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RELATIONSHIP BETWEEN SPATIOTEMPORAL PARAMETERS AND CLINICAL OUTCOMES IN CHILDREN WITH BILATERAL SPASTIC CEREBRAL PALSY: CLINICAL INTERPRETATION PROPOSAL

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ABSTRACT

Background: Understanding the links between gait disorders, impairments, and activity limitations is essential for correctly interpreting the instrumented gait analysis. We aimed to evaluate the relationships between spatiotemporal parameters and clinical outcomes in children with bilateral spastic cerebral palsy, and find out whether spatiotemporal parameters provide clinical information regarding gait pattern and walking.

Methods: Data from 19 children with bilateral spastic cerebral palsy (nine males, ten females, 9.6 ± 2.8 years old) were collected retrospectively. All children underwent an instrumented gait analysis and a standardized clinical assessment. Seven spatiotemporal parameters were calculated: non-dimensional cadence, stride length, step width, gait speed, first double support, single support, and time of toe off. Clinical outcomes included measures of two different components of the International Classification of Functioning, Disability and Health - Children and Youth version: body functions and structures (spasticity, contractures and range of motion, and deformities), and activities and participation (gross motor function, and walking capacity). Pearson correlation, ANOVA, Student's t, Mann-Whitney U, and Kruskal-Wallis tests were used to analyze relationships. Spatiotemporal parameters related to clinical outcomes of body functions and structures were interpreted as outcome measures of gait pattern, while those related to clinical outcomes of activities and participation were interpreted as outcome measures of walking.

Results: Non-dimensional cadence, stride length, and gait speed showed relationships ($p < 0.05$) with hip flexors spasticity and hindfoot deformity, ankle plantar flexors spasticity, and hindfoot deformity, respectively. All spatiotemporal parameters except non-dimensional cadence showed correlation ($p < 0.05$) with gross motor function and walking capacity.

Conclusions: Spatiotemporal parameters provide clinical information regarding both gait pattern and walking.

KEYWORDS: gait analysis, correlation, child, cerebral palsy.

1. Introduction

Cerebral palsy (CP) is the most common cause of chronic childhood motor disability with a prevalence of above 2 per 1000 live births [1]. CP describes a group of permanent disorders affecting movement and posture that are attributed to non-progressive lesions in the developing fetal or infant brain [2]. Spasticity is often the dominant motor disorder [3], along with loss of selective motor control and impaired balance [4]. Secondary musculoskeletal problems like muscle contractures, muscle weakness, bony deformities and joint instability appear as a consequence of growth and development of the musculoskeletal system [4]. Their interaction, occurring at multiple levels, affects the quality and efficiency of gait and other aspects of motor function [4], contributing to activity limitation and participation restriction. The Instrumented Gait Analysis (IGA) allows a precise and rigorous quantification of gait characteristics, through the use of objective data (including spatiotemporal (ST), kinematic, kinetic and surface electromyography data) that cannot be appreciated visually or measured during a static physical examination [5]. The IGA is often used in the assessment of ambulatory children with CP, for multiple purposes including the identification and understanding of gait disorders, the refinement of clinical decision-making, and the evaluation and understanding of the effects of treatments on gait disorders [4–6]. However, the reliability, validity and clinical utility of the IGA have not been well established yet [4,7]. One of the disadvantages of the IGA is the large amount of data collected and analyzed, which makes it a complicated instrument to use and difficult to interpret [8]. Understanding the links between gait disorders and clinical impairments, that is, between gait parameters and clinical outcomes, is essential for correctly interpreting the IGA [6].

The International Classification of Functioning, Disability and Health: Children and Youth version (ICF-CY) provides a universal framework for defining and classifying functioning and disability in children worldwide, so it can help to standardize the selection of outcome measures in children with CP [9]. The ICF-CY covers the functioning and disability through four different components (body functions (b) and structures (s), activities and participation (d), environmental factors (e), and personal factors), using 1685 categories [10]. Spasticity, muscle weakness, contractures and range of motion, and deformities can be assessed as body functions and structures (muscle tone functions (b735), muscle power functions (b730), mobility of joint functions (b710), and structure of lower extremity (s750)), and gross motor function as activities and participation (mobility (d4)) [9,11]. On the other hand, there are two

categories of the ICF-CY related to gait: gait pattern functions (b770) at body functions an structures level, and walking (d450) at activities and participation level [10]. According to these categories, two different types of outcome measures used to assess gait have been distinguished: outcome measures of gait pattern, and outcome measures of walking [7]. For the activities and participation component, two constructs are available in the ICF-CY: capacity (executing tasks in a standard environment), and performance (executing tasks in the current environment) (10). Therefore, we can also distinguish between outcome measures of walking capacity, and outcome measures of walking performance.

ST parameters are the gait parameters most frequently used in the assessment of children with bilateral spastic CP [12]. ST parameters provide information about the spatial and temporal characteristics of gait, based on the gait cycle, such as gait speed (m/s), cadence (steps/min), stride time (s), stride length (m), and single support (% of gait cycle) [6]. Gait parameters, including ST parameters, are considered the gold standard in CP gait classification systems [13], used as outcome measures of gait pattern. On the other hand, Gage et al. [14] suggested that ST parameters may provide information regarding functional walking. The objective of the present study is to evaluate the relationship between seven different ST parameters (cadence, stride length, step width, gait speed, first double support, single support, and time of toe off (TO)) used as outcome measures in children with bilateral spastic CP [12], and different types of clinical outcomes (including measures of body functions and structures, and activities and participation). Our hypotheses are: 1) ST parameters are related to clinical outcomes at body functions and structures level; and 2) ST parameters are related to clinical outcomes at activities and participation level. We aimed to find out whether ST parameters provide clinical information regarding both gait pattern and walking.

2. Materials and Methods

Data were collected retrospectively from a previous study.

2.1. Participants

The potentially eligible participants were children with a diagnosis of bilateral spastic or mixed CP, age between 4 and 14 years, Gross Motor Function Classification System (GMFCS) levels I to III, and ability to carry out simple verbal instructions. No child had surgery within the previous 12 months, botulinum neurotoxin A injections within the previous 4 months, moderate or severe pain, severe visual impairment, or lower limb asymmetry above 3 % of the height. Exclusion criteria were: 1) disability to walk 4 m independently without assistive

devices; and 2) unavailability to process at least six gait cycles (three right and three left). The study was approved by the institutional Research Ethics Committee, and parents gave written informed consent for participating in the study.

2.2. Instrumented gait analysis

Each child walked barefoot, without orthosis or assistive devices, at self-selected speed on a 7-meter walkway. A minimum of three trials were collected. Two reflective markers (0.015 m radius) were placed on each foot (right and left), one on the posterior end of the calcaneus (heel marker) and the other on the second metatarsal head (toe marker), according to the foot markers placement of the Plug-in-Gait model [15]. Three-dimensional marker coordinates were measured using a six infrared cameras system (SMART-D, BTS Bioengineering, Milan, Italy). Data were recorded at a sample frequency of 140 Hz, and filtered using a fourth order low pass Butterworth filter with a cutoff frequency of 6 Hz. Additionally, lateral and frontal views of feet motion were video recorded.

Gait events (foot strike (FS) and TO) were objectively detected using an adaptation of Ghoussayni's algorithm for children with CP [16]. For each child, six gait cycles (three right and three left) were selected. For each gait cycle, seven ST parameters were computed: 1) cadence (steps/min) was calculated dividing 120 by stride time, considering stride time (s) as the time difference between two consecutive FS of the same foot [17] (**Equation 1**); 2) stride length (m) was computed as the distance between the heel marker at two consecutive FS of the same foot [17]; 3) step width (m) was computed as the medio-lateral distance between the heel markers (right and left) at two consecutive FS; 4) gait speed (m/s) was calculated as stride speed, dividing stride length by stride time [17]; 5) first double support (% of the gait cycle) was computed as the time difference between initial FS and opposite TO, normalized to stride time; 6) single support (%) was calculated as the time difference between opposite TO and opposite FS, normalized to stride time; and 7) time of TO (%) was computed as the time difference between initial FS and TO, normalized to stride time (**Fig. 1**).

$$Cadence\left(\frac{steps}{min}\right) = \frac{1\ cycle}{stride\ time(s)} \times \frac{2\ steps}{1\ cycle} \times \frac{60\ s}{1\ \mathrm{min}} = \frac{120}{stride\ time(s)} \quad (1)$$

For each ST parameter, the mean value corresponding to the six gait cycles was calculated. Cadence was normalized (non-dimensional (ND) normalization) to leg length [18], due to its statistically significant correlation with relevant factors such as age, weight, and leg length (**Table 1**).

2.3. Clinical assessment

Children were physically examined (including measures of spasticity, contractures and passive range of motion (pROM), and deformities), and functionally assessed (including measures of gross motor function, and specifically walking capacity) by a physical therapist.

Spasticity was measured bilaterally in hip flexors, hip adductors, knee flexors, knee extensors, and ankle plantar flexors, using the Modified Ashworth Scale. Contractures and pROM measures included bilateral hip flexors contracture, hip abduction, hip rotations (internal and external), knee flexors contracture, and ankle plantar flexors contracture. Hip flexors contracture was evaluated using two methods: 1) as rectus femoris contracture (presence), using the Duncan-Ely test [14]; and 2) as hip flexors contracture (presence), using the Thomas test [19]. Hip abduction (degrees) was measured in supine, both with knee and hip flexed and extended [20]. Hip rotations (degrees) were measured in prone, with knee flexed to 90º [19]. Knee flexors contracture was evaluated as hamstring contracture (degrees), using the bilateral popliteal angle [14]. Ankle plantar flexors contracture (degrees) was evaluated using the Silverskiold Test [14]. Deformities were evaluated bilaterally, including: 1) femoral anteversion (degrees) in prone, with the knee flexed to 90º [14]; 2) patella alta (presence) in supine, with the knee extended [14]; 3) tibio-femoral angle (degrees) in supine; 4) tibial torsion, using the measurement of the bi-malleolar axis (degrees) [14]; 5) hindfoot (neutral, varus or valgus) both in prone (unloaded) and standing (loaded) [14,19]; 6) arch of the foot (normal, high or low) in standing [14]; 7) flat foot (presence), using the Root test [14]; 8) forefoot (neutral, abduction or adduction) in prone [14,19]; and 9) toe (normal, hallux valgus or claw) in supine [19]. The mean value of right and left sides (for quantitative clinical outcomes), and the most affected side (for qualitative clinical outcomes) were considered to take into account the interrelationship of the two sides [21] and its effect on overall gait disorders.

Gross motor function was evaluated using the Gross Motor Function Measure 66 (GMFM-66, score), and walking capacity was evaluated using the dimension E (walking, running and jumping) of the GMFM-88 (%).

2.4. Statistical Analysis

The sample size was calculated considering the correlation coefficients obtained between gait speed and the GMFM (dimension E or total score) in previous studies [22,23]. With a correlation coefficient of 0.66, accepting an alpha risk of 0.05 and a beta risk of 0.2 in a two-

sided test, and anticipating a drop-out rate of 0 % (for being a retrospective study), the minimum sample size needed was 16. The normality distribution of ST parameters was tested with the Shapiro-Wilk test. Difference of means tests for both normal distribution independent samples (ANOVA and Student's t) and non-normal distribution independent samples (Mann-Whitney U and Kruskal-Wallis) were used to analyze the statistical significance of differences between independent samples of ST parameters in relation to qualitative clinical outcomes. Pearson correlation coefficients were used to evaluate the correlation between ST parameters and quantitative clinical outcomes. A *p*-value lower than 0.05 was considered. The Statistical Package for the Social Sciences (SPSS v.26) was used.

3. Results

Twenty-two potentially eligible participants were identified. Three children were excluded (**Fig. 2**). Nineteen children (nine males and ten females) with a diagnosis of bilateral spastic CP, a mean age of 9.6 ± 2.8 years, and GMFCS levels I to III were included in the present study (**Table 2**). Mean and standard deviation of ST parameters, grouped by GMFCS, are shown in **Table 3**.

All ST parameters, except ND cadence, showed statistically significant ($p < 0.05$) correlations with the GMFM-66 and the GMFM-88-E, at activities and participation level. Higher gross motor function and higher walking capacity were related to longer stride length, shorter step width, higher gait speed, shorter first double support, longer single support, and shorter time of TO (**Table 4**).

Some ST parameters showed relationships with some clinical outcomes at body functions and structures level. Statistically significant differences between independent samples of ND cadence in relation to hip flexors spasticity and hindfoot deformity were found (**Table 5**). Higher ND cadence was related to lower hip flexors spasticity and varus in prone. Statistically significant differences between independent samples of stride length in relation to ankle plantar flexors spasticity were found (**Table 5**). Longer stride length was related to lower ankle plantar flexors spasticity. Statistically significant differences between independent samples of gait speed in relation to hindfoot deformity were found (**Table 5**). Slower gait speed was related to valgus in standing. No relationship was found between ST parameters and contractures and pROM outcomes.

4. Discussion

Nineteen children with bilateral spastic CP, from 4 to 14 years of age, and with different GMFCS levels were assessed with IGA and clinical assessment. The relationships between ST parameters and clinical outcomes were studied in order to understand the links between gait disorders, impairments and activity limitations, and thus improve the clinical interpretation of ST parameters (as outcome measures of gait pattern and/or walking). We considered that gait parameters related to impairments (at body functions and structures level) provide clinical information regarding gait pattern, while gait parameters related to activity limitations (at activities and participation level) provide clinical information regarding walking (**Fig. 2**).

The main findings of the present study were the statistically significant ($p < 0.01$) correlations between the GMFM (total score and dimension E), and six of the seven ST parameters (stride length, step width, gait speed, first double support, single support and time of TO), which confirm the link of ST parameters with gross motor function, and specifically with walking capacity. On the other hand, we found some statistically significant ($p < 0.05$) relationships between ST parameters and clinical outcomes at body functions and structures level: 1) spasticity: we found that ND cadence and stride length were related to hip flexors and ankle plantar flexors spasticity, respectively; 2) deformities: we found that ND cadence and gait speed were related to hindfoot deformity; and 3) contractures and pROM: we did not find any relationship with ST parameters.

Some limitations should be considered when interpreting the results of this study: 1) relationships between ST parameters and other impairments such as muscle weakness were not studied; 2) relationships between ST parameters and walking performance were not studied; and 3) relationships between ST parameters and activity limitations and participation restrictions beyond mobility (self-care, domestic life, interpersonal interactions and relationships, major life areas, and community, social and civil life) were not studied.

Previous studies had reported relationships between ST parameters and clinical outcomes in children with CP [20,22–28]. However, most of them only studied cadence, stride length and/or gait speed [22,24–27], and specific types of clinical outcomes at body functions and structures level, or activities and participation level [23–25,27,28]. Regarding walking capacity, two studies [22,28] had already found correlations between the GMFM-88-E and stride length, gait speed and/or step width. Sullivan et al. [22] also reported correlation between the GMFM-88-E and cadence, which was not found in our study. Regarding gross motor function, Damiano and Abel [23] had already found correlations between the GMFM

(total score) and stride length, gait speed, double support and single support. They [23] also reported correlation between the GMFM (total score) and cadence, which was not found in our study. Regarding spasticity, Desloovere et al. [20] did not find our relationships, but they found that cadence was related to knee flexors spasticity, and that stride length, gait speed and time of TO were related to hip flexors and hip adductors spasticity. Ross and Engsberg [26] reported correlations between stride length, and ankle plantar flexors, knee flexors and hip adductors aggregate spasticity. Regarding deformities, Desloovere et al. [20] found statistically significant correlation between time of TO and femoral anteversion, which was not found in our study. Hösl et al. [27] found that gait speed and stride length were significantly related to patella alta, which was not found in our study. Regarding contractures and pROM, Desloovere et al. [20] reported various correlations between ST parameters (cadence, stride length, gait speed, and time of TO), and clinical outcomes (hip flexors contracture, hip abduction, knee flexors contracture, and ankle plantar flexors contracture), which were not found in our study. Discrepancies in the results may be due to different causes such as heterogeneity in sample characteristics, ST parameter calculation methods, clinical outcomes, and statistical methods [29].

The selection of an appropriate outcome measure depends on many factors, for example the psychometric properties [9]. Interpretability (the degree to which qualitative meaning, that is, clinical or commonly understood connotations, can be assigned to an instrument's quantitative scores or change in scores) should also be considered when selecting outcome measures [30]. Clinicians and researchers need to consider what areas of functioning, disability and health they want to study [9]. Current outcome measures in the field of CP primarily focus on assessing neuromusculoskeletal and movement-related functions (b7) (including gait pattern), and mobility (d4) (including walking) [9]. The findings of the present study (relationships between cadence, stride length and gait speed, and impairments such as spasticity and deformities) support the clinical use of determined ST parameters as outcome measures of gait pattern. On the other hand, our findings (correlations between all ST parameters except cadence, and the GMFM) also support the use of determined ST parameters as outcome measures of walking. This contribution is clinically relevant since the main goal of most interventions is to improve gross motor function [26]. Moreover, walking is part of the brief ICF Core Set for children and youth with CP [11].

The present study proposes a methodology for clinically interpreting gait parameters as outcome measures of gait pattern and/or walking, based on their relationship to different types of clinical outcomes (body functions and structures, and activities and participation). This methodology was applied to ST parameters, but it can also be applied to other types of gait parameters (e.g., kinematic, kinetic and sEMG data). Having a set of gait parameters related to impairments, activity limitations, and/or participation restrictions will improve the three main clinical applications of the IGA in the assessment of children with bilateral spastic cerebral palsy: 1) the identification and understanding of gait disorders; 2) the clinical decision making; and 3) the evaluation and understanding of treatment effects. On the other hand, having a set of objective outcome measures of walking will allow the development of new measurement systems for the assessment of walking, not only in the clinical environment (walking capacity) but also in the daily life environment (walking performance). Therefore, the IGA can help clinicians to move towards evidence-based practice.

In conclusion, ST parameters are linked with gross motor function, and specifically with walking capacity, at activities and participation level. ST parameters are also linked with impairments such as spasticity and deformities, at body functions and structures level. The IGA yields outcome measures able to objectively assess the two gait categories of the ICF-CY: gait pattern and walking. Further research should be conducted to understand the links between other types of gait parameters (kinematic, kinetic and sEMG data), impairments, and activity limitations, using the ICF-CY.

ETHICAL STATEMENT

The patients and/or their families were informed that data from the research would be submitted for publication, and gave their consent.

CONFLICT OF INTEREST

None

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REFERENCES

1. Pakula AT, Van Naarden Braun K, Yeargin-Allsopp M. Cerebral palsy: classification and epidemiology. Phys Med Rehabil Clin N Am. 2009 Aug;20(3):425–52.
2. Rosenbaum P, Paneth N, Leviton A, Goldstein M, Bax M, Damiano D, et al. A report: the definition and classification of cerebral palsy April 2006. Dev Med Child Neurol Suppl. 2007 Feb;109:8–14.
3. Rethlefsen SA, Ryan DD, Kay RM. Classification systems in cerebral palsy. Orthop Clin North Am. 2010 Oct;41(4):457–67.
4. Narayanan UG. The role of gait analysis in the orthopaedic management of ambulatory cerebral palsy. Curr Opin Pediatr. 2007 Feb;19(1):38–43.
5. Chang FM, Rhodes JT, Flynn KM, Carollo JJ. The role of gait analysis in treating gait abnormalities in cerebral palsy. Orthop Clin North Am. 2010 Oct;41(4):489–506.
6. Armand S, Decoulon G, Bonnefoy-Mazure A. Gait analysis in children with cerebral palsy. EFORT Open Rev. 2016 Dec;1(12):448–60.
7. Zanudin A, Mercer TH, Jagadamma KC, van der Linden ML. Psychometric properties of measures of gait quality and walking performance in young people with Cerebral Palsy: A systematic review. Gait Posture. 2017 Jul 4;58:30–40.
8. Cimolin V, Galli M. Summary measures for clinical gait analysis: a literature review. Gait Posture. 2014 Apr;39(4):1005–10.
9. Schiariti V, Klassen AF, Cieza A, Sauve K, O'Donnell M, Armstrong R, et al. Comparing contents of outcome measures in cerebral palsy using the International Classification of Functioning (ICF-CY): a systematic review. Eur J Paediatr Neurol EJPN Off J Eur Paediatr Neurol Soc. 2014 Jan;18(1):1–12.
10. World Health Organization. International classification of functioning, disability and health: children & youth version. In Geneva; 2007.
11. Schiariti V, Selb M, Cieza A, O'Donnell M. International Classification of Functioning, Disability and Health Core Sets for children and youth with cerebral palsy: a consensus meeting. Dev Med Child Neurol. 2015 Feb;57(2):149–58.
12. Gómez-Pérez C, Font-Llagunes JM, Martori JC, Vidal Samsó J. Gait parameters in children with bilateral spastic cerebral palsy: a systematic review of randomized controlled trials. Dev Med Child Neurol. 2019;61(7):770–82.

13. Papageorgiou E, Nieuwenhuys A, Vandekerckhove I, Van Campenhout A, Ortibus E, Desloovere K. Systematic review on gait classifications in children with cerebral palsy: An update. Gait Posture. 2019;69:209–23.
14. Gage JR, Schwartz MH, Koop SE, Novacheck TF. The Identification and Treatment of Gait Problems in Cerebral Palsy. 2 edition. London: Mac Keith Press; 2009. 660 p.
15. Kainz H, Graham D, Edwards J, Walsh HPJ, Maine S, Boyd RN, et al. Reliability of four models for clinical gait analysis. Gait Posture. 2017;54:325–31.
16. Gómez-Pérez C, Martori JC, Puig Diví A, Medina Casanovas J, Vidal Samsó J, Font-Llagunes JM. Gait event detection using kinematic data in children with bilateral spastic cerebral palsy. Clin Biomech. 2021 Dec 1;90:105492.
17. Carcreff L, Gerber CN, Paraschiv-Ionescu A, De Coulon G, Newman CJ, Armand S, et al. What is the Best Configuration of Wearable Sensors to Measure Spatiotemporal Gait Parameters in Children with Cerebral Palsy? Sensors. 2018 Jan 30;18(2):394.
18. Stansfield BW, Hillman SJ, Hazlewood ME, Lawson AM, Mann AM, Loudon IR, et al. Normalisation of gait data in children. Gait Posture. 2003 Feb;17(1):81–7.
19. Cottalorda J, Violas P, Seringe R, French Society of Pediatric Orthopaedics. Neuro-orthopaedic evaluation of children and adolescents: a simplified algorithm. Orthop Traumatol Surg Res OTSR. 2012 Oct;98(6 Suppl):S146-153.
20. Desloovere K, Molenaers G, Feys H, Huenaerts C, Callewaert B, Van de Walle P. Do dynamic and static clinical measurements correlate with gait analysis parameters in children with cerebral palsy? Gait Posture. 2006 Nov;24(3):302–13.
21. Sangeux M, Wolfe R, Graham HK. One side or two? Dev Med Child Neurol. 2013;55(9):786–7.
22. Sullivan E, Barnes D, Linton JL, Calmes J, Damiano D, Oeffinger D, et al. Relationships among functional outcome measures used for assessing children with ambulatory CP. Dev Med Child Neurol. 2007 May;49(5):338–44.
23. Damiano DL, Abel MF. Relation of gait analysis to gross motor function in cerebral palsy. Dev Med Child Neurol. 1996 May;38(5):389–96.
24. Goudriaan M, Nieuwenhuys A, Schless S-H, Goemans N, Molenaers G, Desloovere K. A new strength assessment to evaluate the association between muscle weakness and gait pathology in children with cerebral palsy. PloS One. 2018;13(1):e0191097.

25. Shin HI, Sung KH, Chung CY, Lee KM, Lee SY, Lee IH, et al. Relationships between Isometric Muscle Strength, Gait Parameters, and Gross Motor Function Measure in Patients with Cerebral Palsy. Yonsei Med J. 2016 Jan;57(1):217–24.
26. Ross SA, Engsberg JR. Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. Arch Phys Med Rehabil. 2007 Sep;88(9):1114–20.
27. Hösl M, Böhm H, Seltmann M, Dussa CU, Döderlein L. Relationship between radiographic patella-alta pathology and walking dysfunction in children with bilateral spastic Cerebral Palsy. Gait Posture. 2018 Feb;60:28–34.
28. Kurz MJ, Arpin DJ, Corr B. Differences in the dynamic gait stability of children with cerebral palsy and typically developing children. Gait Posture. 2012 Jul;36(3):600–4.
29. Papageorgiou E, Simon-Martinez C, Molenaers G, Ortibus E, Van Campenhout A, Desloovere K. Are spasticity, weakness, selectivity, and passive range of motion related to gait deviations in children with spastic cerebral palsy? A statistical parametric mapping study. PloS One. 2019;14(10):e0223363.
30. Mokkink LB, Terwee CB, Patrick DL, Alonso J, Stratford PW, Knol DL, et al. The COSMIN study reached international consensus on taxonomy, terminology, and definitions of measurement properties for health-related patient-reported outcomes. J Clin Epidemiol. 2010 Jul;63(7):737–45.

FIGURES

Fig. 1. Graphical representation of spatiotemporal parameters. FS, foot strike; TO, toe off; FDS, first double support.

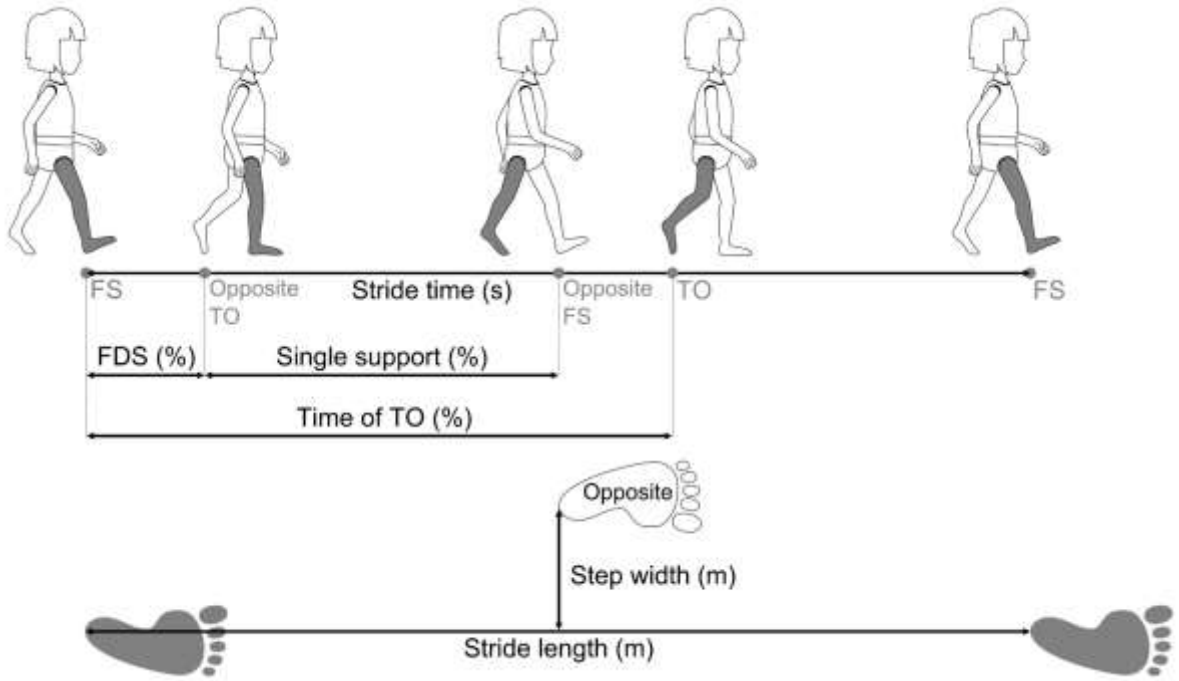
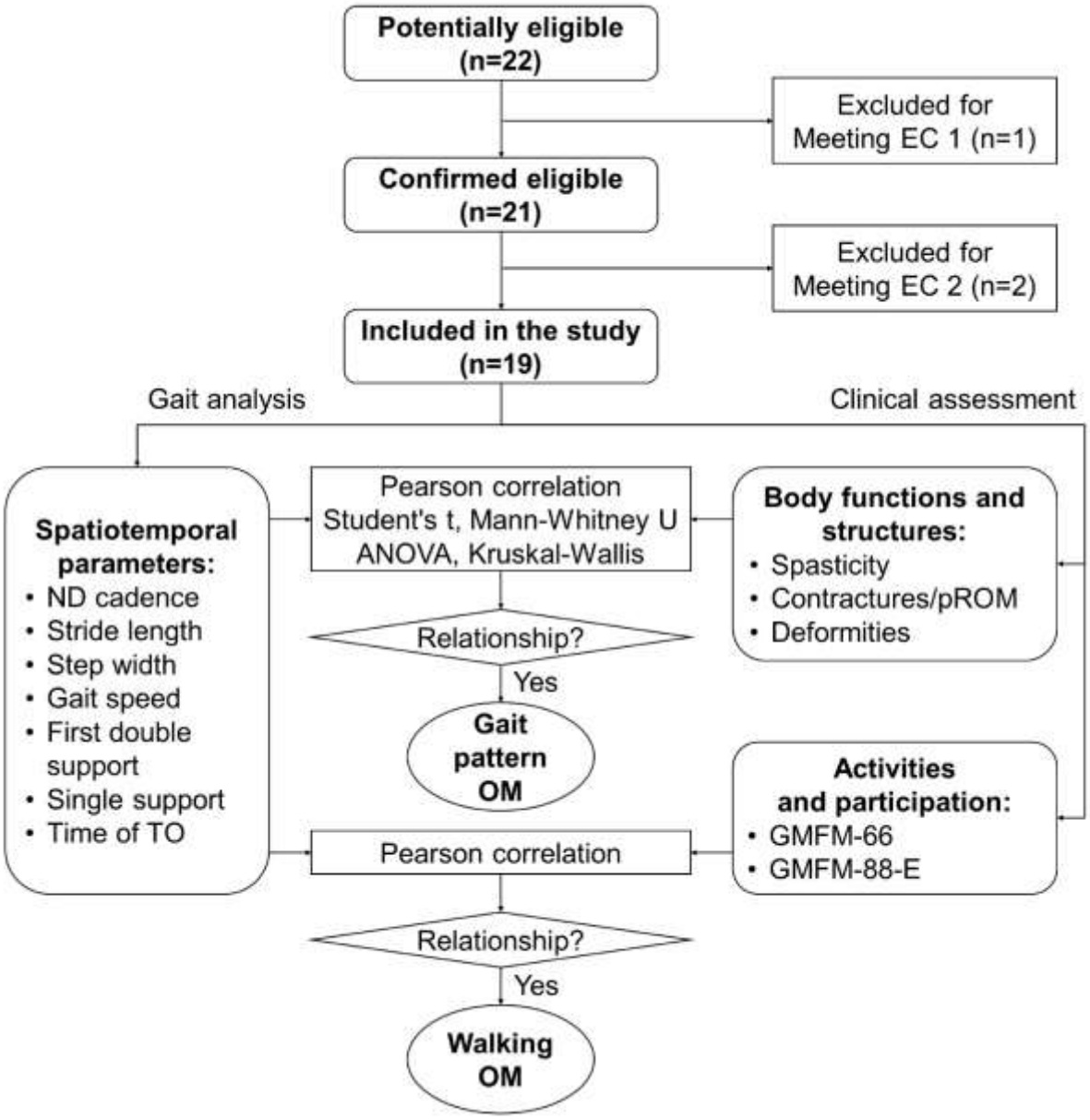


Fig. 2. Study flow diagram. EC, exclusion criteria; ND, non-dimensional; TO, toe off; pROM, passive range of motion; GMFM-66, Gross Motor Function Measure 66; GMFM-88-E, Gross Motor Function Measure 88 dimension E (walking, running, jumping); OM, outcome measure.



TABLES

Table 1. Correlation coefficients between spatiotemporal parameters and relevant factors.

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Relevant factors	**Spatiotemporal parameters**				
	Cadence (steps/min)	ND cadence	Stride length (m)	Step width (m)	Gait speed (m/s)
Age (y)	-0.725**	-0.408	0.209	0.205	-0.141
Weight (kg)	-0.553*	-0.247	0.307	-0.108	0.011
Leg length (m)	-0.767**	-0.439	0.228	0.110	-0.136
ND, non-dimensional. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.					

Table 2. Participants' characteristics

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ID	**Sex**	**CP type**	**GMFCS, level**	**Age, y**	**Weight, kg**	**Height, m**	**Leg length, m**	**PT, HPW**	**BoNT-A**	**Surgery**	**Orthosis**	**Assistive device**
1	Male	Mixed	III	6.3	17.4	1.10	0.55	1.50	Yes	No	Yes	No
2	Female	Spastic	II	9.4	22.5	1.30	0.66	0.75	Yes	No	Yes	No
3	Male	Spastic	III	9.9	34.9	1.32	0.70	1.00	Yes	Yes	Yes	Crutches
4	Female	Spastic	III	12.1	41.5	1.47	0.74	3.50	Yes	Yes	Yes	Crutches
5	Male	Spastic	II	7.9	26.8	1.32	0.66	2.00	Yes	Yes	Yes	No
6	Female	Spastic	III	8.1	46.2	1.25	0.65	2.50	Yes	Yes	No	Walker
7	Male	Spastic	II	12.1	50.2	1.57	0.82	1.00	Yes	No	No	No
8	Female	Spastic	II	8.8	24.2	1.25	0.63	0.00	Yes	No	Yes	No
9	Female	Mixed	III	13.3	39.9	1.54	0.79	1.50	No	No	No	Wheelchair
10	Female	Mixed	II	11.5	28.5	1.32	0.71	1.00	No	No	No	Walker
11	Male	Mixed	II	12.7	39.7	1.57	0.85	0.50	Yes	Yes	No	No
12	Female	Spastic	I	13.2	54	1.54	0.81	1.00	Yes	No	No	No
13	Male	Spastic	II	12.8	33.4	1.45	0.77	1.00	Yes	Yes	No	No
14	Female	Spastic	I	4.9	21.3	1.09	0.53	2.00	Yes	Yes	Yes	No
15	Male	Spastic	II	8.3	29.9	1.31	0.69	1.50	Yes	No	Yes	No
16	Female	Mixed	II	12.5	34.4	1.44	0.76	0.50	No	No	No	No
17	Male	Spastic	III	6.5	19.1	1.05	0.55	1.00	Yes	No	Yes	Crutches
18	Female	Spastic	II	6.9	18.1	1.10	0.56	2.00	No	No	Yes	No
19	Male	Spastic	II	5.8	27.9	1.20	0.61	2.00	No	No	Yes	No

ID, identification; CP, cerebral palsy; GMFCS, Gross Motor Functional Classification System; PT, physical therapy; HPW, hours per week; BoNT-A, botulinum neurotoxin A.

Table 3. Spatiotemporal parameters (mean and standard deviation), grouped by GMFCS

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Spatiotemporal parameters	**GMFCS**						**TOTAL (n=19)**	
	Level I (n=2)		**Level II (n=11)**		**Level III (n=6)**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Cadence (steps/min)	130.20	27.80	115.94	19.90	124.34	20.24	120.09	20.12
ND cadence	0.28	0.02	0.25	0.04	0.26	0.03	0.26	0.03
Stride length (m)	1.00	0.18	0.86	0.22	0.65	0.18	0.81	0.23
Step width (m)	0.10	0.02	0.11	0.05	0.15	0.07	0.12	0.05
Gait speed (m/s)	1.07	0.04	0.84	0.25	0.67	0.23	0.81	0.25
First double support (%)	8.55	2.00	12.28	6.54	16.18	4.99	13.12	6.06
Single support (%)	41.69	2.19	38.11	6.31	34.67	4.67	37.40	5.77
Time of toe off (%)	58.47	2.44	62.21	6.37	65.88	4.47	62.98	5.82
GMFCS, Gross Motor Functional Classification System; SD, standard deviation; ND, non-dimensional.								

Table 4. Significant correlation coefficients between spatiotemporal parameters and quantitative clinical outcomes.

Table 4. Significant correlation coefficients between spatiotemporal parameters and quantitative clinical outcomes.							
Clinical outcomes	**Spatiotemporal parameters**						
	ND cadence	Stride length (m)	Step width (m)	Gait speed (m/s)	First double support (%)	Single support (%)	Time of toe off (%)
GMFM-66 (score)	-	0.776**	-0.586**	0.683**	-0.581**	0.549*	-0.568*
GMFM-88-E (%)	-	0.756**	-0.639**	0.715**	-0.616**	0.584**	-0.610**
ND, non-dimensional; GMFM-66, Gross Motor Function Measure 66; GMFM-88-E, Gross Motor Function Measure 88 dimension E (walking, running, jumping). * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.							

Table 5. Significant relationships between spatiotemporal parameters and qualitative clinical outcomes.

Table 5. Significant relationships between spatiotemporal parameters and qualitative clinical outcomes.							
Clinical outcomes	**Significant ANOVA statistic**			**Significant Kruskal-Wallis statistic**			
	ND cadence	Stride length (m)	Step width (m)	Gait speed (m/s)	First double support (%)	Single support (%)	Time of toe off (%)
Hip flexors spasticity (score)	6.157**	-	-	-	-	-	-
Ankle plantar flexors spasticity (score)	-	3.713*	-	-	-	-	-
Hindfoot deformity – unloaded (type)	7.177*	-	-	-	-	-	-
Hindfoot deformity – loaded (type)	-	-	-	6.912*	-	-	-
ND, non-dimensional. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.							