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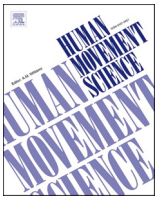

Interlimb coordination and spatiotemporal variability during walking and running in children with developmental coordination disorder and typically developing children

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ABSTRACT

Background: A different interlimb coordination and higher variability in movement patterns is evident in children with Developmental Coordination Disorder (DCD). The impact of DCD on interlimb coordination during walking and running is unknown.
Aim: To assess interlimb coordination and spatiotemporal variability during overground walking and running in children with and without DCD.
Methods: Children with DCD and typically developing children (TDC), from 8 to 12 years participated. Children were equipped with portable sensors. Participants walked and ran for 3 min in an oval-path at their comfortable pace. Interlimb coordination, expressed by the phase coordination index (PCI), and spatiotemporal variability (coefficient of variance (CoV)) were collected.
Results: Twenty-one children with DCD and 23 TDC participated. During walking, PCI showed similar values in both groups, but a higher spatiotemporal variability was observed in children with DCD. During running, PCI was higher (reduced coordination) in children with DCD than TDC and a higher spatiotemporal variability was shown.
Conclusions and implications: Only during running, interlimb coordination of children with DCD was lower than TDC. During both walking and running tasks, spatiotemporal variability was higher in DCD. Current results implicate that difficulties in children with DCD is more prominent when motor coordination is more challenged.
What this paper adds: This paper adds to the literature on coordination and gait pattern in children with Developmental Coordination Disorder (DCD) through a cross-sectional analysis of interlimb coordination and variability of spatiotemporal measures of overground walking and running. Overground walking and running were performed in a large oval-path allowing the assessment of coordination and gait patterns in an ecological valid set-up. Our results indicate that during a more demanding task, namely running, children with DCD display a less coordinated running pattern, expressed by a significantly higher phase coordination index, than typically developing peers. During walking, the interlimb coordination was similar between both groups. The current result is in accordance with the hybrid model of DCD that states that motor coordination difficulties in DCD are dpendent on the interaction of the task, individual and environment. This

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highlights the importance of implementing running assessments in children with DCD and the need for task-oriented running training in clinical practice The study also supports previous findings that children with DCD show a higher variability in their gait pattern of both walking and running, expressed by higher coefficient of variance of spatiotemporal measures, than typically developing peers. Further understanding in the normal development of interlimb coordination during walking and running from childhood into adulthood will enhance interpretations of the phase coordination index in children with and without DCD.

1. Introduction

Developmental Coordination Disorder (DCD) is a chronic neurodevelopmental disorder with a prevalence of approximately 6% in school-aged children (Blank et al., 2019). The presentation and severity of DCD is heterogenous (Vaivre-Douret, 2014). Individuals with DCD exhibit deficits in different aspects of motor performance, postural and motor control (Subara-Zukic et al., 2022; Verbecque et al., 2021). For example, movement skills requiring timing and coordination, like running or catching a ball, are impaired (Asmussen, Przysucha, & Zerpa, 2014; Baker, 1981; Baldi, Caravale, & Presaghi, 2018; Przysucha & Maraj, 2014). Walking and running are basic fundamental movement skills which are important for proper development of fitness and overall health (Lubans, Morgan, Cliff, Barnett, & Okely, 2010). Most children walk or run every day, for example while playing on a playground or doing sports. Activities such as running, walking, and jumping, which are crucial for overall fitness and health in young children, often pose challenges for those with DCD (Cermak et al., 2015). Specially, the gait pattern of children with DCD is visually described as a 'clumsy' gait pattern and falls are frequently reported (Fong et al., 2016). Children with DCD run slower and have a lower physical function, characterized by a lower cardiorespiratory fitness and lower anaerobic capacity (Diamond, Downs, & Morris, 2014; Rivilis et al., 2011). As a result, individuals with DCD may demonstrate a lower desire to participate in play and sports, including walking or running, thereby reducing their opportunities to develop proficient motor skills and attain adequate fitness levels (Yu, Capio, Abernethy, & Sit, 2021).

Walking and running requires continuous and rhythmic coordination of the lower legs in order to execute antiphase left-right steps, to effectively constrain the center of mass within their dynamic base of support during gait (Townsend, 1985). Locomotor coordination specifies this ability to maintain a context and phase dependent cyclic relationship between different body segments and joints in both spatial and temporal domains during gait (walking, running) (Krasovsky & Levin, 2010). Poor coordination can impair the ability to adapt to different environments or sudden disruptions (Krasovsky et al., 2012). This may increase the risk of falls (James et al., 2017) and impose mobility limitations (James et al., 2016). Despite extensive research on age-related changes in gait coordination, there has been limited research into deficits in lower limb coordination specifically during walking and running in DCD. While some evidence suggests lower limb incoordination in DCD during treadmill walking (Rosengren et al., 2009), the impact of DCD on lower limb coordination during overground walking and running remains uncertain.

Different methodologies can be used to assess locomotor coordination, ranging from walking on a treadmill to overground walking as on approach for gait analysis and from high technology gait labs to low cost wearable sensors. Furthermore, there is a broad range of outcome measures that are used to specify locomotor coordination, with a focus on either the spatial or temporal domain of locomotor coordination (Goetschalckx et al., 2021; Krasovsky & Levin, 2010). A promising measure to assess interlimb coordination during walking or running is the phase coordination index (PCI). The PCI quantifies temporal coordination of left-right stepping, and encompasses two subcomponents, namely the accuracy ($P\varphi ABS$) and consistency (φCV) in antiphase generation (M. Plotnik, Giladi, & Hausdorff, 2007). The PCI thus gives a broader view on both the accuracy and variability in temporal gait coordination, which is not feasible with traditional spatiotemporal measures (e.g. velocity, step length, cadence). The PCI can be extracted by wearable sensors. It is a sensitive metric that can differentiate between disease severity in persons with Multiple Sclerosis (M. Plotnik, Wagner, Adusumilli, Gottlieb, & Naismith, 2020) or between different aging groups (Zadik et al., 2022). Previous research focused mainly on the influence of neurological diseases and aging on interlimb coordination in gait and suggested that neurological diseases (e.g. Parkinson's disease, stroke, multiple sclerosis) and aging, contribute to reduced interlimb coordination, as demonstrated by a higher PCI while walking (Patel, Enzastiga, Casamento-Moran, Christou, & Lodha, 2022; M. Plotnik et al., 2020; S. B. Richmond, Swanson, Peterson, & Fling, 2020; Zadik et al., 2022). Interlimb coordination of the lower limbs while walking and running, expressed by the PCI, is not yet reported in children (Goetschalckx et al., 2021).

Until now, research in children with DCD focused on interlimb coordination during finger tapping tasks (Roche, Viswanathan, Clark, & Whitall, 2016; Volman, Laroy, & Jongmans, 2006), or more complex multilimb tasks, such as clapping while jumping and clapping while marching (de Castro Ferracioli, Hiraga, & Pellegrini, 2014; Mackenzie et al., 2008; Whitall et al., 2006). Results suggest that the coordination patterns of children with DCD are characterized by a higher variability in coupling two limbs or multi-limb actions, highlighting the potential of coordination differences between DCD and typically developing peers in a variety of tasks. Surprisingly, the impact of DCD on interlimb coordination of the lower limbs during overground walking and running in children, has been poorly investigated (Goetschalckx et al., 2021).

In terms of walking and running in children with DCD, studies focused mainly on the average spatiotemporal parameters and their variability (coefficient of variation). Although the average spatiotemporal measures during walking are most often studied in DCD, there is only limited research showing that these measures are clearly different between children with DCD compared to their typically developing peers (Smith, Ward, Williams, & Banwell, 2021). In contrast to average spatiotemporal measures, spatiotemporal variability seems to be more sensitive to distinguish children with and without DCD (Smith et al., 2021). Little research in DCD has focused

on running, which is an important daily skill and part of different sports. Running is characterized by the absence of a double support phase, and the existence of a flight phase. Subsequently, running can been seen as a more complex task than walking in terms of dynamical postural control, accurate timing, and a complex interaction of the neuromuscular system (Sudlow et al., 2023), factors that are known to influence coordination in children with DCD (Wilson, Smits-Engelsman, Caeyenberghs, & Steenbergen, 2017). The hybrid multi-component model of motor skill development is proposed to explain performance deficits in DCD through dynamical interactions at the individual, task and environmental levels (Wilson et al., 2017). This dynamical interplay among the individual, the task and the environment may either impede or enhance motor coordination and performance. However, until now, no study examined the role of task complexity, by comparing walking and running. A better comprehension of coordination difficulties within DCD during walking and running may guide task-oriented walking and running training in clinical practice, oriented on timing and coordination difficulties.

Therefore, this study examined interlimb coordination and spatiotemporal variability during both walking and running in children with and without DCD. Considering previous studies suggesting interlimb coordination difficulties during lower limb or multi-limb tasks (de Castro Ferracioli et al., 2014; Mackenzie et al., 2008; Whitall et al., 2006; Wilmut, Wang, & Barnett, 2022), we hypothesized that children with DCD, compared to TDC, would show a higher phase coordination index (reduced interlimb coordination) during walking and running compared to TDC. We hypothesized that differences in interlimb coordination between groups will be more prominent during running, a more complex task with an increased need for a more specific phase timing, timed control of force and dynamical postural control. Lastly, based on previous studies (Smith et al., 2021) we hypothesize that spatiotemporal variability in spatiotemporal measures would be higher in children with DCD compared to TDC during both walking and running.

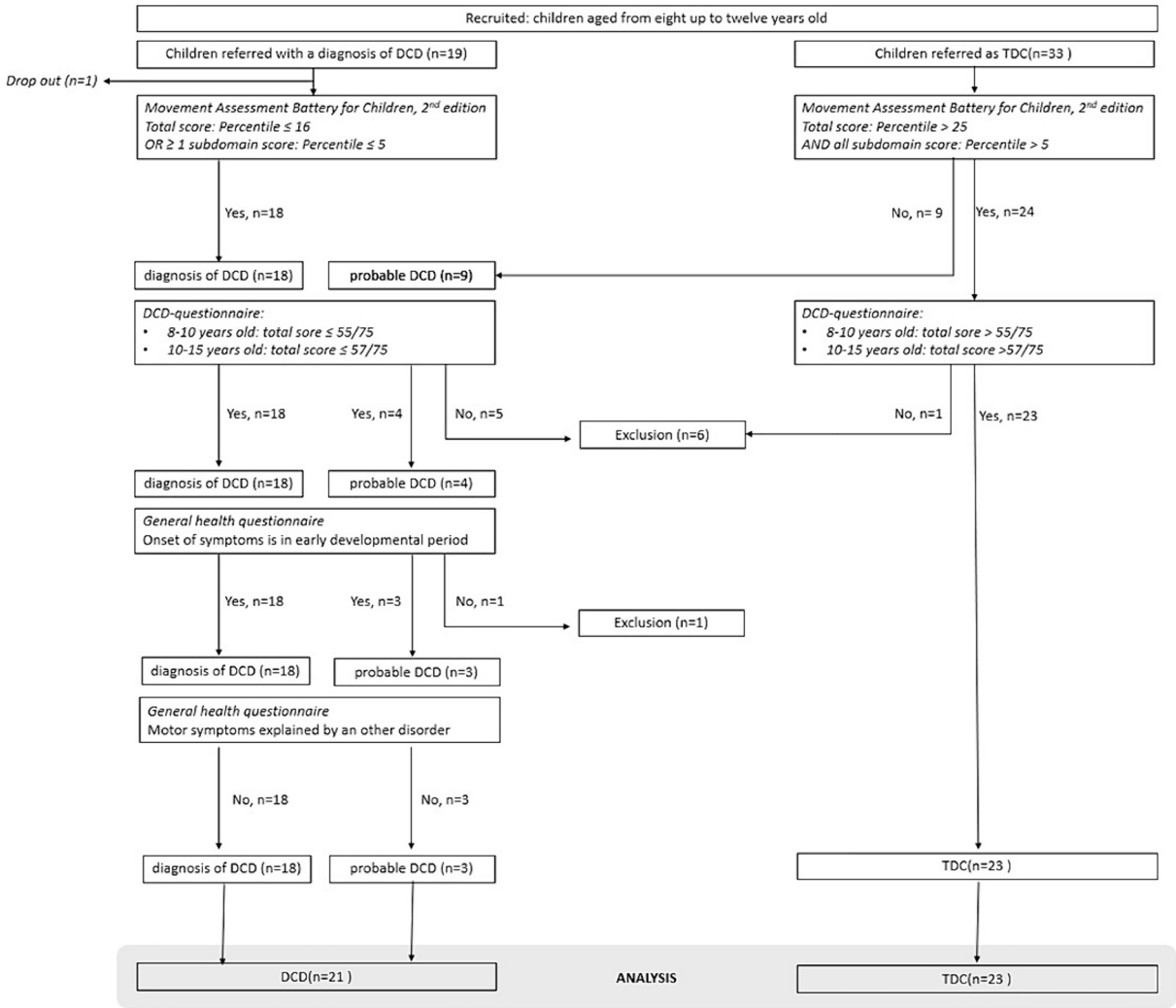

Fig. 1. Flow chart for inclusion of the participants and grouping them into the group of children with Developmental Coordination disorder (DCD) or typically developing children (TDC).
Abbreviations: number (n), Developmental Coordination Disorder (DCD), Typically developing children (TDC)

2. Methods

2.1. Participants

It is assumed that gait velocity is mature at 7–8 years of age (Dusing & Thorpe, 2007; Müller, Müller, Baur, & Mayer, 2013; Sutherland, Olshen, Cooper, & Woo, 1980), and therefore, only children starting from the age of eight years old could participate in this study. Fifty-two children were recruited through physiotherapists, sports centres and schools by using flyers and social media posts. Participants ranged from eight up to twelve years and were included in either the DCD ($n = 21$) or TDC ($n = 23$) groups, according to the criteria within the Diagnostic and Statistical Manual of Mental Disorders, fifth edition (DSM-V) (Association, A. P, 2013; Blank et al., 2019). The selection process is detailed in Fig. 1. To elaborate, children were included in the DCD group based on the following four criteria: a) they had a total percentile score $\leq$ P16 or subdomain score $\leq$ P5 on the Movement Assessment Battery for Children edition 2 (m-ABC-2) (Wuang, Su, & Su, 2012) and b) the motor impairments negatively influenced activities of daily life, using the parent-reported Developmental Coordination Disorder Questionnaire (DCD-Q, Dutch translation Coördinatie Vragenlijst voor Ouders (CVO)), and c) their motor symptoms started during childhood, verified using a parent-reported general health questionnaire, and d) their motor function problems could not be explained by an other neurological, musculoskeletal, intellectual disorder or genetic disorder, verified using a parent-reported general health questionnaire. Children were included in the TDC group if a) the m-ABC-2 total percentile was $\geq$P25, and b) the parents did not report a negative influence of motor impairments in activities of daily life, verified by the parent-reported Developmental Coordination Disorder Questionnaire (DCD-Q, Dutch translation CVO), and c) they had no neurological, orthopaedical, cardiorespiratory or intellectual impairment that could affect their motor abilities (verified using a health questionnaire). However, we also noticed that children referred to us as TDC fulfilled the four DCD criteria. Subsequently these participants ($n = 3$) were labelled as probable DCD and included in the DCD group for analyses. Children were excluded if they did not meet the selection criteria of the (probable) DCD, nor the TDC group ($n = 7$), or if the testing could not be completed due to behavioral problems (drop-out, $n = 1$).

2.2. Study design and procedure

This study was an observational cross-sectional case-controlled study including participants with DCD and typically developing children (TDC). Approval of the Medical Ethical Committee (B1152020000009) was obtained at Hasselt University and the study was registered at the clinical trials.gov registry (NCT04891562). Written informed consent was obtained from parents or guardians of the children.

Participants toke part in two session over two separate days. During the first session, descriptive measures (*see 2.3. Descriptive measures*) were collected. The experimental paradigm with walking and running (*see 2.4. Experimental paradigm*) was performed during the second session and took place in a sport hall. Each testing session took approximately 90 min.

2.3. Descriptive measures

2.3.1. Demographic information and general health

Basic demographic information was obtained by a parent-reported general health questionnaire. The questionnaire was composed of questions related to relevant demographic information such as age, early development and medical history In addition, the child's height (centimeters), leg length (centimeters) and bodyweight (kilograms) were measured.

2.3.2. Motor performance: gross and fine motor skills, and postural control

The m-ABC-2 is a standardized and norm-referenced test to assess gross (static and dynamic balance, aiming and catching) and fine motor functions (manual dexterity) in children aged between 3 and 16 years. The raw score of each subdomain can be converted to percentiles by using reference tables by age. A total percentile scores $\leq$16 or a subdomain percentile score $\leq$ 5 are interpreted as 'likely to have motor problems' (Wuang et al., 2012). The total duration of the m-ABC-2 ranges between 20 and 40 min. The m-ABC-2 shows good to excellent interrater and test-retest reliability and fair to good validity.

The Kids Balance Evaluation Systems test for children (Kids BESTest) was performed. The Kids BESTest is an adapted version of the BESTest for adults which was designed to evaluate postural control in the adult population (Horak, Wrisley, & Frank, 2009). Dewar and colleagues transformed the BESTest into a reliable paediatric version (age 8–14), the Kids-BESTest. The test's reliability was established in children with cerebral palsy (R. Dewar, Claus, Tucker, Ware, & Johnston, 2019) and the validity of seven specific items were explored against technical measures (posturography and movement analysis) (R. M. Dewar et al., 2022; R. M. Dewar, Tucker, Claus, Ware, & Johnston, 2021). The Kids-BESTest contains 36 items spread across six domains, each covering one postural control system (R. Dewar, Claus, Tucker, Ware, & Johnston, 2017; Horak et al., 2009): biomechanical constraints (5 items), stability limits and verticality (7 items), transitions/anticipatory (6 items), reactive (6 items), sensory orientation (5 items), and stability in gait (7 items). Each item is evaluated with a 4-point ordinal rating scale between 0 (unable to perform independently) and 3 (normal performance). Since the scoring was minimally adjusted for children, a maximal item score reflects an adultlike performance. An age-specific version was therefore developed considering typical development of postural control in children aged 5–14 (Verbecque et al. Reliability of age adapted Kids BESTest, in progress). The performance can be expressed by a domain score and a total score, using percentages. Higher percentages indicate better performances (R. Dewar et al., 2017; R. Dewar et al., 2019).

Fig. 2. Experimental set-up. Participants were instructed to walk and run at their comfortable tempo for three minutes per task in an oval pathway (20 × 15 meters) in a sports hall.

2.4. Experimental paradigm: walking and running

Continuous three-minutes walking and running in a sport hall was used to assess interlimb coordination and spatiotemporal measures. Participants were instructed to walk and run (randomized) at their comfortable tempo for three minutes per task in an oval pathway (20 × 15 meters) in a sports hall (see Fig. 2.). A familiarization trial was performed to ensure that they understood the instruction.

Participants were equipped with two wearable sensors (Physilog 5, GaitUp ®) which were placed on the dorsum of each shoe. The Physilog® 5 inertial sensors are valid sensors to capture gait parameters in adolescents (Carroll, Kennedy, Koutoulas, Bui, & Kraan,

Table 1
Descriptive characteristics (mean ± standard deviation) of participants.

		DCD (n = 21)	TDC (n = 23)	p value
Age (years)		10.27 ± 1.53	10.37 ± 1.25	ns[a]
Age category	$n \leq$ 10 years old (%)	13 (61.90%)	12 (52.17%)	ns[b]
	n ≥ 10 years old (%)	8 (38.10%)	11 (47.83%)	
Body weight (kilograms)		36.85 ± 10.60	36.00 ± 6.89	ns[c]
Body length (centimeters)		143.16 ± 14.45	144.60 ± 9.68	ns[d]
Leg length (centimeters)		74.90 ± 8.49	77.53 ± 6.64	ns[d]
Gender	n (%male)	17 (81%)	9 (39%)	**<.01**[b]
Comorbidity diagnosis	Total %	35%	0%	
	AD(*H*)D (n)	3		
	ASD (n)	3		
	CVI (n)	1		
	Learning disorder (n)	2		
DCDQ (/75)		35.14 ± 9.92	70.44 ± 3.34	**<.0001**[c]
m-ABC-2 (percentile 0–100)	Total	7.34 ± 10.20	62.96 ± 19.82	**<.0001**[c]
	Manual dexterity	11.00 ± 17.33	58.43 ± 32.61	**<.0001**[c]
	Aiming and catching	9.47 = 13.31	49.35 ± 24.54	**<.0001**[c]
	Balance	19.85 ± 25.86	62.04 ± 18.62	**<.0001**[a]
Kids BESTest (0–100%)	Total	79.66 ± 8.15	94.02 ± 3.83	**<.0001**[c]
	Biomechanical constraints	88.89 ± 11.80	97.97 ± 3.73	**<.0001**[a]
	Limits of stability and verticality	68.48 ± 11.71	84.06 ± 10.80	**0.0001**[a]
	Anticipatory postural adjustments	75.13 ± 16.63	96.14 ± 6.58	**<.0001**[c]
	Reactive postural responses	84.39 ± 10.34	95.41 ± 6.19	**<0.001**[a]
	Sensory orientation	91.75 ± 8.14	99.13 ± 2.30	**<.001**[c]
	Stability in gait	69.31 ± 17.37	91.44 ± 9.47	**<.0001**[c]

Abbreviations: n = number, Developmental Coordination Disorder Questionnaire (DCDQ), Movement Assessment Battery – second edition (m-ABC-2), Kids Balance Evaluation Systems Test (Kids BESTest), Attentional deficit (hyperactivity) disorder (AD(H)D), autism spectrum disorder (ASD), cerebral visual impairment (CVI).
Two-sided p-values < .05 were considered as significant.
[a] Wilcoxon signed rank test.
[b] Fisher's Exact test.
[c] Welch's Test.
[d] Independent t-test.

Table 2
An overview of locomotor coordination outcomes, gait variability and spatiotemporal gait parameters.

		Outcome	Walk		Run		Mixed model analysis ANOVA	Post-hoc multiple comparison
			DCD (n = 21)	TDC (n = 23)	DCD (n = 21)	TDC (n = 23)		
Interlimb coordination		PCI (%)	6.59 (5.92–7.92)	6.21 (5.05–6.97)	8.33 (6.73–13.19)	5.07 (4.33–7.02)	Log(PCI) Group*task: F(6.09), $p < .05$	DCD-TDC: run: t(5.18), $p < .0001$
		φCV (%)	3.56 (3.17–4.11)	3.36 (2.86–3.69)	4.75 (3.64–7.31)	2.71 (2.29–3.81)	Log(φCV) Group*task: F(8.52), $p < .01$	DCD: run-walk: t (2.85), $p < .01$ DCD-TDC: run: t(5.55), p < .0001
		Pφ*ABS* (%)	3.24 (2.63–3.81)	2.80 (2.20–3.22)	3.48 (3.08–5.89)	2.83 (1.91–3.21)	Log(Pφ*ABS*) Group: F(24.05), p. < 0.0001	DCD-TDC: t(4.90), p < .0001
Absolute spatiotemporal parameters	walking and running	Cadence (steps/min)	122.18 (116.22–124.65)	122.33 (119.46–127.05)	176.69 (168.88–184.07)	171.27 (168.13–180.80)	Task F(1684.48), $p < .0001$	Walk-run: t(41.04), p < .0001
		Velocity (meters/s)	1.25 (1.17–1.41)	1.39 (1.28–1.49)	2.22 (1.95–2.38)	2.45 (2.33–2.74)	Group*task F(5.78), p < .05	DCD: walk-run: t (13.63), p < .0001 DCD-TDC: run: t (−4.59), p < .0001 TDC: walk-run: t (17.74), p < .0001
		Step length (meters)	0.62 (0.57–0.71)	0.68 (0.64–0.73)	0.73 (0.66–0.83)	0.87 (0.77–0.92)	Group*task F(7.69), p < .01	DCD: run-walk: (4.29), p.0001 DCD-TDC run: t (−4.54), p < .0001 TDC: run-walk: t (8.50), p < .0001
	Specific for walking	Double support % gait cycle	21.75 (19.27–24.80)	21.25 (19.16–22.42)	*not applicable in running*			ns
		Stance% gait cycle	60.93 (59.69–62.45)	60.68 (59.60–61.28)				ns
		Swing% gait cycle	39.07 (37.55–40.31)	39.32 (38.72–40.40)				ns
	Specific for running	Contact time (milliseconds)	*not applicable in walking*		299.77 (252.45–332.40)	243 (226.37–264.62)		t(−3.19), p < .01
		Flight time (milliseconds)			85.18 (63.22–124.23)	128.93 (110.27–157.56)		t(3.17), p < .01
		Nondimensional cadence	33.41 (31.79–35.46)	34.55 (33.78–35.71)	49.48 (47.84–51.12)	49.48 (47.09–51.13)	Task F(2010.78), p < .0001	Walk-run: t(44.84), p < .0001
Non dimensional spatiotemporal parameters		Nondimensional velocity	0.47 (0.44–0.53)	0.49 (0.48–0.53)	0.79 (0.73–0.91)	0.91 (0.86–0.98)	Group*task F(4.26), p < .05	DCD: run-walk: t (12.74), p < .0001 DCD-TDC run: t (−3.93), p < .001 TDC run- walk: t (16.32), p < .0001
		Nondimensional step length	0.85 (0.81–0.90)	0.87 (0.80–0.92)	1.01 (0.94–1.08)	1.13 (1.01–1.19)	Group*task F(6.88), p < .05	DCD run-walk: t(4.18), p. < 0.0001 DCD – TDC run: t

(*continued on next page*)

Table 2 (*continued*)

	Outcome	Walk		Run		Mixed model analysis ANOVA	Post-hoc multiple comparison
		DCD (n = 21)	TDC (n = 23)	DCD (n = 21)	TDC (n = 23)		
Variability in spatiotemporal gait parameters	Cadence CoV (%)	2.90 (2.58–3.60)	2.31 (2.01–2.91)	3.09(2.44–3.74)	1.90 (1.54–2.35)	Log (cadence CoV) Group*task: F(6.02), p < .05	(−3.86), $p < .001$ TDC run-walk: t(8.17), p < .0001 DCD-TDC: run: t(5.91), p < .0001 DCD-TDC: walk: t (3.07), p < .01 TDC: run-walk: t (−3.20), p < .01
	Velocity CoV (%)	4.80 (3.82–6.54)	3.89 (3.32–4.66)	9.73 (7.10–10.81)	5.79 (4.72–6.13)	Log (speed CoV) Group*task: F(5.22), p. < 0.05	DCD: walk-run: t (7.83), p < .0001 DCD-TDC: run: t(5.66), p < .0001 DCD-TDC: walk: t (2.87), p < .01 TDC: walk-run: t (4.89), p < .0001
	Step length CoV (%)	5.57 (4.84–6.80)	4.55 (4.00–4.99)	9.19 (7.19–10.53)	5.74 (4.79–6.20)	Log (step length CoV) Group*task: F(5.52), p. < 0.05	DCD run-walk: t(6.09), p < .0001 DCD-TDC run: t(6.60), p < .0001 DCD-TDC: walk: t (2.87), p. < 0.01 TDC: walk-run: t (2.98), $p < 0.01$

Abbreviations: Phase Coordination Index (PCI), Variability in antiphase coordination (φCV (%)), Accuracy antiphase coordination (PφABS (%)), Coefficient of Variance (CoV), Log transformation (Log). Median and interquartile range (25%;75%) are reported in the table.

2022; Rudisch et al., 2021).

2.4.1. Primary outcome measures

The primary outcome measure of the experimental paradigm was interlimb coordination, quantified by the Phase Coordination Index (PCI). The PCI is a timing measure of each a footstep in relation to the next one. In other words, it represents the antiphase timing relationship of contralateral footsteps, expressed in consistency and accuracy. Shortly, the relative phase (φ) represents the relative timing of contralateral heel strikes, determining the phase, as this is normalization of the step time with respect to the stride time. Ideally, the relative phase for each step is 180° for accurate antiphase interlimb coordination. The consistency of the phase generation is represented by the Coefficient of variation (φCV) of the relative phases, and is calculated by the following formula: φCV = (SD φ / mean φ) x 100, where SD is the standard deviation of φ.

The overall accuracy in generating anti-phased stepping is expressed by PφABS, the absolute difference between the value φi and 180°. PφABS = absolute value of (mean (φi-180°) / 180°) x100.

Phase coordination index (%) is the sum of φCV and PφABS, expressed as a percentage. A lower PCI% implies a higher phase control and coordination. Detailed information is described in (M. Plotnik et al., 2007).

2.4.2. Secondary outcome measures

Spatiotemporal measures were collected to describe gait during walking and running. The following spatiotemporal measures were collected: cadence (steps per minute), gait velocity (meters per second), step length (meters), percentage in stance phase (%, walking), percentage in swing phase (%, walking), percentage in double support (%, waking), flight time (milliseconds, running) and contact time (milliseconds, running). In addition, the nondimensional measures of cadence, velocity and step length were calculated, taking into account the leg length of the participants (Stansfield et al., 2003). Lastly, spatiotemporal variability was quantified by the coefficient of variation (CoV) by using the following formula: CoV = (SD/mean)*100 (Wilmut, Gentle, & Barnett, 2017).

2.5. Statistical analysis

Descriptive data was checked for normality by using the Shapiro-Wilk test. An independent *t*-test was used for normal distributed data. Non-normal distributed data was analyzed by a Wilcoxon-signed rank test. A Welch's test was used if the data was not normally distributed and homoscedasticity was not met. A mixed-model analysis of variance was applied on primary and secondary outcomes with group (DCD, TDC) as between-subject factor and task (walk, run) as within-subject factor. Main effects (group, task) and the interaction effect of group*task were included in the mixed-model analysis and the significance level was set to <0.05. If an interaction effect existed, post-hoc student's t-test with Holm Bonferroni correction was used for multiple comparison. Normal distribution was visually checked using conditional residual quantile plots. Outliers were screened using the quantile range outliers (tail quantile 0.1, Q2) of the outlier detection method within JMP® Pro16.1.0. The number of outliers was very low (<1% of the total sample size). Statistical analysis was performed including detected outliers. Log transformation was used if normal distribution of the data was not met (PCI, PφABS, φCV, CoV stride-time, CoV cadence, CoV gait velocity, CoV step length). JMP®Pro16.1.0 was used for all statistical analysis.

3. Results

3.1. Participants

Forty-four children were included in the statistical analysis, of which 21 were included in the DCD group and 23 in the TDC group. No statistical differences were found between groups with regards to age, body weight, body length or leg length. The mean age of the participants in the DCD group and TDC group were respectively 10.27 years old and 10.37 years old. A significant higher proportion of the children in the DCD group were boys (81%) compared to the proportion of boys in the TDC group (39%). Groups differed significantly in the scores of the m-ABC2 test (total and subdomain percentiles), DCDQ and Kids BESTest (total % and subdomain %). A full overview of the participant characteristics can be found in Table 1.

3.2. Primary outcome measures: interlimb coordination

An overview of the interlimb coordination parameters (median, interquartile range) by group for walking and running can be found in Table 2.

3.2.1. Phase coordination index: Log(PCI)

An interaction effect was found for group*task (F(6.09), $p = .0177$). Post hoc multiple comparison revealed that children with DCD run with a significantly higher interlimb coordination (PCI) than their typically developing peers (t(5.18), $p < .0001$), indicating that children with DCD show a less coordinated running pattern than TDC. However, no significant between-group difference in PCI was observed while walking (t(1.39), $p = .1686$). No significant difference between tasks was observed in log(PCI).

Individual profiles of the PCI across groups during three minutes walking and running is plotted in Fig. 3A. Based on the PCI quantiles of the TDC group during running, the figure is divided in ranges (≥75% = orange, ≥97.5% = red). The PCI of six children with DCD (29% of the DCD sample) was situated above the 97.5% quantile of the PCI of the TDC group during (see Fig. 3A, red colored range).

The distribution of the step-by-step relative phases of two cases are visualized in Fig. 3B and C. In Fig. 3B, the step-by-step relative phase of one case with DCD during three minutes walking (red triangles) and running (blue circles) is plotted. During running, step-by-step relative phases deviates more from the 'ideal' relative phase of 180° (large PφABS). In addition, the distribution of the step-by-step relative phases is more variable during running compared to walking (large φCV). This higher inaccuracy (PφABS) and the higher variability (φCV) of the step-by-step relative phases result in a larger average PCI during running compared to walking. In contrast, in Fig. 3C, the step-by-step relative phase of one age and gender matched TDC case is plotted. Within this TDC case, the PCI does not increase during running compared to walking.

3.2.1.1. Variability in interlimb coordination: log(φCV). An interaction effect was observed for group*task. After post-hoc comparison, results indicated that children with DCD run with significantly higher log(φCV) (t(5.55), $p < .0001$) than their typically developing peers. Only within the DCD group, the log(φCV) is significantly higher during running compared to walking (t(2.85), $p = .0067$).

3.2.1.2. Accuracy in interlimb coordination: log(PφABS). Statistical analysis showed a main effect of group (F(24.05), $p < .0001$), indicating that log(P*φABS*) of children with DCD is significantly higher than the phase error of typically developing peers (t(4.90), $p < .0001$). In both groups, no significant difference in log(P*φABS*) was present between the tasks walking and running.

Results of interlimb coordination (median group values) during walking and running, is visualized in Fig. 4.

3.3. Secondary outcomes

An overview (median, interquartile range) of the spatiotemporal gait measures (absolute values, non-dimensionless values and coefficient of variation) is reported in Table 2.

3.3.1. Spatiotemporal gait measures

Results of spatiotemporal measures revealed that children with DCD run with a significantly lower absolute gait velocity (t(−4.59), $p < .0001$) and shorter absolute step length (t(−4.54), $p \leq 0.0001$) than typically developing peers. Similar results were found for the non-dimensionless spatiotemporal gait parameters. Children with DCD ran with a significantly shorter flight time (t(3.17), $p = .0030$)

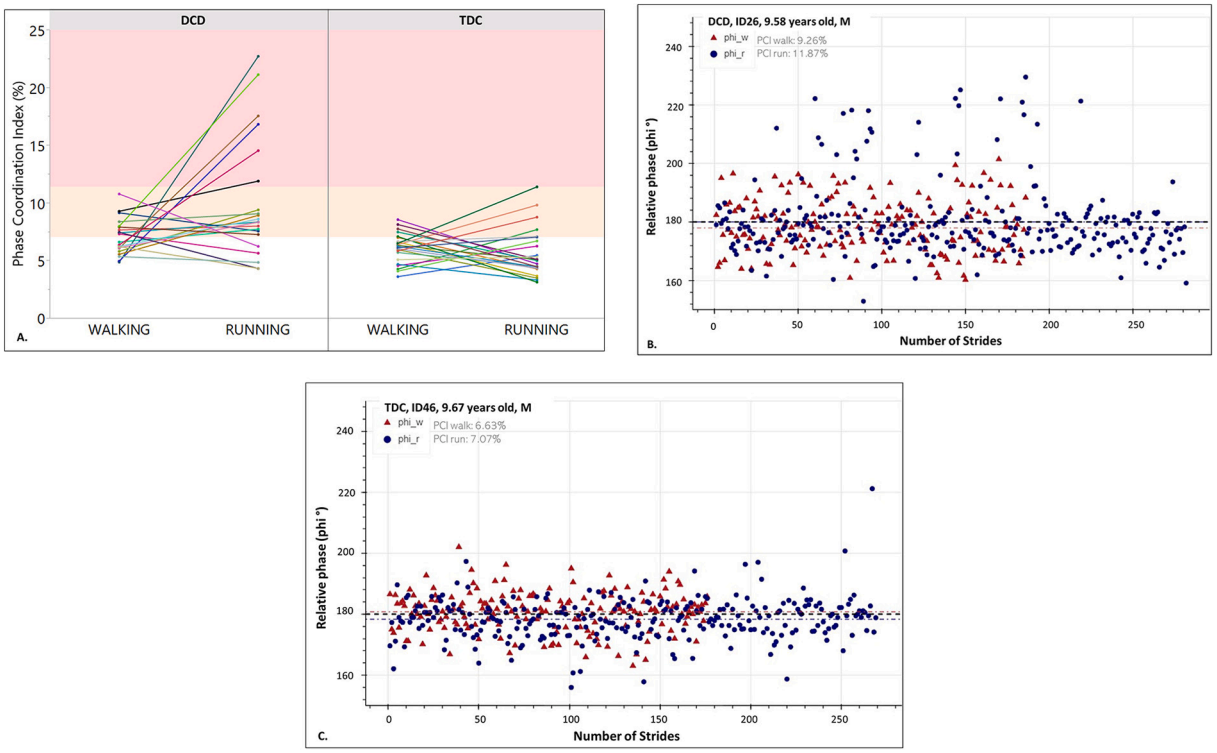

Fig. 3. Individual profiles of the Phase Coordination Index across groups during three minutes of walking and running. Fig. 3A. The figure is divided in ranges based on the quantiles of the observed phase coordination index of the typically developing children while running (≥75% = orange, ≥97.5% = red). Every line represents an individual profile of the phase coordination index of an participant. Fig. 3B. Distribution of the step-by-step relative phases of a case with Developmental Coordination Disorder during 3 min of walking (red, triangles) and running (blue, circles). Fig. 3C. Distribution of the step-by-step relative phases of an age and gender matched typically developing child during 3 min of walking (red, triangles) and running (blue, circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

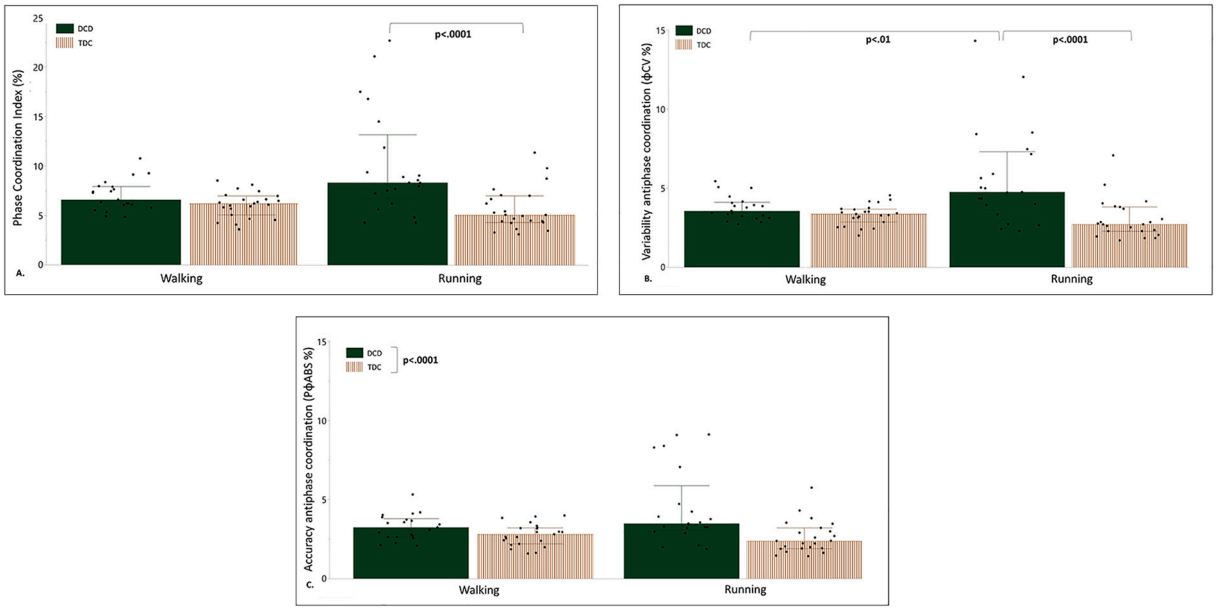

Fig. 4. Children with Developmental Coordination Disorder (DCD, green, full) run with a lower interlimb coordination (interaction effect group*task, $p = .0132$), expressed by a higher phase coordination index (PCI, %) than typically developing children (TDC) (Fig. 4A). The higher PCI in children with DCD was the result of a higher variability (Fig. 4B) and inaccuracy (Fig. 4C) of antiphase coordination. Bars represents median and interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and longer contact time (t(−3.19), $p = .0031$) than TDC.

While walking, no significant between-group differences were found in absolute gait velocity, step length or cadence, nor in the non-dimensionless parameters. No significantly differences were found in the percentage of the gait cycle in stance phase (t(−0.65), $p = .5223$), % in swing phase (t(0.65), p = .5223), or in double support (t(−0.63), $p = .5298$) between groups.

3.3.2. Spatiotemporal gait variability

A significant interaction effect of group*task in CoV cadence (F(6.02), $p = .0184$), CoV step length (F(5.52), $p = .0236$) and CoV velocity (F(5.22), $p = .0274$) was found. Post-hoc multiple comparison revealed that children with DCD show a significantly higher variability (CoV) in cadence, step length and gait velocity than TDC both during walking and running. Moreover, in both groups, the variability in gait velocity and step length was significantly higher during running than walking. Only in the TDC group, a significant difference was found in the variability of cadence between tasks, indicating a higher variability in cadence during walking than running.

4. Discussion

This study aimed to examine interlimb coordination and spatiotemporal variability of gait during overground walking and running in children with and without Developmental Coordination Disorder aged eight up to twelve years. Our results indicate that children with DCD display a less coordinated running pattern, expressed by a significantly higher phase coordination index, than typically developing peers. During walking, the interlimb coordination was similar between both groups. The current results on interlimb coordination during walking and running partly confirmed our hypothesis. Next, our results confirmed that children with DCD, compared to TDC, have a larger variability in spatiotemporal measures during both walking and running.

Interlimb coordination during walking and running was examined and expressed by PCI, which encompass both accuracy and consistency antiphase timing of left-right stepping. To our knowledge, this was the first study that objectively assessed interlimb coordination expressed by the PCI in TDC and DCD children during overground walking and running. Overground walking and running in a large oval-path allowed for assessing coordination and gait patterns in an ecologically valid set-up. We observed that children with DCD showed a similar interlimb coordination (PCI) when walking compared to TDC, yet a lower interlimb coordination (higher PCI) was observed in children with DCD during running as compared to TDC. The higher PCI in children with DCD during running was the result of a higher variability (CVφ) and lower accuracy (PφABS) in antiphase coordination. Even though the current study is the first to assess interlimb coordination by the PCI during overground walking and running in children, previous studies examining coordination in children with DCD also showed a lower accuracy and higher variability in coordination during a range of tasks (pedalo task, multilimb task, tapping task) (de Castro Ferracioli et al., 2014; Volman and Geuze, 1998a; Mackenzie et al., 2008; Roche, Wilms-Floet, Clark, & Whitall, 2011; Volman & Geuze, 1998b; Whitall et al., 2006; Wilmut et al., 2022). Although in general children with DCD significantly increased their PCI while running compared to walking, individual inspection of the data revealed

different trends within the PCI. To elaborate, the PCI of eight children with DCD remained relative stable or decreased during running compared to walking. In contrast, thirteen children within the DCD group (62% of the DCD sample) increased their PCI during running compared to walking. Furthermore, the PCI of six children with DCD (29% of the DCD sample) was situated above the 97.5% quantile of the PCI of the TDC group while running (see Fig. 3A, red range). The distribution of the step-by-step relative phases of a case with DCD is visualized in Fig. 3B. This plot confirm our results of the accuracy (PφABS) and the variability of the relative phase (φCV). To elaborate, in Fig. 3B, the step-by-step relative phases deviates more from the 'ideal' relative phase of 180° (large PφABS). In addition, the distribution of the step-by-step relative phases is more variable during running compared to walking (large φCV). This higher inaccuracy (PφABS) and the higher variability (φCV) of the step-by-step relative phases result in a larger average PCI during running compared to walking. In contrast, in Fig. 3C, the step-by-step relative phase of one age and gender matched TDC case is plotted. Within this TDC case, the PCI does not increase during running compared to walking. These individual differences confirm the heterogeneity in DCD (Lust et al., 2022; Meachon, 2022). In addition, these results highlight the need for a comprehensive assessment of running in DCD and consequently, a task-oriented training that is based on individual assessments.

Only one study examined coordination variability during treadmill walking, using elliptical Fourier analysis (Rosengren et al., 2009). Results of Rosengren et al. (2009) show a higher variability in the movement pattern of the shank and thigh of children with DCD compared to typically developing peers during treadmill walking. In contradiction with the literature that suggest coordination difficulties during a range of tasks, including treadmill walking (Rosengren et al., 2009), we did not observe interlimb coordination differences between groups during walking. This different finding in coordination variability during walking might be attributed to the use of a different outcome measure (Elliptical Fourier analysis versus PCI) and/or methodology (treadmill versus over ground) to assess coordination variability. Locomotor coordination outcomes can be categorized in outcomes that assess the temporal domain or more the spatial domain of coordination (Goetschalckx et al., 2021; Krasovsky & Levin, 2010). More specifically, the Elliptical Fourier analysis can be categorized as an outcome measures that assesses the spatial domain of coordination, whereas the PCI is more in accordance with the characteristics of an outcome measure of the temporal domain of coordination (Goetschalckx et al., 2021; Krasovsky & Levin, 2010). Next, when using a treadmill approach, children walk with a lower walking velocity, shorter stride and stance time, larger step width, larger peak joint angles at knee and hip (Senden et al., 2022). These spatiotemporal adaptations might suggest that treadmill walking is more challenging than overground walking, provoking a higher variability during treadmill walking.

In the current study, lower interlimb coordination was observed in DCD during the more challenging running task. We propose different mechanisms that might underly the observed differences in interlimb coordination between groups during running, yet not while walking. Given the shift from a double support phase to a flight phase while running, a faster phase timing, a more specific timed control of force, power generation and dynamical postural is needed during running compared to walking (Cappellini, Ivanenko, Poppele, & Lacquaniti, 2006). Following the speed-accuracy trade-off, the accuracy of motor control decreases when the speed of the motor task is increased (Fitts, 1954), resulting in the observed inaccuracy of antiphase coordination (PφABS) in children with DCD as compared to TDC while running. Given the fast timing during running, one should rely more on feedforward mechanisms for accurate motor control, which is known to be deficient in children with DCD (Adams, Lust, Wilson, & Steenbergen, 2014), and as a consequence gives rise to a higher variability in the movement pattern of children with DCD. Another factor that may play a role within the interlimb coordination difficulties of DCD are the reported atypical neural structures and functions of networks supporting motor planning, coordination and timing, such as the mirror neuron system (Biotteau et al., 2016; Reynolds et al., 2015), altered white matter microstructure in the corpus callosum, sensorimotor, corticospinal, cortico-cerebellar and frontoparietal pathways (Brown-Lum, Izadi-Najafabadi, Oberlander, Rauscher, & Zwicker, 2020; Hyde et al., 2019; Langevin, Macmaster, Crawford, Lebel, & Dewey, 2014; McLeod, Langevin, Dewey, & Goodyear, 2016) and the cerebellum (Biotteau et al., 2016; Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Gill, Lang, & Zwicker, 2022; Subara-Zukic et al., 2022). In other neurological populations, such as in persons with Multiple Sclerosis, the integrity of the corpus callosum is found to be related to interlimb coordination while overground walking (Sutton B. Richmond, Peterson, & Fling, 2022). In addition, the cerebellum plays an important role in smooth coordination and timing of motor control (Barlow, 2002; Slutsky-Ganesh, Anand, Diekfuss, Myer, & Grooms, 2023). Therefore, it might be of interest to explore different neural areas, including the corpus callosum, cerebellum, and functional networks that relate with interlimb coordination deficits in individuals with DCD.

Higher variability in DCD is evident across a range of task (B. C. Smits-Engelsman & Wilson, 2013; Subara-Zukic et al., 2022; Wade & Kazeck, 2018). In this study, spatiotemporal parameters showed significantly different variability between groups, during both walking and running. In all outcomes (cadence, velocity and step length), the children with DCD showed a higher variability than their typically developing peers, supporting previous findings (Smith et al., 2021). Even during normal gait, variability is evident, given that relatively small stride-to-stride fluctuations of temporospatial measures is required to adapt to environmental changes. It is suggested that increased gait variability during highly controlled environments or minimal task constraints, as in this study set-up, may relate to increased risk of falls (Hausdorff, 2005). This is a frequently reported symptom in children with DCD (Fong et al., 2016). When considering spatiotemporal variability between tasks, the variability in velocity and step length was lower during walking compared to running. The lower variability, found during walking, might be related to the different maturation process of walking and running. Literature suggest that the maturation of spatiotemporal variability during walking may be expected around the age of 13 in typically developing children. However, spatiotemporal variability of running may not be fully matured before the age of 17 (Hausdorff, Zemany, Peng, & Goldberger, 1999; Kung, Fink, Legg, Ali, & Shultz, 2019).

The difference in spatiotemporal variability between walking and running may be explained by different bodily dimensions or absolute spatiotemporal measures. In this study, it was found that children with DCD walk with a similar absolute and non-dimensionless cadence, gait velocity and step length as those without DCD (TDC). This lack of between group differences while walking is consistent with earlier findings from level-ground walking in DCD (Cherng, Liang, Chen, & Chen, 2009; Deconinck,

Savelsbergh, De Clercq, & Lenoir, 2010; Du, Wilmut, & Barnett, 2015). However, while running, differences were found between groups in absolute and non-dimensionless running velocity and step length. These results indicated that children with DCD run slower and with shorter steps than their peers. Moreover, individuals with DCD spend a shorter time in flight phase and have a longer contact time while running, compared to TDC. Chia, Licari, Guelfi, and Reid (2014) reported similar results of slower running velocity and shorter step length in DCD children compared to TDC (Chia et al., 2014). The slower running velocity might be related to a different propulsion strategy in DCD than TDC (Diamond et al., 2014). Diamond et al. (2014) observed that children with DCD use a different propulsion strategy compared to TDC, which was characterized by a diminished ankle power generation at push off during running, yet not during walking (Diamond et al., 2014). In addition, the slower velocity, shorter step length, shorter flight phase and longer contact time seen in children with DCD while running, might be a compensation strategy of poorer dynamical postural control, which becomes challenged giving the absence of a double-support phase while running.

Some methodological limitations apply. One can argue that the study population was not matched by sex given that more boys were included in the DCD group than the TDC group. However, we do not expect that the sex difference would impact our results in this study population given that sex differences in gait patterns are less prominent prior to puberty (Sudlow et al., 2023). Next, the self-selected comfortable running velocity in children with DCD and TDC was not similar. Previous studies found a negative relation between gait velocity and PCI when walking at a self-selected speed in persons with Multiple Sclerosis (S. B. Richmond et al., 2020) or at a lower than preferred speed in young adults (Meir Plotnik, Bartsch, Zeev, Giladi, & Hausdorff, 2013). We verified this by applying a correlation between PCI and gait velocity and found no significant correlations in children with DCD ($p = .7076$, spearman rho $= -0.0870$), nor within the TDC group ($p = .1996$, spearman rho $= 0.3612$). Thus, differences in PCI between groups during running are likely not related to the slower running velocity in children with DCD compared to TDC. Finally, we observed outliers in a few outcome measures, comprising <1% of the total sample size. Notwithstanding, these outliers had no impact on the main effects or interaction effects reported in this study (unpublished analysis).

The findings of the present study have several implications. Our results add to the literature by showing that task constraints amplify motor deficits in DCD. Specifically, the results highlight the difference in interlimb coordination during running in DCD. Given the frequent reported falls in DCD (Fong et al., 2016) and the implications of walking and running on participation in play and sports, walking and running might be important tasks to assess and train in clinical practice. Important to note are the observed individual within-group differences in interlimb coordination, especially within the DCD group. These individual differences implicate an individual tailored assessment and intervention in DCD. Numerous task-oriented intervention approaches exist in DCD, however only a small amount of studies focus on walking and running in DCD (B. Smits-Engelsman et al., 2018). In this study, we demonstrate that coordination and variability during walking and running can be assessed by wearable sensors. Further studies might therefore implement assessment of interlimb coordination during short trials of walking and running to examine differences in interlimb coordination and variability in the gait pattern after a task-oriented walking or running intervention.

Several findings of the present study call for further investigation. Firstly, giving the novelty of the PCI in children while walking and running further studies are warranted to obtain normative reference values for interlimb coordination, including test-retest reliability and clinically meaningful change. Secondly, we recommend a longitudinal study to gain a more comprehensive understanding of the maturation of interlimb coordination, from childhood up to adulthood. Maturation of gait emerges from a complex interaction between different factors, including (but not limited to) biological age, biomechanical maturation of joints dynamics, muscle recruitment, anthropometric characteristics and neural maturation (Bach, Daffertshofer, & Dominici, 2021; Hausdorff et al., 1999; Kraan, Tan, & Cornish, 2017; Kung et al., 2019; Sudlow et al., 2023). Therefore a comprehensive longitudinal study, including different aspect of maturation is recommended. Lastly, our results highlight the difference in interlimb coordination during running in DCD and the higher spatiotemporal variability during both walking and running compared to TDC.

In conclusion, the results demonstrate that during a more complex task, namely running, children with DCD show a lower interlimb coordination (higher PCI), higher spatiotemporal variability and lower running velocity, shorter flight time, longer contact time and shorter step length than typically developing peers. During walking, children with DCD show a higher spatiotemporal variability compared to TDC. This lower interlimb coordination while running, greater variability and slower running velocity highlight the need for implementation of a running assessment and to consider task-oriented running training in clinical practice.

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CRediT authorship contribution statement

Mieke Goetschalckx: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing – original draft. **Lousin Moumdjian:** Conceptualization, Methodology, Resources, Software, Supervision, Writing – review & editing. **Peter Feys:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing. **Eugene Rameckers:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

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Data availability

Data will be made available on request.

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