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Walking adaptability improves after treadmill training in children with Developmental Coordination Disorder: A proof-of-concept study

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ABSTRACT

Background: Children with Developmental Coordination Disorder (DCD) have motor coordination deficits leading to difficulties in sports and play that require adaptations of the walking pattern. Children with DCD indeed demonstrate poorer walking adaptability (WA) compared to typically developing children, but it remains elusive whether WA can be improved by training.

Research question: Does augmented-reality treadmill training lead to improvements in WA in children with DCD?

Methods: Seventeen children with DCD were included in this proof-of-concept intervention study. They received a six-session training on the C-mill, a treadmill on which gait adjustments can be evoked by projected visual context. The effect of the training was evaluated before (M1), directly after training (M2) and after 6 months follow-up (M3) using the WAL-K (single and double run) and WA-tasks on the C-mill (as a single and with concurrent visuo-motor and cognitive task). In addition, parents completed a questionnaire on their perception of the training. Linear Mixed Model analyses were performed to assess the differences in WAL-K scores and success rates on the WA-tasks between M1-M2 and M1-M3.

Results: Children significantly improved on the WAL-K double run and on all three WA-tasks between M1-M2 and M1-M3. Children did not improve on the WAL-K single run. Parents found the training useful and fun for their child and indicated that their child fell less frequently.

Significance: The results show that C-mill training had positive and task-specific effects on WA in children with DCD, which effects generalized to an overground task and were retained at 6 months follow-up. This may help children with DCD to better participate in daily activities. Future research should include a control group to examine the effectiveness of the training program compared to receiving no training and may also examine the effect of the training on participation in daily life.

1. Background

Children with Developmental Coordination Disorder (DCD) are impaired in both gross and fine motor coordination [1]; the estimated prevalence of DCD is 5–6% in school aged children [2]. Children with DCD experience difficulties in daily activities such as sports, play, and school activities, and parents often report their children to be clumsy and to fall frequently [3]. As a result of their motor problems, children with DCD participate less in physical activities compared to their peers, especially in team sports [2]. This may lead to psychosocial problems –such as social anxiety or depression– or physical health problems –such as obesity or decreased physical fitness [2].

A prominent hypothesis concerning motor problems of children with DCD is a deficit in the internal modeling of movement (i.e. predictive control) [4]. The central nervous system uses an internal model to predict the future location of moving limbs enabling rapid online corrections during movement. A deficit in predictive control limits both the speed and accuracy of online error correction in gross and fine motor

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activities in children with DCD [4–8]. Predictive control is also essential during walking, when frequent and rapid modifications of the walking pattern have to be made to handle the demands of the environment like puddles, obstacles or uneven surfaces [9]. This so-called walking adaptability is highly relevant in children's daily activities such as avoiding objects or playmates during sports or playtime. Children with DCD perform worse on walking adaptability tasks compared to typically developing (TD) children[10–12], which performance deficit is further aggravated when a secondary motor or cognitive task is added [12–14]. Yet, while recent studies have demonstrated that predictive control of the upper extremity can be improved by training [15,16], such studies related to walking adaptability in children with DCD are still lacking.

The aim of this proof-of-concept study was to examine the effect of augmented reality treadmill training on walking adaptability in children with DCD. Children practiced on the C-mill (Motek Medical, Culemborg, the Netherlands), in which the treadmill belt was augmented with visual context (targets/obstacles) to provoke walking adaptations. The characteristics of training tasks were aligned with the specific motor control deficits in children with DCD, i.e. "tasks that demand precision (both spatial and temporal), advanced planning, or that stress the system in a way that requires some adaptation/adjustment at a perceptual-motor level to maintain stability" [6]. We hypothesized that C-mill training would yield significant improvements in walking adaptability tasks on the treadmill, and that these task-specific training effects would also generalize to an overground walking adaptability task. In interpreting the results of this uncontrolled study, we will also discuss our findings in light of reference values of TD children [12,17].

2. Methods

2.1. Participants

Twenty-seven children with DCD, 6–12 years old, were recruited from the patient database of Tolbrug Specialized Rehabilitation, patients' association, physical therapy practices, and schools. Children needed to have a formal diagnosis of DCD from a medical practitioner, or had to meet the DSM-V criteria as tested by the researcher (RK) [17,18]. In addition, the children had to perform below the median age-adjusted reference walking adaptability scores of TD children [12,17]. Exclusion criteria were temporary complaints influencing walking ability, or neurological, orthopedic, cardiovascular, or visual problems. Parents gave written informed consent prior to participation. The study was approved by the regional Medical Ethical Committee Arnhem-Nijmegen (2016–2885).

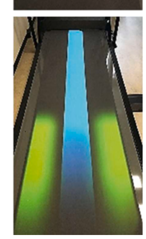
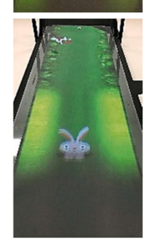
2.2. Study protocol

The children received six 30-minute sessions of C-mill training (180 min) in three weeks which is comparable to other studies which found improvements of motor skills in children with DCD after interventions of 120 and 200 min, respectively [19–21]. At baseline, descriptive data were collected regarding age, gender, height, weight, and current sport activities. Data of the most recent assessment of the MABC-2 were obtained from the child's physical therapist. If this assessment was more than 6 months ago, the MABC-2 was reassessed [22]. Walking adaptability assessments were conducted at baseline (M1), after the training period (M2), and after a follow-up period of 6 months (M3). All measurements and training sessions were performed by a specialized pediatric exercise therapist (RK) at Tolbrug Specialized Rehabilitation in 's-Hertogenbosch or Radboud university medical center in Nijmegen, The Netherlands between September 2017 and December 2018.

2.3. C-mill training

Training sessions (see Table 1) were performed at comfortable walking speed and participants were instructed not to use the handrails.

Table 1
Training protocol.

	Exercise		Duration (min)
1	Determination of comfortable walking speed (only in training sessions 1 and 2)		2
2	Warming up at comfortable walking speed		3
3	Target stepping: with variation in step length, step width, and symmetry. Difficulty was increased by increasing the irregularity between steps.		5
4	Obstacle avoidance: projection of unilateral or bilateral obstacles in front of the left or right foot, with differing available response times and sizes. Visual and auditory feedback on performance was given. Difficulty was increased by increasing the sizes and available response times.		5
5	Slalom walking: projection of a slalom walking path with cones in the corners. Visual feedback on performance was given. Difficulty was increased by decreasing the width of the path and increasing the frequency of corners.[a]		2.5
6	Tandem walking: projection of a narrow walking path. Visual feedback on performance was given. Difficulty was increased by decreasing the width of the path.[a]		2.5
7	Fun and functional forest game: projection of targets (footballs or stars) and obstacles (e.g. rabbit, tree, squirrel) in which children received points for successful target hits, but lost points when hitting obstacles. Visual and auditory feedback on performance was given. Children of 6–9 years old performed the game at an easy level; children of 10–12 years old performed the game at a medium level.		4

The comfortable walking speed of training 2 was used in training 3–6. Between all exercises, children had a 1-minute break. The order of exercises 3–6 was different in every session.

[a] The slalom and tandem exercises were alternated: the slalom was performed in sessions 1, 3 and 5; the tandem was performed in sessions 2, 4 and 6.

The type and duration of the exercises were standardized for all participants, but the level of difficulty was adjusted to the individual performance level of the child, based on the therapist's clinical judgment.

The training protocol was designed in line with the international clinical practice recommendations on DCD, which state that training of children with DCD should be activity- or participation-oriented, focused on daily activities, and meeting goals that are relevant in daily life [2]. C-mill training also meets the need of children with DCD for receiving augmented (i.e. extrinsic) feedback when learning novel and complex motor skills [6]. In addition, the interactive and gaming-like training opportunities of the C-mill were deemed particularly engaging and motivating for children.

2.4. Walking adaptability measurements

To evaluate training effects, we conducted the Walking Adaptability Ladder test for kids (WAL-K) and walking adaptability tasks (WA-tasks) on the C-mill. The measurements were performed during separate study visits in the fixed below-mentioned order.

2.4.1. Walking Adaptability Ladder test for Kids (WAL-K)

Children performed the WAL-K, a 10-meter agility ladder with 19 targets successively decreasing in size from 64 to 28 cm [17]. The child was instructed to walk back and forth, while stepping into the targets as fast and accurately as possible. The WAL-K was completed in two conditions: while stepping with one (single run) and both feet (double run) in each target. WAL-K score was calculated as completion time plus a 0.5 s penalty for each mistake (touching a bar, the wrong number of steps in a target, or missing a target). The WAL-K has been shown reliable and valid for measuring walking adaptability in children [17].

2.4.2. WA-tasks on the C-mill

The velocity of the treadmill was set at 3.5 km/h for all C-mill measurements. Following 2-minute familiarization of walking on the treadmill, the WA-tasks were performed. White stepping stones were projected across the entire treadmill relative to foot placement, based on the center of pressure position at mid stance. Approximately 6 stepping stones were visible at any time ahead of the participant, depending on step length. The child was instructed to step on the stepping stones as accurately as possible. Of these stepping stones, 10% randomly changed into an obstacle two steps before expected foot landing, as indicated by the stepping stone changing to red-white color. The child was instructed to step beside the obstacle and then onto the next stepping stone. The child first practiced the task for one minute, then it was recorded for four minutes (≥ 20 obstacles). Importantly, this task was not included in the training sessions. The children performed the WA-task as a single task (WA^{single}), and while concurrently performing a secondary visuo-motor (WA^{motor}) or cognitive task ($WA^{cognitive}$). A 2-minute break was allowed between each task.

The secondary motor task involved stabilizing a tennis ball on a racket. The ball was attached to the racket with a string to prevent it from falling on the treadmill. When the ball fell off the racket, the researcher placed it back. The number of ball drops was counted. The secondary cognitive task involved listening to a piece of music interspersed with sounds (n = 34), such as a doorbell, a ringing phone, and a rooster. The child had to indicate the sound of the rooster (n = 13) by saying 'yes'. The number of omitted/wrong answers was registered. Prior to performing the WA^{motor} and $WA^{cognitive}$, motor and cognitive single task performance was recorded while standing still for two minutes.

WA-task performance was calculated as the weighted score for hitting the stepping stones and avoiding the obstacles. A step was considered successful when the measured center of pressure at mid stance lay within the stepping stone or outside the boundaries of the obstacle. For the secondary visuo-motor and cognitive tasks, error rates per 2 min were determined.

2.5. Questionnaires

At M2 and M3, parents completed a short survey on their perception of the C-mill training using a 5-point Likert scale. At M2, parents rated how much their child experienced the training as fun, difficult, and useful, how they perceived the quality of the supervision, and how likely they would recommend the training to others. At M3, parents rated their child's activity level, falls, responsiveness to the environment during walking, participation in play and sports activities, and self-perception on his/her motor skills in the 6 months after the training. There was also room for additional comments.

Table 2
Descriptive statistics.

Group characteristics, mean (SD)			
Gender	13 boys (76%), 4 girls (24%)		
Age (years)	8.8 (1.7)		
Height (cm)	140 (12)		
Weight (kg)	35.8 (9.5)		
Sports (min/week)	109 (84)		
MABC-2 manual dexterity standard score	4.4 (2.4)		
MABC-2 ball skills standard score	6.5 (3.5)		
MABC-2 balance standard score	6.2 (3.0)		
MABC-2 total standard score	4.4 (2.3)		
	M1 (N = 17)	M2 (N = 17)	M3 (N = 16)
WAL-K, mean (SD, range)			
Single run total score (s)	18.7 (3.6, 13.7–27.0)	19.2 (3.8, 14.2–28.1)	18.2 (3.1, 14.2–25.0)
Single run completion time (s)	17.2 (3.0, 13.7–22.5)	18.0 (3.1, 14.2–24.1)	17.6 (3.0, 13.7–23.0)
Single run mistakes (n)	3.0 (4.8, 0.0–15.0)	2.2 (2.4, 0.0–8.0)	1.3 (1.7, 0.0–6.0)
Double run total score (s)	40.4 (6.9, 29.0–57.2)	37.1 (7.7, 27.5–56.6)	36.5 (7.9, 25.9–51.5)
Double run completion time (s)	32.4 (8.8, 16.8–51.7)	29.9 (6.5, 21.0–45.6)	33.2 (6.3, 25.4–48.5)
Double run mistakes (n)	15.9 (13.0, 0.0–46.0)	14.3 (12.2, 0.0–40.0)	6.8 (6.0, 0.0–20.0)
WA success rate, mean (SD, range)			
WA^{single} (%)	69.3 (18.0, 31.6–95.9)	85.9 (14.1, 39.1–98.8)	91.1 (11.8, 51.9–100.0)
WA^{motor} (%)[a]	54.7 (22.4, 21.1–91.7)	71.8 (20.2, 30.1–94.4)	80.3 (14.3, 35.8–99.3)
$WA^{cognitive}$ (%)[b]	67.2 (17.0, 43.2–99.1)	86.2 (12.3, 54.0–99.0)	90.2 (9.7, 58.8–99.7)
Secondary task performance, median (IQR)			
Visuo-motor task error rate (errors/2 min)			
Single task	1.0 (3.0)	0.0 (1.0)	0.0 (2.0)
Dual task	10.0 (5.9)	7.5 (6.4)	7.8 (8.4)
Cognitive task error rate (errors/2 min)			
Single task	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Dual task	1.5 (1.4)	0.0 (0.5)	0.0 (0.4)

MABC-2 = Movement Assessment Battery for Children, version 2; SS = standard score; WAL-K = Walking Adaptability Ladder test for Kids; WA = Walking Adaptability task.

[a] Data of 3 children were missing at all measurement moments.

[b] Data of one child was missing at M1.

2.6. Statistical analysis

To assess the differences in WAL-K scores (total scores, completion time, and mistakes) and WA success rates (WA^{single}, WA^{motor} and $WA^{cognitive}$) between M1-M2 and M1-M3, Linear Mixed Model (LMM) analyses were performed. Data were normally distributed. Dummy variables for M2 and M3 were included in the model as fixed effects. An unstructured covariance type was used because of the uneven time periods between the measurements. Restricted maximum likelihood was used to estimate the parameters.

For the error rates of the secondary tasks on the C-mill, the differences between M1-M2 and M1-M3 were analyzed using a Friedman test (with post hoc Wilcoxon signed rank test), as these data were not normally distributed. Results of the surveys at M2 and M3 were presented descriptively. All analyses were performed using IBM SPSS Statistics v.25 (IBM Corp., Armonk, NY), and alpha was set at 0.05.

3. Results

Of the 27 recruited children, 6 children were excluded because they performed above the median age-adjusted reference walking adaptability scores of TD children [12], and 4 children declined participation prior to the start of the training. The remaining 17 children (13 boys, 4 girls) with DCD had a mean age of 8.8 (± 1.7) (Table 2) and all completed the six training sessions. Two 6-year-old children and one 8-year-old child did not perform the WA^{motor} because they felt unconfident. For the $WA^{cognitive}$, data of one 10-year-old boy was missing at M1 because he developed motion sickness due to the moving projections on the C-mill. One 10-year-old child was lost to follow-up at M3.

3.1. WAL-K

Double run WAL-K scores significantly decreased (i.e. improved) between M1-M2 (−8%) and M1-M3 (−9%; Table 3 and Fig. 1). Between M1-M2, no significant difference in completion time and mistakes was found. Between M1-M3, children made significantly fewer mistakes (−58%), but no significant difference in completion time was found. Five children (29%) improved more than the previously reported Smallest Detectable Change (SDC) of 6.0 s between M1-M2 [17]. Eight children (50%) improved more than 6.0 s between M1-M3 [17]. No significant differences were found between M1-M2 and between M1-M3 for the WAL-K single run.

Table 3
Results Linear Mixed Model.

	Comparison M1-M2		Comparison M1-M3	
	F (df)	p	F (df)	p
WAL-K				
Single run total score	.70 (1,16.0)	.415	.65 (1,14.6)	.434
Completion time	1.3 (1,16.0)	.267	.327 (1,15.7)	.576
Mistakes	.596 (1,16.0)	.452	4.0 (1,16.1)	.063
Double run total score	4.6 (1,16.0)	.049	5.0 (1,16.1)	.040
Completion time	2.4 (1,16.0)	.140	.083 (1,16.0)	.777
Mistakes	.327 (1,16.0)	.576	7.4 (1,16.1)	.015
WA success rate				
WA^{single}	23.2 (1,16.0)	< 0.001	39.1 (1,16.0)	< 0.001
WA^{motor} [a]	11.4 (1,13.0)	.005	25.3 (1,13.1)	< 0.001
$WA^{cognitive}$ [b]	17.0 (1,15.0)	.001	40.0 (1,15.0)	< 0.001

WAL-K = Walking Adaptability Ladder test for Kids; WA = Walking Adaptability.
[a] Data of 3 children were missing at all measurement moments.
[b] Data of one child was missing at M1.

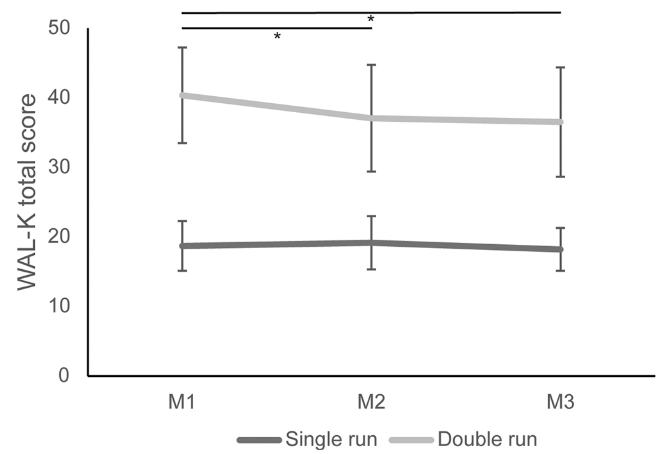


Fig. 1. Mean scores with SDs for the WAL-K total scores. *p < .05; indications of significance only count for the double run.

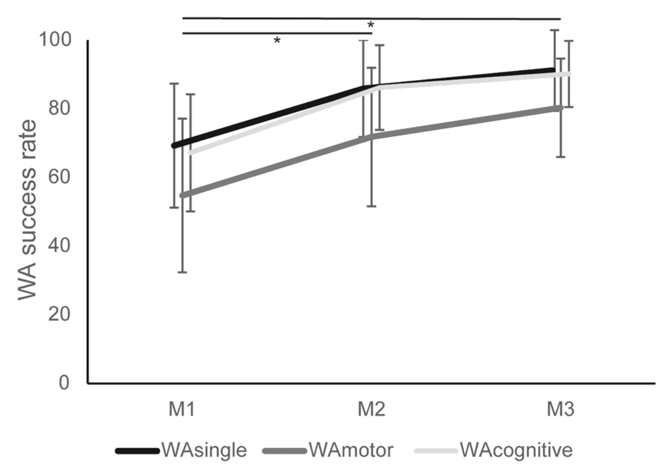


Fig. 2. Mean scores with SDs for the success rates of the WA-tasks. *p < .01; indications of significance count for all three tasks.

3.2. WA-tasks on the C-mill

Success rates of all WA-tasks had significantly improved between M1-M2 (+24–31%) and M1-M3 (+32–47%; Table 3 and Fig. 2). Children made significantly fewer mistakes on the secondary task during $WA^{cognitive}$ ($X^2 = 11.61$, $p = .003$) between M1-M2 (−67%; $Z = -2.89$, $p = .004$) and M1-M3 (−56%; $Z = -2.35$, $p = .019$). No significant change was seen in secondary task performance for WA^{motor} ($X^2 = 2.23$, $p = .328$).

3.3. Evaluation training

Results of the surveys are displayed in Table 4. At M2, parents were in general positive about the fun their child experienced, the usefulness of the training, and the supervision, while the perceived difficulty of the training was most often rated as neutral. The majority of parents (93%) would recommend the training to others.

At M3, 73% of the parents indicated that their child fell less frequently. About half of the parents indicated that their child better responded to the environment during walking and had a more positive self-perception on his/her motor skills, while the other half of the parents was neutral about these statements. The results concerning physical activity and participation were more variable.

Table 4
Results of the survey on the parents' perception of the training and its utility.

		Totally disagree	Disagree	Neutral	Agree	Totally agree
M2 (n = 14)	My child experienced the training as fun			2 (14%)	3 (21%)	9 (64%)
	My child experienced the training as difficult	1 (7%)	4 (29%)	8 (57%)	1 (7%)	
	My child experienced the training as useful			3 (21%)	4 (29%)	7 (50%)
	Supervision during the training was good				2 (14%)	12 (86%)
	I would recommend the training to others			1 (7%)	4 (29%)	9 (64%)
M3 (n = 15)	In the 6 months after the training, my child…					
	… was more active		3 (20%)	5 (33%)	3 (20%)	4 (27%)
	… fell less			4 (27%)	8 (53%)	3 (20%)
	… better responded to the environment during walking			8 (53%)	5 (33%)	2 (13%)
	… participated more in play and sports activities		1 (7%)	9 (60%)	4 (27%)	1 (7%)
	… had a more positive self-perception on his/her motor skills			7 (47%)	5 (33%)	3 (20%)

4. Discussion

The aim of this proof-of-concept study was to examine the effect of C-mill augmented reality treadmill training on walking adaptability in children with DCD. We found improvements on treadmill-based walking adaptability tasks, and we observed generalization of training effects to an overground walking adaptability task (WAL-K double run). These effects were seen immediately after training and were retained after 6 months follow-up.

The improved success rates on all three WA-tasks on the C-mill confirm the expected task-specific effects of the C-mill training program on walking adaptability. These effects correspond with earlier research that demonstrated the importance of task-specificity of training for improving motor skills in children with DCD [2]. Compared to the mean scores of 69 TD children in a previous study (mean age 8.9 years, SD 1.9), the walking adaptability success rates of the children with DCD at baseline were on average 1.3–1.7 SDs lower, yet at the follow-up assessment, the performance of the children with DCD had advanced to values of 0.13 below to 0.28 SDs above the mean scores of TD children [12]. As the particular WA-tasks were not included in the training, these findings may suggest a training-induced normalization of walking adaptability performance in children with DCD. Yet, as the context on the C-mill during training and assessments was similar, it is likely that the improved walking adaptability success rates can at least partly be attributed to familiarization with these types of treadmill-based tasks.

In addition to the improved success rates following training and after follow-up, we also observed improvements in secondary task performance while performing the WA-task, albeit only significantly for the cognitive task. These results indicate that after training, children needed to allocate less attentional resources to the WA-task –while also achieving better success rates– and had more capacity left to focus on the secondary task, possibly due to improved automatization of walking adaptability skills.

Importantly, the effects of training were not only observed on the C-mill-based WA-tasks, but also generalized to walking adaptability overground. This transfer to an overground task is particularly relevant, since children with DCD are known to have difficulties with the transfer of training effects to daily life situations [2]. At baseline, average double run WAL-K scores were 2.1 SDs below the age-adjusted reference values of TD children, whereas after follow-up, this difference was reduced to 1.4 SDs below reference values [17]. These improvements on the WAL-K double run were not only significant, but exceeded the previously reported SDC value of 6 s in half of the children with DCD at the follow-up measurement [17]. Hence, this confirms the presence of a clinically relevant effect of training on overground walking adaptability in children with DCD, yet they did not advance to the performance level of TD children [17]. The transfer to daily life was also supported by the results of the questionnaire; the majority of parents reported fewer falls, and half of the parents responded that their child better attended to the environment. It may be of interest for future studies to explore whether adding overground walking adaptability exercises during training may further improve the generalization of the training effects.

In contrast to the observed improvements on the WAL-K double run, no significant effects were found on the single run, whereas the baseline performance deficit on the single run (2.0 SDs below reference values of TD children) was in the same order of magnitude to that on the double run. As the observed improvement on the double run total score after follow-up was largely due to a reduction in the number of mistakes (i.e. accuracy) without significant changes in completion time, it may be suggested that the lower number of mistakes on the single run (3.0 vs. 15.9 on the double run) left relatively little room for improvement in task accuracy. This is partly in line with the results of previous research, showing that following Wii balance training, task accuracy in a dynamic balance game was more sensitive to change than speed [20].

Our training was designed to challenge the children's predictive control by provoking rapid and unexpected changes of the walking pattern. Although our outcome measures did not exclusively assess predictive control deficits, the results generally support an improvement in predictive control as the underlying mechanism. It is known that problems with predictive control are being magnified during dual tasks [6], hence the reduction in dual task costs that we found in the WA^{motor} and $WA^{cognitive}$ fits with the suggested improvement in predictive control. In addition, the generalization of the training effect to the untrained, overground context of the WAL-K double run and the retention after 6 months follow-up are in line with this hypothesis. However, with the current results we cannot provide conclusive evidence on whether children improved their predictive control after walking adaptability training, so this warrants further research.

This proof-of-concept study comes with some limitations. The lack of a control group precludes identifying to what extent the observed improvements may be explained by learning effects on the task itself. It must be mentioned, though, that the improvements in WAL-K double run scores (3.3 at M2 and 3.9 s at M3) exceed the previously reported test-retest difference in TD children of 2.6 s [17]. Therefore, we believe that children showed a real improvement on the WAL-K after training. A second limitation concerns the relatively short intervention period of only 180 min. Although this may not be intensive enough to fully achieve the potential benefits of C-mill training in children with DCD, we deliberately chose this limited training period because the largest gains are generally achieved in the first sessions of an intervention [23] and previous studies also found improved motor skills after short interventions (120 and 200 min) in children with DCD [19–21]. It remains an open question whether a longer training period or a blended C-mill and overground training program might result in larger gains.

In conclusion, C-mill training was well-received by the children and their parents and it appears promising for improving walking adaptability in children with DCD, which skill is highly relevant in daily life activities. The current study gives directions for possible measurement tools and effect sizes, which information is needed for conducting a definite trial on the efficacy of C-mill training for improving walking adaptability in children with DCD. Based on the present results, we recommend using the double run of the WAL-K as the primary outcome measure for such a trial.

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Conflict of interest statement

The authors have no competing interests to declare.

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