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The effects of dual tasks on gait in children with cerebral palsy

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ABSTRACT

Aim: To assess the gait and cognitive performances of children with cerebral palsy (CP) during dual tasks (DT) in comparison to typically developing (TD) children.

Method: This prospective, observational, case-control study included 18 children with CP (7 girls, 11 boys; median age 12 [10:13] years and 19 controls (9 girls, 10 boys; median age 12 [10:13y6mo] years). Performances were recorded during a simple walking task, 5 DT (walking + cognitive tasks with increasing cognitive load), and 5 simple cognitive tasks (while sitting). Gait parameters were computed using an optoelectronic system during walking tasks. Six parameters were selected for analysis by a principal component analysis. Cognitive performance was measured for each cognitive task. The dual-task cost (DTC) was calculated for each DT.

Results: Gait performance decreased in both groups as DT cognitive load increased (e.g., walking speed normalized by leg length, in simple task: 1.25 [1.15:1.46] s^{-1} for CP, 1.53 [1.38:1.62] s^{-1} for TD; DT with highest load: 0.64 [0.53:0.80] s^{-1} for CP, 0.95 [0.75:1.08] s^{-1} for TD). The CP group performed significantly worse than TD group in every task (including the simple task), but DTC were similar in both groups. A task effect was found for the majority of the gait parameters.

Interpretation: The reduced gait performance induced by DT may generate underestimated difficulties for children with CP in daily-life situations, where DT are common. This should be considered in clinical assessments.

1. Introduction

Cerebral palsy (CP) is the most frequent motor disability in childhood, affecting 1.8:1000 births in Europe [1]. CP affects motor control and frequently cognitive functions. Up to 65% of children with CP have executive, visuospatial, and attention deficits as well as learning disabilities [2]. These impairments, combined with motor limitations, can lead to increased difficulties in circumstances where cognitive and motor tasks are performed simultaneously [3], since both tasks compete for the brain's resources [4]. While motor assessments are largely used to guide therapeutic decisions, cognitive-motor interferences are rarely taken into account.

The dual task (DT) paradigm - performing a motor task and a cognitive task simultaneously - has been widely used to study cognitive–motor interferences [5,6]. DT protocols have been used to investigate the risk of falls among older adults [7] and patients with neurological disorders, such as Alzheimer's disease or multiple sclerosis [8,9]. They have rarely been studied in pediatric populations. DT assessments are appropriate to investigate the automaticity of motor control in children with and without developmental disorders [10–13]. The underlying concept is that when a motor task is adequately learned the dedicated attentional resources are low, which allows a second task to be executed concurrently [10]. In children with CP, few studies have assessed performances during DT despite the fact that they might be relevant to understand their difficulties in daily life. Reilly et al. showed an increase of body sway in children with CP during a DT in standing, greater than in TD children [14]. Three studies concluded that a DT induces a decrease in walking speed in small samples of children with

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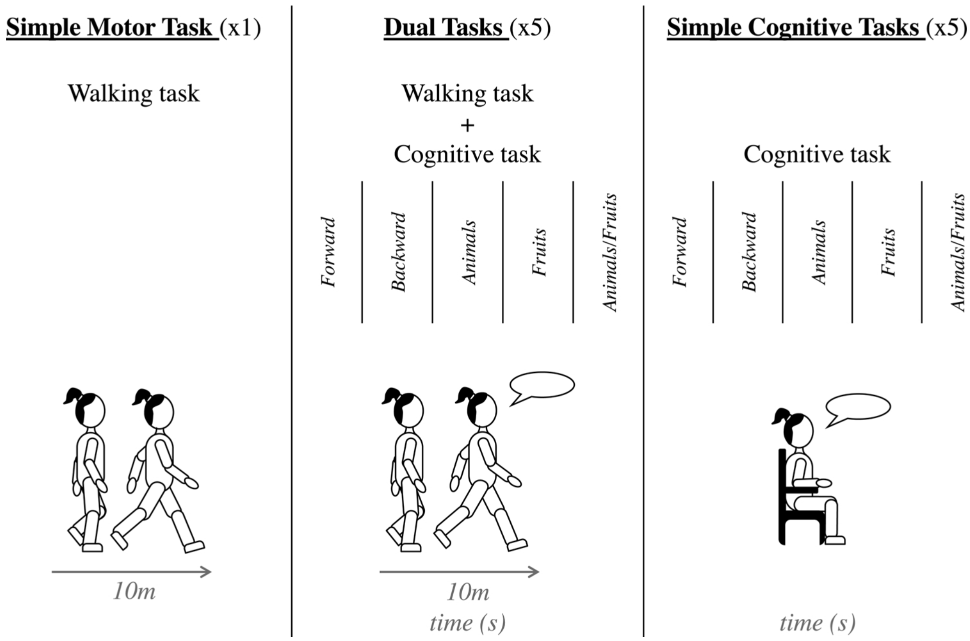

Fig. 1. Experimental protocol including the simple motor task (SmT), the dual tasks (DT), and the simple cognitive tasks (ScT).

CP (≤15) [4,12,15]. Step length, step time, and their variability changed significantly under two DT (number memorization and sound recognition) in comparison to a simple walking task [15]. The common limitations reported by the authors concerned the baseline differences between groups and the degree of cognitive demand, unadjusted to the simple task abilities of the participants [15]. The dual-task cost (DTC), which expresses change between the simple task and the DT [3,16], is used to overcome this limitation. Considering the small sample sizes and heterogeneity of motor and cognitive tasks in previous studies, further exploration of the impact of DT in children with CP is essential. This could improve the understanding of their everyday-life difficulties [14] leading to improvements of therapeutic strategies [17].

Although walking speed is the first-line parameter to describe an individual's overall gait performance [5], it does not describe gait completely [18]. Children with CP are also affected by problems of gait symmetry, regularity, stability, and coordination [19], thus complementary parameters should be used to evaluate gait in this population. Pace, rhythm, asymmetry, variability, and postural control have previously been identified as five independent domains relevant for describing gait in the elderly [20] and adults with hip fracture [18]. These domains are relevant to characterize the effects of DTs in children with CP.

This study aimed to assess the effects of DTs (using increasing cognitive loads) on gait and cognitive parameters in children with CP compared with TD controls. We hypothesized that 1) the performances of both groups would decrease under DT conditions, and 2) children with CP would experience a greater decrease due to motor and cognitive impairments resulting in higher DTCs.

2. Method

2.1. Participants

This prospective, observational, case-control study included 18 children diagnosed with CP followed in a pediatric neuro-orthopedic clinic of a tertiary hospital. Eligibility criteria were: 1) age 8–16 years old, 2) ability to walk 50 m without mechanical walking aids (canes, tripods, walker) and/or orthoses, 3) Gross Motor Function Classification System (GMFCS) level I or II [21], and 4) regular school curriculum. Twenty controls with equivalent ages and sex proportions, recruited via hospital employees and patients' acquaintances, were also included. Participants were excluded in cases of borderline or low intellectual ability (IQ < 80) and/or behavioral symptoms which might affect participation in the protocol. No exclusion criteria were specified regarding treatments, but none of the children had surgery or botulinum toxin injections during the year prior to the assessment. Informed consent was obtained from each participant and their parents. The hospital's institutional ethics committee approved the study protocol (CCER-15-203).

2.2. Protocol

Each participant was evaluated once in the hospital's motion analysis laboratory. Participants were asked to walk along a straight 10-meter walkway (simple motor task: SmT) and then to repeat this while performing five successive cognitive tasks, thus creating DT. Each task was performed once to avoid any anticipation effect of the DT [22]. After a short rest, participants were asked to sit comfortably on a chair with armrests and a backrest and to perform the same cognitive tasks in the time taken to perform that task while walking 10 m (simple cognitive tasks: ScT). Fig. 1 illustrates the experimental protocol.

The cognitive tasks were: counting forward from zero ('*Forward*'), counting backward from 50 ('*Backward*'), enumerating animal names ('*Animals*'), enumerating fruit names ('*Fruits*'), and alternatively enumerating animal and fruit names ('*Animals/Fruits*'). These tasks were selected as they were of short duration and could be performed orally (out loud), while walking and sitting, close to natural conditions. The tasks' level of complexity was considered to increase with the required attentional load, as follows: *Forward* < *Backward* < *Animals* < *Fruits* < *Animals/Fruits*. Tasks were performed in a randomized order to avoid any fatigue effect. Before each measurement, a trained evaluator gave standard instructions. Participants were asked to perform both tasks (motor and cognitive) to the best of their ability, without prioritization.

2.3. Data acquisition

Participants were equipped with 16 reflective markers (14 mm diameter) placed on specific anatomical landmarks of the pelvis and the lower limbs according to the Plug-in Gait model [23]. Markers' trajectories were recorded using a twelve-camera motion analysis system

Table 1
General characteristics of the study sample.

	Groups				
	TD (n = 19)	CP (n = 18)	p-value	95% CI	ES
Individuals characteristics					
Female (%)[k]	7 (47%)	9 (39%)	0.231	−21% to 5%	.089
Age (year)[u]	12 [10:13.5]	12 [10:13]	0.951	−2 to 2	.943
Body mass (kg)[u]	40 [31.5:47]	45 [40:57.7]	0.153	−18 to 2	.168
Body height (m)[u]	1.53 [1.41:1.64]	1.53 [1.46:1.64]	0.704	−0.13 to 0.08	.088

[k] = values are n (%) and Pearson Khi2 test were used; [u] = values are median [interquartile range] and Mann-Whitney U test were used; *: $p < 0.05$; ES is Cohen's effect size, 95% CI is 95% confidence interval;

(Oqus7 +, Qualisys, Göteborg, Sweden) at 100 Hz and exported using Matlab R2012 software (Mathworks, Natick, USA) and the Biomechanical Toolkit [24].

2.4. Parameters

2.4.1. Gait parameters

Using the markers' trajectories, 19 gait parameters were computed, representative of 7 gait domains: rhythm, pace, variability, quality, asymmetry, stability, and coordination (Table 2). Domains were selected based on their frequent use in gait analysis and as previously described [18,20].

We chose to analyze the gait parameters of the most affected side for the children with CP (based on muscular strength of the lower limbs, assessed by a physiotherapist using the Medical Research Council testing), and, arbitrarily, the left side for TD children since limb symmetry was assumed [25].

Results were computed as means and standard deviations across the gait cycles for each walking task (each trial).

Stops and backward steps due to any hesitation were discarded. Only entire gait cycles were used for analyses.

In addition, the motor DTC (DTC_{motor}) was computed for each parameter, as described in Kelly et al. [16]:

$$DTCmotor = \frac{|\text{ SmT value} - \text{DT value}|}{\text{DT value}} x100$$

2.4.2. Cognitive scores

The cognitive score consisted of the number of correct responses counted by the evaluator (excluding repetition, omission while counting, and non-existent items) per second of the walking task. The cognitive DTC ($DTC_{cognitive}$) was computed following the same formula [16]:

$$DTCcognitive = \frac{|\text{ScT score} - \text{DT score}|}{\text{DT score}} x100$$

2.5. Statistical analysis

Statistical analyses were performed with RStudio software (version 1.1, Boston, USA). Non-parametric tests were performed since the normality of the distribution of gait parameters was not verified (confirmed by significant Shapiro-Wilk tests) and the sample size was small. Participant details were reported as medians [interquartile range], and gait results were presented in box plots. Participant characteristics were analyzed using Pearson Chi2 and Mann–Whitney U tests.

We used principal component analysis (PCA) [26] to select the gait parameters which explained the most variance within the whole population and for all the tasks. The principal components (PC) were selected so that at least 70% of variance was explained [27]. Parameters with loading factors (i.e. correlation coefficient between variables and PC), in absolute values, greater than 0.5, were considered relevant. If more than one parameter was found to be relevant within a domain, only the parameter with the highest loading factor was selected.

Furthermore, CP and TD groups were compared using Mann–Whitney U tests. Comparisons within the groups, between tasks were assessed using Friedman ANOVA tests. The level of significance was set at 0.05. The level of significance after Bonferroni adjustments was calculated from the number of tests.

3. Results

3.1. Population description

We included 19 TD children and 18 children with CP (12 unilateral, 6 bilateral; 16 GMFCS I, 2 GMFCS II). One TD child was an extreme outlier: he often stopped with backward steps resulting from hesitations, and was excluded from the study. Table 1 shows the characteristics of the study sample. Groups were not statistically different with regards to sex ($p = 0.231$), age ($p = 0.951$), height ($p = 0.704$), and weight ($p = 0.153$).

3.2. Variable selection

The selection of variables is illustrated in supplementary data (Supplementary Fig. 1). The first 5 PC explained 74.3% of the variance and were selected for our analysis. From these, sixteen parameters had loading factors greater than 0.5 (in absolute value). For each gait domain, the variable with the highest loading factor was selected. However, to allow comparisons with other studies, the walking speed was selected despite the fact that it had the second highest loading factor (0.89, compared to 0.90 for stride length).

We therefore included the following six variables for analysis in our study: walking speed, walk ratio, hip range of motion (ROM), stride-length coefficient of variation (CV), stride time, and heel clearance.

3.3. Dual-task effects on the motor task

The results are presented as box plots in Fig. 2, and the corresponding table is available in supplementary data (Supplementary Table 1). The distribution of the six selected gait parameters for each group and task was heterogeneous, particularly among children with CP. The $DTCs_{motor}$ are represented in Fig. 3. Results of the comparison between the CP and TD groups (group effect) and within groups between tasks (task effect) are presented in Table 3.

3.3.1. Within-group comparisons: task effects

Decreasing gait performances were observed in both groups as the cognitive load of the tasks increased: walking speed, heel clearance, and hip ROM decreased; walk ratio, stride-length CV, and stride time increased. A significant task effect was found within both groups and for all parameters except the walk ratio in the CP group. A significant difference between tasks was also found for the DTC_{motor} except for the walk ratio DTC_{motor} in both groups.

Table 2
Gait domains, gait parameters, definitions, and units.

Domain	Parameter	Definition	Unit
Rhythm	Stride Time	Time between 2 successive foot strikes	s
	Stance Duration	Stance duration	% of GC [1]
	Cadence	Number of steps/min	step.min^{-1}
Pace	Stride Length	Stride length normalized by leg length	[-]
	Step Length	Step length normalized by leg length	[-]
	Walking Speed	Walking speed normalized by leg length	s-1
Variability	Gait SD	Kinematic variability based on 9 kinematic waveforms: pelvic tilt, obliquity, and rotation, hip flexion, abduction, and rotation, knee flexion, ankle dorsiflexion, and foot progression angle [27]	°
	Stride-Time CV [2]	Stride-time variability	%
	Stride-Length CV [2]	Stride-length variability	%
Quality	Pelvis ROM [3]	Maximum–minimum pelvic obliquity	°
	Hip ROM [3]	Maximum hip flexion–maximum hip extension	°
	Knee ROM [3]	Maximum knee flexion–maximum knee extension	°
	Ankle ROM [3]	Maximum dorsiflexion–maximum plantarflexion	°
	Gait Profile Score (GPS)	Index of overall kinematic deviation based on 9 joint angles: pelvic tilt, obliquity, and rotation, hip flexion, abduction, and rotation, knee flexion, ankle dorsiflexion, and foot progression angle [28]	°
Asymmetry	Step-Length Asymmetry Index (AI)	100*(|left step length - right step length|)/ ((left step length + right step length) * 0.5)	%
	Step-Time AI	100*(|left step time - right step time|)/ ((left step time + right step time) * 0.5)	%
Stability	Step Width	Distance between heels normalized by pelvis width at initial contact	[-]
	Heel Clearance	Maximum heel height during swing with respect to minimum during stance [29]	m
Coordination	Walk Ratio	Ratio step length/cadence [24]	min.step^{-1}

[1] GC = Gait Cycle.
[2] CV = Coefficient of Variation.
[3] ROM = Range Of Motion.

3.3.2. Between-group comparisons: group effects

Children with CP walked with lower walking speed, heel clearance, and hip ROM, and higher walk ratio, stride-length CV, and stride time than the TD children. For each task, including the simple task, the CP and TD groups showed significant differences in walking speed, hip ROM and heel clearance. The walk-ratio was significantly different between CP and TD groups in the DT-*Animals* and *Animals/Fruits*. The stride length CV showed significant difference for the DT-*Backward*.

The CP and TD groups did not show any significant differences in their DTC_{motor} except for the walk ratio in the 3 most difficult DT (*Animals*, *Fruits*, and *Animals/Fruits*).

3.4. Dual-task effects on cognitive performance

3.4.1. Within-group comparisons: task effects

A significant task effect was found in the TD group for *Forward* and *Backward* counting (p = 0.02 and 0.04, respectively): TD children enumerated more items in ScT than in DT. No task effects were found for the TD group's other tasks or for any of CP group's tasks ($p > 0.173$).

3.4.2. Between-group comparisons: group effects

No group effects were found for *Forward* and *Backward* tasks ($p > 0.331$). A significant group effect was found in the scores for verbal fluency tasks (*Animals*, *Fruits,* and *Animals/Fruits*) in both ScT and DT: TD children enumerated more items than children with CP in those tasks. However, no significant differences between the groups were found for $DTC_{cognitive}$.

4. Discussion

We aimed to assess the effects of DT on the gait and cognitive parameters of children with CP. The main finding was the validation of our first hypothesis, since both populations (participants with CP and TD controls) showed decreased performances in DT conditions, although these were not statistically significant for cognitive performance. Furthermore, we demonstrated that children with CP performed worse than their TD counterparts across all tasks, including the simple task, especially for the walking speed, hip ROM and heel clearance. These results were in line with previous reports which showed a significant difference between groups in spatiotemporal parameters while walking with a concurrent task :digit memorization and sound recognition [15] and carrying a box [12]. Similarly to their studies, our group of children with CP exhibited significantly worse gait performances than TD children in the simple walking task. Further analysis of the DTC_{motor} revealed that the group effect was mainly associated with the difference in the simple task, except for the walk-ratio in the verbal fluency tasks. Our second hypothesis was thus not validated, because the costs between DT and simple tasks (whether SmT or ScT) were not significantly higher in children with CP than in TD children for the majority of parameters and all the DT.

Considering that DTC is related to the recruitment of shared cortical resources for both tasks [3], our findings may in fact indicate that CP gait is not more dependent on cortical resources than TD gait during DT. Through cortical activation measures, children with CP have been shown to recruit more cortical area while walking than TD children, leading to automatization defects [28,29]. In literature on aging, this mechanism is known as the « dedifferentiation theory » reflecting the difficulty in recruiting specialized neural mechanisms [30]. We can hypothesize that, while in SmT the brain resources are not equal between the groups, in DT, both groups saturate equally their baseline resources, leading to an absence of DTC difference. Studies using fNIRS in CP population under DT might help the understanding on this topic.

Even though the DTC was not significantly different between groups, children with CP experienced greater gait difficulties when dealing with DT situations than their TD peers. For example, the median walking speed of children with CP in DT-*Backward* corresponded to the median walking speed of TD children in DT-*Animals/Fruits*. For the more complex DT, children with CP demonstrated very low gait performances. They systematically performed lower than TD children, regardless of the task or the parameter.

We observed a progressive effect of DT on gait parameters, depending on the task's cognitive load. This task effect was found for both groups, in agreement with Katz-Leurer et al. [15] but in contrast with Hung et al. [12], who did not find any task effect in the TD group. This can be related to the choice of the secondary task: carrying a box while walking being less challenging than our cognitive tasks. The task effects on DTC_{motor} revealed that cognitive tasks did not affect gait parameters equally (Friedman *p*-values below the level of significance even after

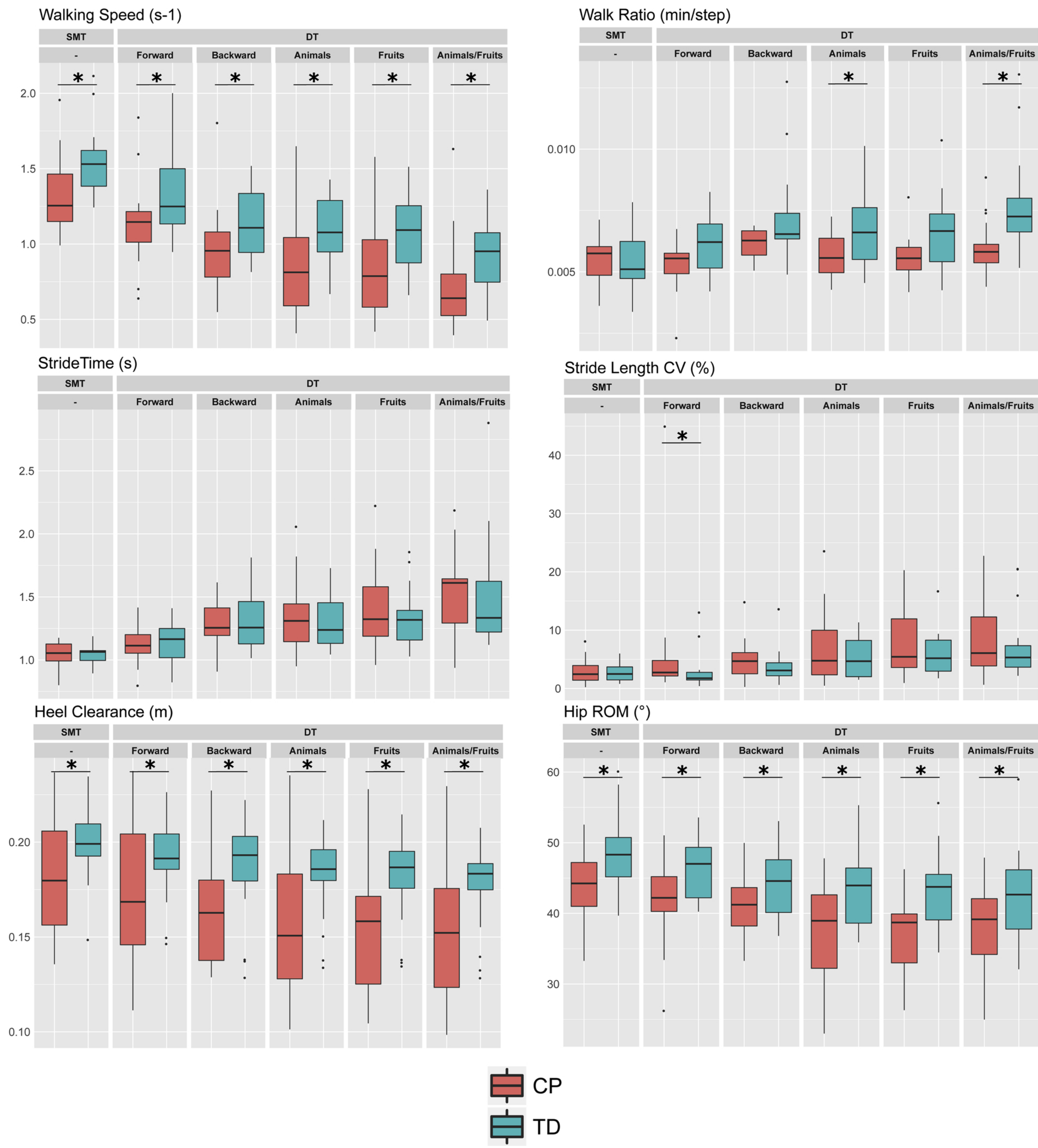

Fig. 2. Gait parameter representation for each task (vertical facets: simple motor task (SmT) and dual tasks (DT)) and each group (cerebral palsy (CP) in red, typically developing (TD) in blue). * indicate significant differences ($p < 0.050$) between groups, assessed by Mann-Whitney U tests (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Bonferroni correction), except for the walk ratio in the CP group for which no significant task effects was found.

The walk ratio is the ratio between step length and cadence, which is supposed to reflect the spatiotemporal coordination of gait and be invariant in spontaneous gait [31]. The walk ratio of TD children increased in DT, which was mostly due to a notable decrease of their cadence whereas their stride length decreased only slightly. Among children with CP, however, both parameters decreased significantly, leading to more constant walk ratios. Although DT affected both spatial and temporal parameters in children with CP, TD children were better able to maintain their stride length.

Although the participants were asked to perform the DT without task prioritization, it appeared that they prioritized the cognitive task. Gait performances decreased, whereas cognitive scores did not change significantly from ScT to DT. This "cognitive-first" strategy, as opposed to "posture-first", has been described in studies on aging [32,33] or patients with Parkinson's disease [34], causing gait instability and falling. Although not extensively studied in children, the "cognitive-first" strategy may reflect a child-specific behavior in DT, since falling is not a major issue in comparison to older adults. We believe that this adopted strategy was also partly due to the nature of the proposed DT: the participants were constrained by the motor task (an imposed distance to walk) and had freedom in the cognitive task.

Six parameters belonging to distinct gait domains were selected on the basis of a multivariate analysis of our data. Besides the domains previously described in the literature (pace, rhythm, variability,

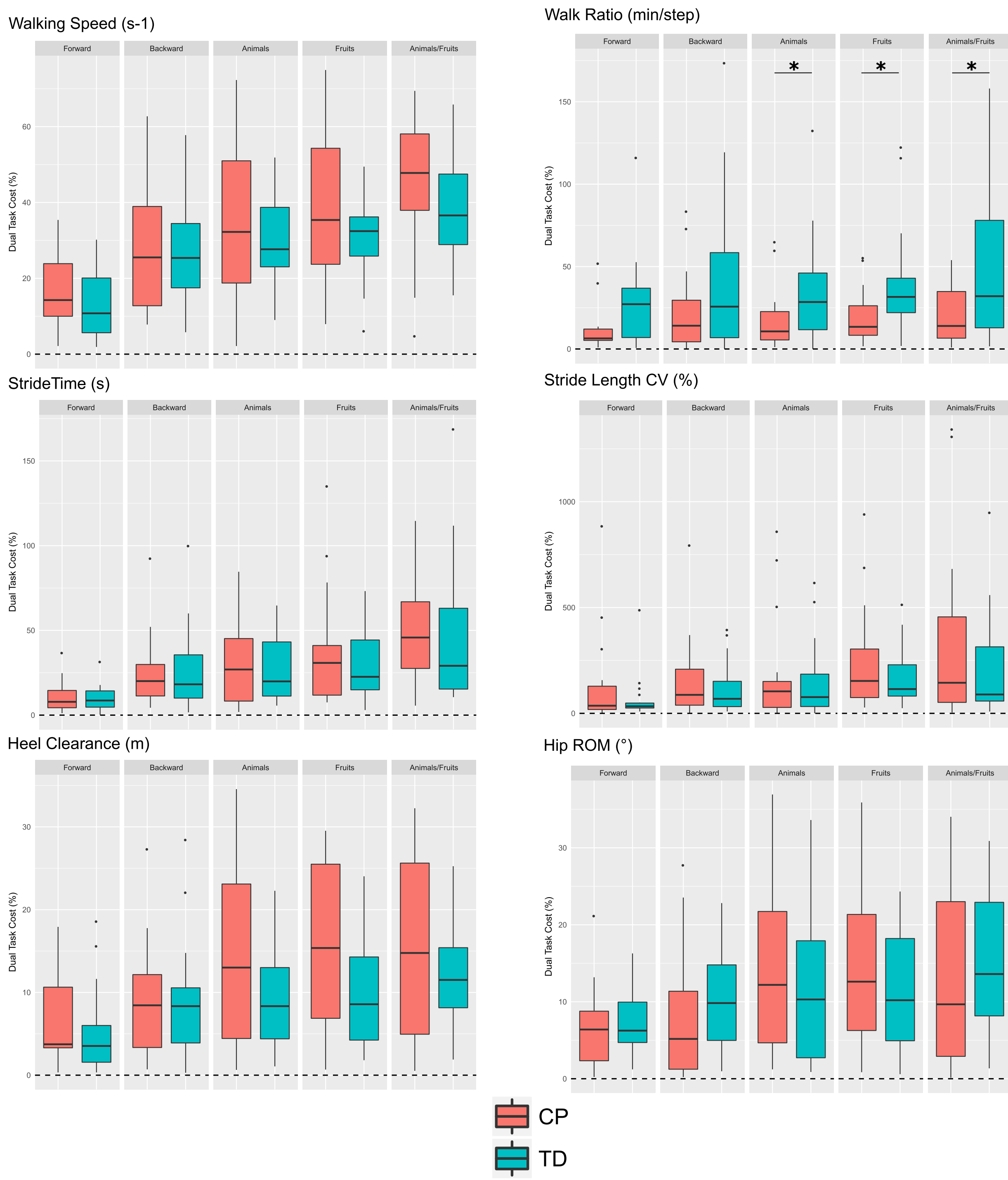

Fig. 3. Dual task costs representation for each task (vertical facets: dual tasks (DT)) and each group (cerebral palsy (CP) in red, typically developing (TD) in blue). * indicate significant differences ($p < 0.050$) between groups, assessed by Mann-Whitney U tests (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

asymmetry, and postural control), parameters relating to gait quality, such as joint angles, were added to the analysis because they provide substantial information about the gait disorders of children with CP [35], are frequently analyzed in gait analysis and were computable using our optoelectronic system. We highlighted the decrease in hip ROM and heel clearance in DT among children with CP and TD children. The present study was the first to use such an approach to assess DT effects, and we believe that it provided a more complete description of gait deviations than previous studies [11,15]. The method of parameter selection included arbitrary choices of thresholds (70% of variance explained, |loading factors| > 0.5) which are debatable, but the conclusions would have been similar with other thresholds.

This study's main limitations were its cohort's heterogeneity. The wide age range includes an age that is a turning point regarding the maturity of gait and attentional resources, which may influence the results [36]. A complementary analysis, available in supplementary data (Supplementary Figs. 2 and 3), supported the idea that the age heterogeneity could be one explanation for the absence of DTC difference between CP and TD groups since the youngest and oldest TD children did not show the same behavior regarding DT. Furthermore,

Table 3
Task effect and group effect results on gait parameters and motor dual-task costs (DTC_{motor}).

	Group	Simple	Forward counting	Backward counting	Animals	Fruits	Animals/fruits	Task effect
		Group effect *p*-value between groups						*p*-value between tasks
Walking Speed	TD	**0.006**	**0.031**	**0.034**	**0.010**	**0.010**	**0.020**	< ***0.001***
	CP							< ***0.001***
Walk Ratio	TD	0.685	0.066	0.075	**0.029**	0.075	***0.001***	***0.014***
	CP							0.061
Stride-Length CV	TD	0.558	**0.031**	0.233	0.730	0.578	0.480	< ***0.001***
	CP							***0.014***
Hip ROM	TD	**0.017**	**0.022**	**0.039**	**0.022**	**0.011**	**0.049**	< ***0.001***
	CP							< ***0.001***
Stride Time	TD	0.574	0.915	0.845	0.620	0.518	0.438	< ***0.001***
	CP							< ***0.001***
Heel Clearance	TD	**0.034**	**0.046**	**0.029**	**0.024**	**0.007**	**0.014**	< ***0.001***
	CP							< ***0.001***
MOTOR DUAL TASK COSTS (DTC_{motor}):								
Walking Speed DTC_{motor}	TD	/	0.313	0.940	0.374	0.343	0.199	< ***0.001***
	CP							< ***0.001***
Walk Ratio DTC_{motor}	TD	/	0.066	0.258	**0.046**	**0.014**	**0.042**	0.454
	CP							0.272
Stride-Length CV DTC_{motor}	TD	/	0.730	0.671	1.000	0.578	0.584	***0.032***
	CP							**0.042**
Hip ROM DTC_{motor}	TD	/	0.538	0.098	0.480	0.358	0.855	***0.002***
	CP							< ***0.001***
Stride-Time DTC_{motor}	TD	/	0.964	1.000	0.753	0.796	0.578	< ***0.001***
	CP							< ***0.001***
Heel Clearance DTC_{motor}	TD	/	0.213	0.869	0.284	0.105	0.538	< ***0.001***
	CP							< ***0.001***

Between-group *p*-values were obtained using Mann–Whitney U tests; between-task *p*-values were obtained using Friedman ANOVA tests. Significant *p*-values (< 0.050) are presented in bold, and significant *p*-values after Bonferroni correction (< 0.001 between groups, and < 0.004 between tasks) are presented in bold and italic. CP and TD stand for cerebral palsy and typically developing, respectively.

even though this study focused on the functional impact of CP, we are aware of the heterogeneous clinical profiles between unilateral (UCP) and bilateral CP (BCP). A complementary sub-analysis, available in supplementary data (Supplementary Fig. 4), comparing children with UCP and BCP did not show any differences regarding DTC, but the number of participants was insufficient within each group to draw a conclusion. Further analysis is needed to provide more specific evidence of the DT effect in the UCP and BCP populations. The power and the generalization of our analyses are limited in light of the small sample size. Another important limitation was the motion analysis system's limited capture volume, which weakens the relevance of certain gait parameters, such as the variability parameters. Additionally, assessment in laboratory settings (in underwear, walking barefoot, etc.) may not reflect real-life situations. To overcome these two last limitations, the use of wearable sensors in daily-life conditions could constitute a relevant alternative.

4.1. Clinical implications

This study emphasized the importance of assessing gait in DT conditions in order to better understand limitations on the activities of children with CP. In children with mild levels of motor impairment, difficulties due to cognitive–motor interferences might be underestimated whereas they should be taken into account when devising therapeutic strategies and discussing specific adaptations at home or in school. For instance, therapists and teachers may adapt environments and instructions in such ways that they are more appropriate for a child's motor, but also cognitive abilities [11]. Our study supports that training programs should integrate DT exercises [4,17]. Since daily life is not isolated from cognitive constraints, the difficulties revealed in this study are likely to influence everyday walking situations in patients' real lives.

5. Conclusion

Interferences between motor and cognitive tasks have significant effects on walking performance in children with and without CP. Failing to account for the effects of dual tasking in daily life may lead to an underestimation of the difficulties encountered by children with CP, including those with mild impairments. The cost of dual tasks should therefore be considered in clinical assessments and treatment planning.

Declarations of interest

None.

CRediT authorship contribution statement

Lena Carcreff: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Joel Fluss:** Conceptualization, Methodology, Resources, Writing - review & editing, Project administration, Funding acquisition. **Gilles Allali:** Methodology, Writing - review & editing. **Nathalie Valenza:** Methodology, Writing - review & editing. **Kamiar Aminian:** Writing - review & editing. **Christopher J. Newman:** Resources, Writing - review & editing, Supervision. **Stéphane Armand:** Conceptualization, Methodology, Software, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gaitpost.2019.02.014.

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