force during initiation of the upward/return movement to an upright position. However, it is likely that the child may then require additional adjustments to control the upright, stabilising phase. By comparison, TD children can anticipate the force and timing needed in the forward movement in order to brake on time just before contacting the can, landing their hand smoothly on it.

Acting in synergy with lower limb muscles, muscles of the trunk also play a significant role in the stooping task; however, the latter tend to be activated less effectively in children with DCD[23,55], perhaps linked to reduced anticipatory control[24,26]. An internal model should anticipate and minimize postural disturbance by generating anticipatory forces that oppose reactive forces that arise from movement. In children with DCD, impaired anticipatory control may explain their tendency to lean more on external support and their increased AP COP velocity which reflects the need for corrective movements during both leaning and rising. In essence, while able to use APA, children with DCD appear to enlist them less frequently and less accurately than their TD peers on the CPT task[55], which impacts postural stability.

Children with DCD often appeared to almost fall forward when stooping when what was required was the smooth application of braking force before contacting the can with their hand, a function of predictive motor control. It would be useful to explore more fully the hypothesis that the primary issue for DCD lies in managing braking forces when descending, and even ascending. More specifically, during ascent, children with DCD may have difficulty controlling the force applied to the can that initiates upward movement, perhaps creating further difficulties when breaking this force to restore balance in upright stance.

When children with DCD return to an upright posture on one leg, which requires a propulsive force to initiate movement, they showed more sway in the AP direction to regain balance because the COP was further forward. An extended time delay in the neuromuscular system, typically spanning from 100 to 300 ms, amplifies sway appreciably by modulating proprioceptive or vestibular/visual gain[42]. This delay hinders the body's ability to promptly adjust to balance perturbations, leading to increased instability. Therefore, achieving balance requires individuals to precisely adjust their intrinsic neuromuscular time delay and feedback gains.

In TD children, movement of the can towards the stance leg saw fewer corrections than the movement away from the stance leg, unlike children with DCD who needed a high number of corrective responses, regardless of direction. This pattern is consistent with other work showing higher COP velocity in DCD and more corrective movements to reach a desired goal position, as observed in a Y-Balance[56] and fine-motor task[57]. This movement pattern is more ballistic-like—rapid movements without adequate control, reflecting their motor coordination difficulties.

Limitations

Given the nature of the CPT, drawing precise distinctions between APA and closed-loop control remains challenging. Both mechanisms contribute to the observed postural adjustments, with APA preparing the body for movement and closed-loop control ensuring ongoing stability. Furthermore, our analysis only included trials that children with DCD were able to complete successfully. This may have influenced our results because those trials excluded may reflect a level of disruption to motor control not seen in the analyzed data. Put another way, excluded trials may better be viewed as "clumsy behaviour", the very thing we set out to investigate. This is an issue for future enquiry.

Conclusions

Our results showed that children with DCD have difficulties in APA, as evidenced by larger movements and higher COP velocities in the AP direction prior to movement initiation and during leaning, ascent, and restoring upright balance. These findings suggest that children with DCD struggle to generate the effective APA necessary to initiate and maintain stability during the dynamic stability task (viz. CPT), leading to greater reliance on external support and more corrective movements. These findings show that the CPT may offer a valuable assessment of the control of posture and balance in children with and without DCD, specifically of the intricate movements involved in stoop-to-reach while maintaining a static base of support. The CPT has strong ecological validity, replicating many real-life situations where individuals must dynamically adapt their posture and COP during functional movements. Incorporating CPT into clinical assessments may improve diagnostic sensitivity and specificity, and help tailor interventions that aim to improve manual handling skills crucial for daily living.

Data availability

The datasets presented in this article are not readily available because of Human Subjects' protections. Requests to access the data sets should be directed to LV, ludvik.valtr@upol.cz.

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Author contributions

LV, LB, and BS: conceptualization, methodology, project administration, and visualization. LV, LB, and BS: formal analysis. PW and BS: supervision. LV, LB, and BS: interpretation of results. LV, LB, RA, DJ, PW, and BS: data curation, investigation, drafting, and review and editing. All authors contributed to the article and approved the submitted version.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The study was approved by the Ethical Committee of the Faculty of Physical Culture, Palacký University Olomouc (FTK 46/2020), and participating schools. Informed consent for publication of identifying images in an online open-access publication was signed by the parents or legal guardians of the children and oral assent was provided by child. All experiments were performed in accordance with relevant guidelines and regulations.

Additional information

Correspondence and requests for materials should be addressed to L.V.