Do children and adolescents with cerebral palsy walk with reduced dynamic stability compared to their typically developing peers? A systematic review.

ROYLE, Alan, HELLER, Ben <http://orcid.org/0000-0003-0805-8170> and DUNN, Marcus <http://orcid.org/0000-0003-3368-8131>

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Do children and adolescents with cerebral palsy walk with reduced dynamic stability compared to their typically developing peers? A systematic review.

1. *Alan Royle, Physiotherapist, Sheffield Children's Hospital NHS Foundation Trust
2. Dr. Ben Heller, Associate Professor, Centre for Sports Engineering Research, Sheffield Hallam University
3. Dr. Marcus Dunn, Research Fellow, Centre for Sports Engineering Research, Sheffield Hallam University

Corresponding author: alan.royle@nhs.net

ABSTRACT

Background: Stability is a prerequisite for functional gait but not routinely quantified in clinical practice for children and adolescents (hereby referred to as young people, YP) with cerebral palsy (CP), for whom improved mobility is a frequent and crucial target for intervention. However, recent advances in technology and the development of appropriate modelling means that such evaluations are viable. This systematic review sought to compile the available literature using instrumented techniques to quantify the stability of YP with CP compared to their typically developing (TD) peers.

Objective: Do ambulant YP with CP walk with reduced dynamic stability compared to their TD peers?

Search criteria: A systematic search was conducted of five databases (Medline, Web of Science, EMBASE, Cinahl, and Cochrane Library) from inception to November 2020. Further citation pearl growing supplemented the search. Studies were included for consideration if their participants included independently ambulant YP with CP aged 0-17. Studies must have employed objective, instrumented measure(s) of dynamic stability during gait and include a TD comparison group. Conference abstracts and other grey literature were included for consideration. Studies were excluded if variability or spatiotemporal parameters (e.g. step width or double support time) were used as a proxy for dynamic stability.

Method: Quality assessment was conducted using a modified STROBE Checklist. Data were extracted using a bespoke form and tabulated by outcome measure. A narrative synthesis was conducted to amalgamate, explore and assess the available evidence, which was informed by the Synthesis Without Meta-analysis guidelines. Due to the diversity of outcome measures used, no meta-analysis was conducted..

Results: Nineteen of 4,971 studies from the initial search were included for quality appraisal and further analysis. All included studies were observational, cross-sectional designs. The total CP cohort numbered 440, including male and female participants with both hemiplegic and diplegia presentations with an average age of 9.8 (±3.1) years. A wide range of measures of dynamic stability were employed, including those using trunk and pelvic accelerations, those pertaining to the centre of mass (CoM) and centre of pressure (CoP) relationship, the margin of stability, non-linear analysis (Maximum Floquent Multiplier), and other novel biomechanical approaches (e.g. the foot placement estimator and dynamic balance index). Additional computational differences of similar measures impeded inter-study comparison. Four studies did not show a significant between-group difference in key parameters. The remaining studies reported differences that were interpreted as either demonstrating reduced dynamic stability during walking for YP with CP, or a requirement of YP with CP to walk with more conservative strategies to maintain dynamic stability. Limited sub-group analysis was available, however, there was some evidence to suggest that dynamic stability was more challenged in YP with diplegia compared to hemiplegic presentations, and in those with greater functional severity (based on Gross Motor Functional Classification).

Limitations: Several factors impede the ability to interpret the results, including: the diversity of outcome measures employed; differences in their methodological application; discrepancies in the definition of principal concepts; and a lack of studies validating outcomes in YP with CP. One author was responsible for the search, quality analysis and synthesis.

Conclusion: A narrative synthesis found that compared to TD, YP with CP may demonstrate a reduced capacity for dynamically stable gait, which can be appreciated either as an increased displacement of the centre of mass from the centre of pressure, with increased excursion and acceleration at the level of the pelvis and trunk, or by virtue of more conservative strategies that effectively increase stability in one or more planes of movement.

These results, however, are not conclusive and often difficult to interpret. Clinicians should continue to conduct individualised assessments of balance and stability for YP with CP and integrate these findings with a broader assessment of gait with caution. Further research is required to integrate the wide variety of outcome measures with other gait parameters, and to validate these measures against current clinical standards.

Introduction

Cerebral palsy (CP) has a prevalence in the UK of around two per 1000 live births and remains one of the most common causes of childhood disability (NICE 2017; Rosenbaum et al. 2006). CP describes a spectrum of permanent disorders caused by non-progressive injury or malformation of the developing brain, primarily resulting in a range of motor and postural disorders and secondary musculoskeletal impairments, which may have a progressive trajectory despite the static nature of the initial injury (NICE 2017; Rosenbaum et al. 2006).

Functionally, children and adolescents (henceforth, young people or YP) with CP frequently present with limited mobility and complex gait characterised by aberrant patterns of movement. Three-dimensional gait analysis (3DGA) is, therefore, a recommended tool to assess an individual's functional performance, inform clinical decision making processes, and improve outcomes (Filho et al. 2008; NICE 2012). However, there is currently no standardised approach to measuring dynamic stability using 3DGA.

Dynamic stability is a prerequisite of gait. It can be defined as the inherent ability of an individual to maintain upright stance through attenuation of - or recovery from - perturbations of varying magnitude and avoid falls (Bruijn et al. 2013; Perry and Burnfield 2010; Pollock et al. 2000; Niiler 2018). Dynamic stability is determined by a multitude of factors, including an individual's inherent afferent and efferent faculties, the task goal, the environment in which the task is to be performed, the external forces present, and additional demands on bodily systems (i.e. dual-tasking) (Pollock et al. 2000; Pardasaney et al. 2013). Consequently, no clear correlation between stability in standing and stability during gait has been established (Niiler 2018). Anecdotally, this disconnect can be observed in those individuals for whom standing statically requires constant corrective steps to stay notionally in one spot, but when walking are able to maintain a remarkably fluid and apparently controlled trajectory.

Advances in methodological approaches and technology that allow for the instrumented measurement of stability during gait provide an opportunity to better understand these phenomena. A systematic review by Chakaborty et al. (2020) identified several studies that suggested reduced dynamic stability in YP with CP, however low study numbers and methodological heterogeneity prevented any firm conclusions. Since their initial literature search in 2018, several new studies have come to light, providing impetus for a further systematic review; one that benefits from a more narrative approach. This review, therefore, seeks to revisit this subject and collate studies that answer the question: Do ambulant young people with cerebral palsy walk with reduced dynamic stability compared to their typically developing peers?

Method

Search Strategy:
The following strategy has been developed with respect to PRISMA guidelines (Page et al. 2021). Five databases (Medline, Web of Science, EMBASE, Cinahl, and Cochrane Library) were searched from inception to November 2020 (to include grey literature excluded by previous literature reviews). The only exception is Rethwilm et al. (2021), which was available online in December 2020. For search terms and example search strategy, see Table 1. For a summary of the inclusion and exclusion criteria, see Table 2.

Additionally, citations from relevant studies were hand-searched and topic experts consulted for knowledge of studies outside of the initial search. Finally, abstracts from key conferences (published in 'Gait & Posture') were screened from September 2017 to December 2020.

One reviewer (AR) was responsible for searching and reviewing articles for inclusion. A protocol was submitted locally, however, this systematic review was not registered at inception (contravening PRISMA guidelines). The search strategy results are outlined in Figure 1.

Search Terms

1. exp Cerebral Palsy/
2. "cerebral palsy".mp.
3. "CP".mp.
4. *Walking/
5. exp Gait/
6. "gait".mp.
7. walk*.mp.
8. "locomotion".mp.
9. mobil*.mp.
10. ambula*.mp.
11. "dynamic stability".mp.
12. stabil*.mp.
13. equilib*.mp.
14. control.mp.
15. "variability".mp.
16. 1 or 2 or 3
17. 4 or 5 or 6 or 7 or 8 or 9 or 10
18. 11 or 12 or 13 or 14 or 15
19. 16 and 17 and 18

Table. 1. *Medline search strategy*

Types of studies:

All empirical, peer-reviewed evidence was considered. Given the likelihood of limited study numbers, the inclusion of grey literature in the final analysis was based upon the number of published studies found and the level of agreement in the evidence, as per Scherer and Salanha (2019). Following quality appraisal, no such literature was included in the final analysis.

Population:

Studies were included for consideration if their participants included YP aged 0-17 years of age diagnosed with CP capable of independent ambulation without the use of walking aids (during the analysis) and meeting the criteria for Gross Motor Function Classification Scale (GMFCS) I-III. Studies must have also included a typically developing (TD) control or comparison group.

Interventions:

An assessment of unchallenged gait at preferred speed on level ground or treadmill was a minimum requirement for each study, allowing for the additional comparison of challenged or constrained gait.

Outcome measures:

This paper was concerned only with studies utilising instrumented measures of dynamic stability during the gait cycle due to the potential of these approaches to overcome the limitations of qualitative scales (Niiler 2018). The inclusion of stride-to-stride variability was changed post hoc for pragmatic and theoretical reasons. First, the search uncovered more eligible studies than originally anticipated. Second, there remains an interpretative paradox regarding stride-to-stride variability: greater variability could plausibly indicate a control deficit requiring reactive strategies to prevent a fall, but it is equally plausible that such variability reflects the system's ability to accommodate perturbations and thereby maintain stability (Bruijn 2011). For this reason, it remains outside the scope of this review. Additionally, averaged or single stride spatiotemporal measures (e.g., step width) will not be considered sufficient as a measure of stability.

Quality Appraisal:

All studies were appraised for quality by one reviewer (AR) using a modified STROBE Checklist (www.strobe-statement.org) for cross-sectional studies, as per Franklin et al. (2015). Every paper was given a score of 0 or 1 for each of the 22 items, with a higher score indicating greater confidence in the study's methodological quality. Due to the paucity of validated risk of bias assessment tools for observational, cross-section studies, the implications of study safeguards on result interpretation are addressed within the narrative.

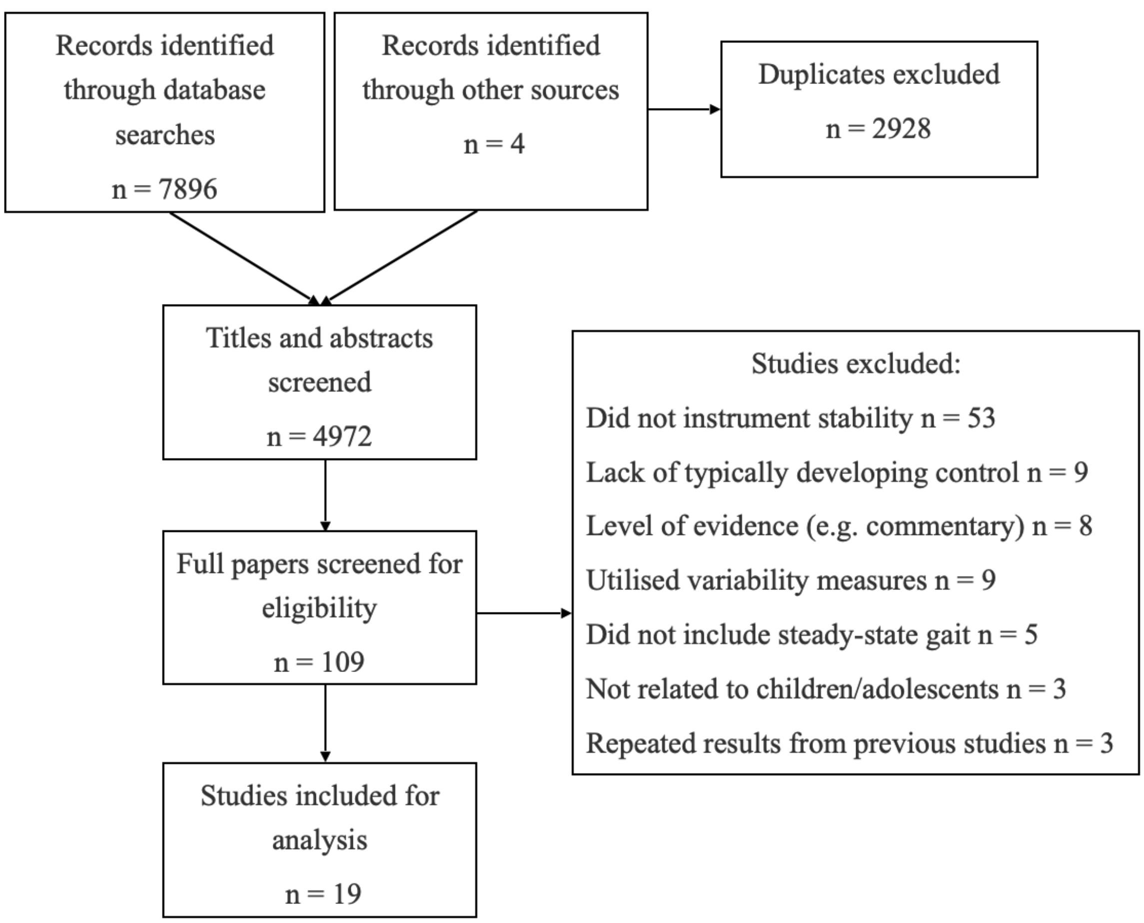
Data Extraction and Synthesis:

All data were extracted using a bespoke form (Appendix 3). Meta-analysis was not possible due to the heterogeneity of outcome measures, their computations, and other methodological variations. Instead, the nine reporting items of the Synthesis Without Meta-analysis (SWiM) guideline (Campbell et al 2019) has been used to structure a narrative synthesis.

Results

Study Quality:

Nineteen studies are included in the final review. A summary of the quality appraisal is documented in Appendix 1, with a mean (±SD) STROBE score of 17.8 (±1.5, maximum possible score 22). With respect to sampling, one study utilised retrospective data, the remainder used convenience sampling, with variable documentation of inclusion/exclusion criteria. No studies justified their sample size, with small numbers often limiting sub-group analysis. Ten studies did not document either precise proportions of GMFCS or CP type, for example diplegia (Di.) or hemiplegia (Hemi.) (Iosa et al. 2012; 2013; 2018; Hsue et al. 2009a; 2009b; Chang et al. 2011; Kurz et al. 2012; Dixon et al. 2016; Niiler et al. 2017; Sharifmoradi et al. 2018). Five studies reported an effect size for the relevant outcome (Dixon et al. 2016; Iosa et al. 2013; 2018; Rethwilm et al. 2021; Tracy et al. 2019;), whilst two studies tested for accuracy (sensitivity/specificity) (Bruijn et al. 2013; Iosa et al. 2018).



Given the number of original, peer-reviewed studies included and following quality appraisal, conference abstracts and other grey literature were rejected (n=8)

Study Characteristics:

All included studies were observational, cross-sectional designs, an approach dictated by the logistical constraints of exploring novel properties and group differences in the absence of intervention.

Cohort:

The mean (+SD) age of YP with CP in the included studies was 9.8 (+3.1) years, with a total of 440 participants of mixed gender. Sample sizes ranged from 9-117 (median 17 IQR 12-31). These YP were predominately graded at GMFCS I-II (minimally/moderately impaired) with a small minority of more impaired individuals (GMFCS III). Participants presented with a mixture of Di. and Hemi., with one study explicitly including a child with dystonic CP (Summa et al. 2016). See Table 3 for a full summary of study characteristics.

Study Outcomes:

Numerous definitions of dynamic stability were identified and influenced the choice of outcome measure: six explored pelvic or trunk acceleration and velocity (Iosa et al. 2012, 2013, 2018; Saether et al. 2014; Summa et al. 2016; Delabista et al. 2016), six utilised parameters pertaining to the CoM-CoP relationship (Hsue et al. 2009a; 2009b; Chang et al. 2011; Feng et al. 2013; Wallard et al. 2014; Malone et al. 2015), five applied the margin of stability (MoS) (Dixon et al. 2016; Delabista et al. 2016; Rethwilm et al. 2021; Sharifmoradi et al. 2018; Tracy et al. 2019), two employed novel biomechanical approaches (foot placement estimator, dynamic balance index) (Bruijn et al. 2013; Niiler et al. 2017), and one a non-linear metric (Maximum Floquet Multiplier) (Kurz et al. 2012).

Four studies did not report any significant difference between the CP and TD groups in key parameters (Iosa et al. 2013; Malone et al. 2015; Tracy et al. 2019; Dixon et al. 2016), whilst there were mixed results in the remaining studies. Evidence of strategies to increase stability, and indicators of gait instability are reported throughout the range of outcome measures, although these conclusions are in some instances dependent on interpretive stances taken by the authors. See Appendix 3 for a full summary of outcomes and results.

Narrative Synthesis:

Bodily accelerations:

Six studies (Iosa et al. 2012, 2013, 2018; Saether et al. 2014; Summa et al. 2016; Delabista et al. 2016) compared the acceleration and velocity characteristics of the pelvis or trunk. In general, higher pelvic and trunk accelerations are considered to be indicative of reduced dynamic stability by virtue of the requirement to conserve momentum through smooth, co-ordinated trajectories of the CoM with relatively minimised excursion of the trunk (Gage et al. 2009; Iosa et al. 2012). The increased average pelvic accelerations reported by Iosa et al. (2012), Saether et al. (2014) and Summa et al. (2016) may therefore support the hypothesis that the gait of YP with CP is less stable. These same results suggested greater instability in YP with Di. versus Hemi., and a positive association with GMFCS (Saether et al. 2014), the former supporting the assertion that YP with Di. have greater balance impairments than those with hemiplegia (Woolacott and Shumway-Cook, 2005). More tentative associations were reported by Summa et al. (2016), who found a negative correlation between Gross Motor Function Measure (GMFM) and averaged accelerations at the level of the head but no such correlation at the level of the pelvis or trunk. Furthermore, later studies by Iosa et al. (2013) and Delabista et al. (2016 found no significant difference in averaged pelvic and maximum trunk accelerations respectively between CP and TD, despite the latter study reporting differences in other stability parameters. The disagreement between Iosa et al. (2013) and the earlier study by the same group (Iosa et al. 2012) is an interesting anomaly given the similarity in protocols and cohort, although the authors acknowledge that participant numbers were small.

A more novel approach adopted by Summa et al. (2016) and Iosa et al (2018) may provide further insight by virtue of their multi-segmental approach that seeks to describe how accelerations are propagated through the body (pelvis to head), again based on a definition of stability in which the maintenance of a minimally displaced trunk and head is paramount. Accelerometers at the pelvis, sternum, and head were used to express the relationship of accelerations from one segment to another, with the assumption that better attenuation (reduced propagation of accelerations from pelvis to head) is an indication of stability. Again, the results were not in strict accord. From pelvis-to-head, Summa et al. (2016) reported no significant difference in attenuation (all planes). Conversely, Iosa et al. (2018) reported a small effect size (ES = 0.166, p = 0.048) with inter-axial analysis showing lower mediolateral (ML) attenuation (suggesting instability). Small differences in the cohort, such as a high proportion of Hemi. presentations and a slightly lower mean GMFCS (1.5 versus 1.75), may explain this difference. Nevertheless, interpretation is not straightforward; Summa et al. (2016) argue that the relatively smaller attenuation found in the TD cohort is not indicative of instability, but rather an indication that they are more capable of accommodating higher accelerations. In other words, there is an interpretative paradox in which YP with CP are always deemed less stable irrespective of the result.

Furthermore, even if we accept the intuitive logic to the application of such metrics as indicators of stability, there remain additional interpretative challenges, not least due to a paucity of data to support their validity and reliability in YP. It should be noted, however, that none of the studies employ acceleration data in isolation, but rather use additional related properties, such as asymmetry and harmony or variability to provide a more complete assessment. However, the extent to which other factors of gait influence these properties is unclear, adding to the challenge of comparing results and possibly explaining the lack of complete agreement (study design, low sample numbers and disease heterogeneity not withstanding).

CoM-CoP Relationships:

An exploration of the relationship between the CoP and the CoM is intuitively attractive by virtue of its association with the established biomechanical understanding of stability as maintenance of the CoM within the BoS. Six studies took this approach.

Despite a heterogeneous collection of parameters, there are clear themes that emerge from these studies in the ML direction: all studies reported greater ML CoM-CoP separation in those with CP compared to TD, which may reflect a common feature of CP gait in which increased ipsilateral trunk sway may counteract insufficient active abductor torque, facilitate weight transfer in double support, or control forward progression (by transforming AP momentum to ML, an equivalent strategy to early walkers) (Gage et al. 2009; Hsue et al. 2009). In addition, this finding was associated with increased step width in all studies in which it was documented (Feng et al. 2013; Chang et al. 2011; Wallard et al. 2014). Increased step width is often considered as a strategy to increase coronal stability given the larger BoS created in double support and based on these data may represent a compensation strategy for the relatively increased coronal instability in single support (recovered in double support). Indeed, Kurz et al. (2012) report an increased maximum Floquet multiplier in their CP cohort (an indicator of the cycle-by-cycle rate of return to the equilibrium given a small perturbation, where a value closer to one indicates a greater number of steps required to return to a theoretical limit cycle). This value positively correlated with step width, supporting the idea that step width is a compensatory strategy. On the other hand, voluntarily increased step width in healthy adults has been associated with reduced stability, suggesting that stability in one plane may be at the expense of stability in others (Kurz at al. 2012).

This paradoxical interpretation may explain the lack of significant correlation between peak inclination angles and this parameter as reported by Feng et al. (2013).

In the anteroposterior (AP) direction the results are more complex. Feng et al. (2013) and Malone et al. (2015) report a reduction in the peak AP inclination angles, whilst Chang et al. (2011) reported reduced AP inclination angles at the beginning of pre-swing and early swing. Hsue et al. (2009) found no difference in averaged divergence of the CoM-CoP, although relative to the gait cycle there is a clear pattern of increased CoM-CoP divergence in single support, versus reduced divergence in double support (a phase of the gait cycle attributed with a 're-establishing' of stability). There is a suggestion that these differences may be partly explained by computational and normalisation differences (Change et al. 2011), although these differences may also present different strategies adopted by YP with CP: one a 'falling forwards' strategy, where a relatively advanced CoM over the CoP in single support provides a passive mechanism to generate momentum that relies on successive foot placements to re-establish stability; the other, a conservative strategy to mitigate against the risk of a requiring more overt saving responses (or a fall). These strategies may be reflected in the results of Wallard et al. (2014) and in a more novel outcome employed by Bruijn et al. (2013), which reported a more posterior foot placement from the predicted 'stable step' in those with CP. Nevertheless, such a discussion remains conjecture as there is insufficient data to compare groups or explore the relationship of reduced CoM-CoP divergence with other factors, such as speed, step length, kinematic patterns, and the foot/floor relationship.

Figure 4.
Summary table of study characteristics and results. The table has been ordered by outcome measure as they are presented within the discussion to facilitate interpretation. Abbreviations include: Anteroposterior (AP), mediolateral (ML), craniocaudal (CC), root mean square (RMS), centre of mass (CoM), centre of pressure (CoP), diplegia (Di.), hemiplegia (Hemi.), no significant statistical difference (NSD), increased (↑), and reduced (↓).

Author(s)	Study Design	Cohort				Conditions and task	Measurement System	Outcome Measure	Result Summary (CP group compared to TD)	STROBE Score (/22)
		Number	Age (years)	Di / Hemi	GMFCS (I-V)					
Iosa et al. (2012)	Observational/ cross-sectional	17 CP 17 TD	5.0 ±2.3 5.7 ±2.5	Hemi.	I-II	Shod, overground, preferred speed	Laboratory-based, single magneto-inertial unit (wearable device)	L2/3 RMS acceleration (m/s²)	↑ AP/ML	17
Iosa et al. (2013)	Observational/ cross-sectional	20 CP 20 TD	5.1 ±2.3 5.9 ±2.7	Hemi.	I-II	Shod, overground, preferred speed (walk) and run	Laboratory-based, single magneto-inertial unit (wearable device)	L2/3 RMS acceleration (m/s²)	NSD all axes	18
Saether et al. (2014)	Observational/ cross-sectional	41 CP 29 TD	10.3 ±3.6 11.7 ±3.8	27 Hemi. 14 Di.	19 I/16 II/6 III	Barefoot, overground Variable speed (slow, preferred, fast)	Laboratory-based, single inertial sensor synchronised with photoelectric cells (gait time)	L2/3 RMS acceleration (m/s²)	↑ all axes	18
Iosa et al. (2018)	Observational/ cross-sectional	12 CP 12 TD	5.7 ±2.3 5.4 ±2.0	7 Hemi. 5 Di.	Mean 1.75 (II)	Overground, preferred speed	Laboratory-based, three magnetoinertial units (wearable devices) and video recordings	Acceleration attenuation coefficient (%)	↓ ML	19
Summa et al. (2016)	Observational/ cross-sectional	20 CP 20 TD	5.70 ±2.3 5.9 ±2.2	15 Hemi. 4 Di. 1 Dystonic	12 I/6 II/2 III	Overground Preferred speed	Laboratory-based, three magneto-inertial units (wearable devices) and video recordings	Acceleration attenuation coefficient (%)	NSD all axes	16
Chang et al. (2011)	Observational/ cross-sectional	12 CP 12 TD	12.4 ±4.4 11.2 ±4.4	Di.	-	Overground, preferred speed	Laboratory-based, total body, 3D kinematic, marker-based motion capture (Vicon, Oxford, UK)	CoM-CoP inclination (° and °/s)	↓ AP ↑ ML	16
Hsue et al. (2009a)	Observational/ cross-sectional	32 CP 10 TD	10.6 ±3.0 10.5 ±2.8	16 Hemi. 16 Di.	-	Barefoot, overground, preferred speed	Laboratory-based, trunk and lower limb, 3D kinematic and kinetic, marker-based motion capture (Motion Analysis Corp, CA) with two force plates	CoM-CoP divergence	↑ ML NSD AP	16
Hsue et al. (2009b)	Observational/ cross-sectional	32 CP 10 TD	10.6 ±3.0 10.5 ±2.8	16 Hemi. 16 Di.	-	Barefoot, overground, preferred speed	Laboratory-based, trunk and lower limb, 3D kinematic and kinetic, marker-based motion capture (Motion Analysis Corp, CA) with two force plates	Instantaneous CoM/CoP acceleration and velocity	↑ (CoM) ↑ ML (CoP) NSD AP (CoP)	16
Feng et al. (2013)	Observational/ cross-sectional	31 CP 23 TD	11.9 ±3.8 11.1 ±3.1	Hemi.	26 I/5 II	Barefoot, overground, preferred speed	Laboratory-based, total body, 3D kinematic and kinetic, marker-based motion capture (Vicon, Oxford, UK) with two strain-gauge force plates.	CoM-CoP inclination (°)	↑	17
Malone et al. (2015)	Observational/ cross-sectional	17 CP 17 TD	10.0 ±2.3 10.1 ±3.7	10 Hemi. 7 Di.	14 I/3 II	Barefoot, overground (even and uneven), preferred speed	Laboratory-based, trunk and lower-limb, 3D kinematic and kinetic, marker-based motion capture (Codamotion, Charnwood Dynamics, Leicestershire, UK) and two Kistler force plates	CoM-CoP inclination (°)	NSD	19
Wallard et al. (2014)	Observational/ cross-sectional	16 CP 16 TD	11.0 ±1.2 11.0 ±1.5	Di. *	II	Barefoot, overground, preferred speed * with "jump gait"	Laboratory-based, full-body, 3D kinematic and kinetic, marker-based motion capture (Vicon, Oxford, UK) and four force platforms	CoM-CoP and kinetic correlation coefficients	↓ AP < ML	18
Kurz et al. (2012)	Observational/ cross-sectional	9 CP 6 TD	7.8 ±2.8 8.0 ±2.4	-	I-II	Shod (±orthoses), treadmill, standardised speed (Froude number)	Laboratory-based, lower limb, 3D kinematic, marker-based motion capture (Vicon, Centennial, CO)	Maximum floquet multiplier	↑	18
Bruijn et al. (2013)	Observational/ cross-sectional	11 CP 24 TD	7.8 (IQR 6) 9.5 (IQR 3.5)	Hemi.	7 I/4 II	Barefoot, overground, variable speed (preferred, fast)	Laboratory-based, total body, 3D kinematic, marker-based motion capture (Vicon, Oxford, UK)	Foot placement estimator (m)	↑ AP NSD ML	21
Niiler et al. (2017)	Observational/ cross-sectional	14 CP 66 TD	10.2 ±5.1 9.2 ±4.3	13 Hemi. 1 Di.	-	Overground, preferred speed	Laboratory-based, trunk and lower limb, 3D kinematic, marker-based motion capture (Motion Analysis Corp, CA)	Dynamic balance index	↑	16
Delabista et al. (2016)	Observational/ cross-sectional	26 CP 24 TD	4-12 5-12	11 Hemi. 15 Di.	8 I/6 II/1 III	Overground, variable speed (preferred, fast), free- and restricted arm-swing	Laboratory-based, total body, 3D kinematic, marker-based motion capture (Vicon, Oxford, UK)	Margin of stability (ML, mm) ML trunk velocity (m/s)	↑ ↑	17
Dixon et al. (2016)	Observational/ cross-sectional	22 CP 54 TD	12.4 ±2.8 11.0 **	Di.	I-II	Overground, straight-line and turn ** (95% CI 10.2 —11.8)	Laboratory-based, total body (TD), lower limb (CP), 3D kinematic, marker-based motion capture (Vicon, Oxford, UK)	Margin of stability (ML, mm)	NSD	20
Rethwilm et al. (2021)	Observational/ cross-sectional	117 CP 25 TD	11 ±3.2 10.4 ±2.5	Di.	38 I/79 II	Barefoot, overground, preferred speed and run	Laboratory-based, trunk and lower limb, 3D kinematics and kinetic, marker-based motion capture (Vicon, Oxford, UK) and two force plates.	Margin of stability (ML, mm)	↑	19
Sharifmoradi et al. (2018)	Observational/ cross-sectional	8 CP 8 TD	7.0 ±1.3 7.2 ±1.1	-	II-III	Barefoot, overground, preferred speed	Laboratory-based, trunk and lower limb, 3D kinematic, marker-based motion capture (Qualisys, Switzerland)	Margin of stability (ML, mm)	↑	17
Tracy et al. (2019)	Observational/ cross-sectional	15 CP 14 TD	8.7 ±2.4 9.1 ±2.5	5 Hemi. 10 Di.	11 I/4 II	Overground, variable speed (preferred, fast), ±cognitive dual-task	Laboratory-based, head, trunk and lower limb, 3D kinematics, marker-based motion capture (Qualisys, Sweden)	Margin of stability (AP and ML, % body height)	NSD	20

Table 3. Summary of Study Characteristics

It is worth reflecting on a similar measure to those documented above developed by Niiler et al. (2017), who utilised an alternative distal reference point, substituting the CoP for a point half between the feet throughout the gait cycle (irrespective of floor contact). Niiler et al. (2017) argue that this reflects a more functional operationalisation of stability, since the swing phase may be ended prematurely should a stabilising step be required. The index is determined by the two-dimensional distance between the CoM and aforementioned distal point normalised by foot length, and was reported as being significantly increased (less stable) throughout the gait cycle irrespective of speed. This measure may be more sensitive than measures of CoM excursion in differentiating between pathological and typical gait, although further work is required to investigate validity, reliability, and accuracy.

Margin of stability:

A limitation of investigating the CoM-CoP relationship concerns the discrete nature of their construct. Some methods attempt to address this limitation and account for the sequential nature of gait by factoring in the inertial characteristics of the CoM, the most ubiquitous of which is the margin of stability (MoS). The MoS is derived by advancing the relative CoM position by a factor of its scaled velocity and determining the distance of this point from the edge of the BoS in the transverse plane (in the AP and ML direction). A positive value indicates a stable condition (within the BoS), and negative value an unstable condition (outside of the BoS). Five studies employed ML MoS. One study (Dixon et al., 2016) did not find any significant difference in the ML MoS, which is in accord with the lack of between group difference in ML foot placement estimator error reported by Bruijn et al. (2013). On the contrary, the ML MoS was increased in three studies irrespective of limb (Delabistita et al. 2016; Rethwilm et al. 2021; Sharifmoradi et al. 2018, no measure of significance reported by the former), whilst Tracy et al. (2019) found a significant difference only on the affected limb of their Hemi. cohort. Multiple linear regression conducted by Rethwilm et al. (2021) found step width to be the most significant predictor of ML MoS, followed by step length. However, both increased and equivalent step widths, and variable speeds are reported in the other studies. The increased stability indicated by these latter studies results appear to run contrary to the increased CoM-CoP divergence and assumptions of instability made by those studies employing acceleration data, although it is worth noting that the accelerations measured were predominately averaged over several strides, whilst the CoM-CoP data reflected both averaged values across strides, as well as peak values within a stride or at certain moments within a stride. The MoS was calculated either as an average across strides, average in single support, or minimum (least stable) in stance. This not only presents an interpretive challenge but raises an important question, namely is it more important to identify the least stable moment in any gait cycle, or is the aggregate stability more important, and in what phase(s) of the gait cycle? Additionally, only one study investigated the MoS in the AP direction (Tracy et al., 2019), reporting no significant difference in a highly functional hemiplegic cohort with equivalent spatiotemporal parameters to TD. Until there is a better understanding of how stability behaves throughout the gait cycle for YP with CP, and in all relevant planes, this heterogeneity may impede further interpretation.

Limitations:

This review has been completed by one author (AR) prohibiting checks for consensus during screening and quality appraisal. The diverse range of outcome measures prohibited any meta-analysis, whilst the small sample numbers, and varied clinical presentations of CP restrict inter-group analysis. Whilst this review was concerned with children and adolescents, this latter group were not well represented. More severely affected YP were also under-represented. Further research is required to understand how dynamic stability relates to age and disease severity in the CP population. In addition, pragmatic concerns constrained the review such that the inclusion of variability measures was not possible, which may otherwise provide some insight into the complex nature of stability.

It is further acknowledged that when considering deviations in trunk and head movement, there are studies that have been excluded that otherwise present comparable gait parameters to those that were included (e.g., root-mean-square of trunk accelerations). The justification for exclusion lies in the lack of emphasis on stability as it pertains to the character of the gait itself (i.e., the parameter is not explicitly identified as being analogous of stability), including a lack of complementary parameters that would allow further interrogation (such as co-ordination or rhythmicity). This peculiarity is considered a necessary limitation of the review.

Summary:

In conclusion, there is evidence to suggest that YP with CP have a reduced capacity for stability during straight-line, steady-state gait compared to their TD peers. This reduced capacity may present as instability that occurs in one or more planes of movement. Alternatively, it may be revealed by the adoption of conservative movement strategies that mitigate against the implied risk of falling. These results should, however, be treated with caution given the level of evidence available, the relatively novel nature of the measures used, and the occasionally inconsistent results.

Clinically, this systematic review reiterates the imperative to consider and assess balance and dynamic stability on an individual basis for YP with CP, especially for those with a Di. or more severe presentation. These assessments of dynamic stability are likely to continue to rely on visual appraisals and functional tests. Finally, further research is required before measures of dynamic stability are viable in routine clinical practice.

Key Points:

- The ability to maintain balance and prevent falls has been highlighted as a priority by those with CP, yet the objective measurement of dynamic stability during walking - the ability to maintain balance, manage perturbations, and avoid falls - is not routine clinical practice. This systematic review presents evidence that some YP with CP demonstrate reduced stability during gait compared to TD peers, and that in the sagittal plane this may be a consequence of preserving forward progression.
- Conversely, this systematic review also presents evidence that YP with CP may employ conservative strategies to maintain or improve their stability during gait, a likely mechanism to minimise the risk of requiring saving reactions or falling.
- Further understanding of the interaction of dynamic stability with other characteristics and parameters of gait, or its use as a tool to predict falls and measure treatment outcomes is limited by the diversity of outcomes used, differences in their methodological application, and paucity of validation studies in YP with CP, which provides a clear direction for future research.
- Clinicians should assess dynamic stability during walking for YP with CP on an individual basis, especially for those with a diplegic or more severe functional presentation. At present, such assessments may rely on visual or functional tests.
- Integrating assessments of dynamic stability with the broader gait analysis requires careful consideration of the impact on other gait characteristics.

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Appendix 1: Summary of Quality Appraisal

Appendix 1.

Summary table of study appraisal using a modified STROBE checklist (for cross-sectional studies (**www.strobe-statement.org**), as per Franklin et al. (2015). Each of 22 items is scored as 0 or 1 depending on whether an item is satisfied. A higher score is indicative of a study that satisfies more of the STROBE checklist items. Items: 1. Title and abstract; 2. Background/rationale; 3. Objectives; 4. Study design; 5. Setting; 6. Participants; 7. Variables; 8. Data Sources; 9. Bias; 10. Study size; 11. Quantitative variables; 12. Statistical methods; 13. Participants; 14. Descriptive data; 15. Outcome data; 16. Main results; 17. Other analyses; 18. Key results; 19. Limitations; 20. Interpretation; 21. Generalisability; 22. Funding.

Study	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Total
Bruijn et al. (2013)	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	21
Chang et al. (2011)	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	0	1	0	1	1	1	16
Delabista et al. (2016)	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	1	0	1	1	1	0	1	17
Dixon et al. (2016)	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	20
Feng et al. (2013)	1	1	1	1	1	1	1	1	0	0	1	1	0	0	1	1	0	1	0	1	1	1	17
Hsue et al. (2009a)	1	1	1	1	1	1	0	1	1	0	1	1	0	0	1	1	0	1	0	1	1	1	16
Hsue et al. (2009b)	1	1	1	1	1	1	0	1	1	0	1	1	0	0	1	1	0	1	0	1	1	1	16
Iosa et al. (2012)	1	1	1	1	0	1	1	1	1	0	1	1	0	0	1	1	0	1	1	1	1	1	17
Iosa et al. (2013)	1	1	1	1	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	18
Iosa et al. (2018)	1	1	1	1	1	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	19
Kurz et al. (2012)	1	1	1	1	1	0	1	1	1	0	1	1	0	0	1	1	1	1	0	1	1	1	18
Malone et al. (2015)	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	19
Niiler et al. (2017)	1	1	1	1	1	1	1	1	1	0	1	1	0	0	1	1	0	1	0	1	1	0	16
Rethwilm et al. (2021)	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	1	19
Saether et al. (2014)	1	1	0	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	18
Sharifmoradi et al. (2018)	1	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	0	1	1	1	17
Summa et al. (2016)	1	1	1	1	1	0	1	1	1	0	1	1	0	0	1	1	0	1	0	1	1	1	16
Tracy et al. (2019)	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	20
Wallard et al. (2014)	1	1	1	1	1	0	1	1	0	0	1	1	0	0	1	1	0	1	1	1	1	1	18

Appendix 2: Summary of Cohort

Appendix 2.
Summary table of study cohort characteristics. Abbreviations include cerebral palsy (CP), typically developing (TD), diplegia (Di), hemiplegia (Hemi), years (yrs), gross motor function classification scale (GMFCS).

Author(s)	Cohort				Conditions
	Number	Age (years)	Di / Hemi	GMFCS (I-V)	
Bruijn et al. (2013)	11 CP 24 TD	7.8 (IQR 6) 9.5 (IQR 3.5)	Hemi.	7 I/4 II	Barefoot, overground, variable speed (preferred, fast)
Chang et al. (2011)	12 CP 12 TD	12.4 ±4.4 11.2 ±4.4	Di.	-	Overground, preferred speed
Delabista et al. (2016)	26 CP 24 TD	4-12 5-12	11 Hemi. 15 Di.	8 I/6 II/1 III	, variable speed (preferred, fast), free- and restricted arm-swing
Dixon et al. (2016)	22 CP 54 TD	12.4 ±2.8 11.0 **	Di.	I-II	Overground, straight-line and turn ** (95% CI 10.2 —11.8)
Feng et al. (2013)	31 CP 23 TD	11.9 ±3.8 11.1 ±3.1	Hemi.	26 I/5 II	Barefoot, overground, preferred speed
Hsue et al. (2009a)	32 CP 10 TD	10.6 ±3.0 10.5 ±2.8	16 Hemi. 16 Di.	-	Barefoot, overground, preferred speed
Hsue et al. (2009b)	32 CP 10 TD	10.6 ±3.0 10.5 ±2.8	16 Hemi. 16 Di.	-	Barefoot, overground, preferred speed
Iosa et al. (2012)	17 CP 17 TD	5.0 ±2.3 5.7 ±2.5	Hemi.	I-II	Shod, overground, preferred speed
Iosa et al. (2013)	20 CP 20 TD	5.1 ±2.3 5.9 ±2.7	Hemi.	I-II	Shod, overground, preferred speed (walk) and run
Iosa et al. (2018)	12 CP 12 TD	5.7 ±2.3 5.4 ±2.0	7 Hemi. 5 Di.	Mean 1.75 (II)	Overground, preferred speed
Kurz et al. (2012)	9 CP 6 TD	7.8 ±2.8 8.0 ±2.4	-	I-II	Shod (±orthoses), treadmill, standardised speed (Froude number)
Malone et al. (2015)	17 CP 17 TD	10.0 ±2.3 10.1 ±3.7	10 Hemi. 7 Di.	14 I/3 II	Barefoot, overground (even and uneven), preferred speed
Niiler et al. (2017)	14 CP 66 TD	10.2 ±5.1 9.2 ±4.3	13 Hemi. 1 Di.	-	Overground, preferred speed
Rethwilm et al. (2021)	117 CP 25 TD	11 ±3.2 10.4 ±2.5	Di.	38 I/79 II	Barefoot, overground, preferred speed and run
Saether et al. (2014)	41 CP 29 TD	10.3 ±3.6 11.7 ±3.8	27 Hemi. 14 Di.	19 I/16 II/6 III	Barefoot, overground Variable speed (slow, preferred, fast)
Sharifmoradi et al. (2018)	8 CP 8 TD	7.0 ±1.3 7.2 ±1.1	-	II-III	Barefoot, overground, preferred speed
Summa et al. (2016)	20 CP 20 TD	5.70 ±2.3 5.9 ±2.2	15 Hemi. 4 Di. 1 Dystonic	12 I/6 II/2 III	Overground Preferred speed
Tracy et al. (2019)	15 CP 14 TD	8.7 ±2.4 9.1 ±2.5	5 Hemi. 10 Di.	11 I/4 II	Overground, variable speed (preferred, fast), ±cognitive dual-task
Wallard et al. (2014)	16 CP 16 TD	11.0 ±1.2 11.0 ±1.5	Di. *	II	Barefoot, overground, preferred speed * with "jump gait"

Appendix 3: Results Table

Appendix 3.
Summary of study results during steady-state walking. Results presented as a comparison of the cerebral palsy group (CP) relative to the typically developing group (TD), with metric values and.or differences and p values (where available). Where results pertain to all 3 orthogonal axes, only statistically significant results are presented. Abbreviations include F-test (F), effect size (ES), anteroposterior (AP), mediolateral (ML), craniacaudal (CC), root mean square (RMS), centre of mass (CoM), CoP (centre of pressure), diplegia (Di.), hemiplegia (Hemi.), mid-stance (MS), pre-swing (PS), early swing (ES), late swing (LS), step width (SW), step length (SL).

Measure of Dynamic Stability	Study	Results	Spatiotemporal Parameters (CP compared to TD)
Accelerometry/Magneto-Inertial Measurement Units			
L2/L3 (close to CoM) RMS Acceleration (m/s^2)	Iosa et al. (2013)	No significant difference (averaged across all 3 axes, $p = 0.089$, $F = 3.042$, ES = 0.161)	Speed and step length not significantly different
	Saether et al. (2014)	Increased in all axes ($p < 0.02$, $0.5 < z$-scores < 1) (by 21.6%/31.0%/39.9% in AP/ML/CC respectively)	No significant difference in speed, cadence, and step length
	Iosa et al. (2012)	Increased in AP/ML ($p < 0.039$) Tri-axial analysis of variance $p < 0.001$, $F = 14.48$	No significant difference in speed
Minimum peak acceleration (m/s^2)		Reduced in CC (i.e. greater de-acceleration, $p = 0.02$)	
Peak-to-peak angular velocity (m/s)		Increased in AP/ML ($p < 0.022$)	
Pelvic RMS acceleration (m/s^2)	Summa et al. (2016)	Increased in AP/ML/CC ($p < 0.01$, $F = 14.61$)	Speed (normalised and non-normalised) not significantly different. Cadence increased, step length decreased
Sternum RMS acceleration (m/s^2)		Increased in AP/ML/CC ($p < 0.05$, $F = 8.04$)	
Trunk Accelerations Maximum ML trunk velocity (m/s)	Delabistita et al. (2016)	Increased ($p = 0.004$) Di. by approx. 115%; Hemi. by approx 60% N.B. No significant difference in max. trunk excursion and acceleration in coronal and transverse planes	Normalised double support time increased in Di (not Hemi) Normalised speed reduced Di > Hemi Normalised step width increased (Di and Hemi) Normalised step length increased (Di > Hemi)
Pelvis-to-head attenuation coefficients (%)	Summa et al. (2016)	No significant difference in any plane N.B. Pelvis-to-sternum and sternum-to-head increased and reduced respectively ($F = 9.181$, $p = 0.005$ and $F = 12.708$, $p = 0.001$)	Speed (normalised and non-normalised) not significantly different. Cadence increased, step length decreased
	Iosa et al. (2018)	Lower attenuation in ML axis ($p < 0.05$) Analysis of variance: $p = 0.048$, $F = 4.38$, ES = 0.166	Speed not significantly different

Appendix 3: Results Table

Appendix 3.

Summary of study results during steady-state walking. Results presented as a comparison of the cerebral palsy group (CP) relative to the typically developing group (TD), with metric values and.or differences and *p* values (where available). Where results pertain to all 3 orthogonal axes, only statistically significant results are presented. Abbreviations include F-test (*F*), effect size (ES), anteroposterior (AP), mediolateral (ML), craniacaudal (CC), root mean square (RMS), centre of mass (CoM), CoP (centre of pressure), diplegia (Di.), hemiplegia (Hemi.), mid-stance (MS), pre-swing (PS), early swing (ES), late swing (LS), step width (SW), step length (SL).

Measure of Dynamic Stability	Study	Results	Spatiotemporal Parameters (CP compared to TD)
CoM-CoP divergence			
RMS (%)	Hsue et al. (2009a)	Increased ML throughout gait cycle Di. ML 9.97 ±2.32, Hemi. ML 7.93 ±2.20, TD ML 5.97 ±1.07 ($p < 0.05$ comparing all groups) N.B. Not significant in AP all groups, nor in ML on unaffected leg in single support for Hemi. group	Normalised double support time increased (Di and Hemi)
CoM-CoP peak separation (mm)	Malone et al. (2015)	Reduced CP 122.19 ±33.33, TD 160.69 ±73.59 ($p = 0.0274$)	Step length reduced. Speed, cadence, double support time not significantly different
CoM-CoP inclination			
Angle at start of MS/PS/ES, end of LS (°) AP ML	Chang et al. (2011)	Reduced in AP at PS/ES (by -27.9% and -22.7% respectively, $p = 0.033$ and 0.024) Increased in ML at MS/ES/LS (by 48.2%, 63.5%, and 74.9% respectively, $p = 0.041$, 0.005, 0.011). N.B. Reduced in ML at PS (-24.5%, $p = 0.043$)	Reduced speed, step length, cadence and step length Step wdith increased
Angular velocity at start of MS/PS/ES, end of LS (°/s) AP ML		Reduced in AP at all points (-25.5%, -67%, -70.9%, -25.6%, $0.017 < p < 0.048$) No significant difference in ML, with exception of PS (240.6% $p = 0.049$)	
Peak AP CoM-CoP inclination angle (°)	Feng et al. (2013)	Reduced (posterior i.e. loading response, $p < 0.05$)	Increased step width Speed, step length, stride length and cadence not significantly different
	Malone et al. (2015)	Reduced, CP 9.17 ±2.4, TD 11.57 ±4.76 ($p = 0.0327$)	Step length reduced. Speed, cadence, double support time not significantly different

Appendix 3: Results Table

Appendix 3.
Summary of study results during steady-state walking. Results presented as a comparison of the cerebral palsy group (CP) relative to the typically developing group (TD), with metric values and.or differences and *p* values (where available). Where results pertain to all 3 orthogonal axes, only statistically significant results are presented. Abbreviations include F-test (*F*), effect size (ES), anteroposterior (AP), mediolateral (ML), craniacaudal (CC), root mean square (RMS), centre of mass (CoM), CoP (centre of pressure), diplegia (Di.), hemiplegia (Hemi.), mid-stance (MS), pre-swing (PS), early swing (ES), late swing (LS), step width (SW), step length (SL).

Measure of Dynamic Stability	Study	Results	Spatiotemporal Parameters (CP compared to TD)
Peak ML CoM-CoP inclination angle (°)	Feng et al. (2013)	Increased ($p < 0.05$) N.B. Not correlated with SW, compared to strong correlation in TD ($r = 0.825$)	See above
	Malone et al. (2015)	No significant difference ($p = 0.272$)	See above
Instantaneous CoM velocity and acceleration	**Hsue et al. (2009b)**	**Increased in all axes (Di. and Hemi., $p < 0.05$)**	Normalised double support time increased (Di. and Hemi.)
Instananeous CoP velocity and acceleration		**Velocity increased in ML (Di. and Hemi., $p < 0.05$) Acceleration increased in ML (Di, p < 0.05, not Hemi.) Velocity and acceleration AP, not significant (Di. and Hemi.)**	
CoM-CoP trajectories relative to propulsive forces			
Correlation coefficient	Wallard et al. (2014)	Reduced ML>AP CP AP 0.59 ±0.26, TD AP 0.87 ±0.05 ($p < 0.05$) CP ML 0.68 ±0.24, TD ML 0.88 ±0.05 ($p < 0.05$)	Step width increased Speed reduced Cadence increased Step length reduced
Time difference between CoM-CoP trajectory and propulsive forces (s)		Increased CP AP 0.05 ±0.30, TD 0.01 ±0.01 ($p < 0.05$) CP ML 0.07 ±0.14, TD 0.02 0.01 ($p < 0.05$)	
Dynamic Balance Index	Niiler et al. (2017)	Increased (i.e. less stable), mean in stride by 87.8% and max in stride by 144% ($p < 0.05$)	Speed reduced Step width increased
Margin of Stability			
AP - Minimum in stride and single support ML - Minimum in stride and single support (% Body Height)	Tracy et al. (2019)	No significant difference Increased (i.e. more stable) on affected limb (Hemi. group, $p < 0.01$, ES = 0.34)	Speed, cadence, step width not significantly different
ML - Minimum in stance (mm)	Delabistita et al. (2016)	Di. 0.064 ±0.005, Hemi. 0.062 ±0.005, TD 0.045±0.004 N.B. Significance not reported between groups at preferred speed. No significant interaction reported with speed or restricted arm-swing.	Speed, step length and stride length reduced (Di. > Hemi.) Step width not significantly different (Di. and Hemi.)

Appendix 3: Results Table

Appendix 3.
Summary of study results during steady-state walking. Results presented as a comparison of the cerebral palsy group (CP) relative to the typically developing group (TD), with metric values and/or differences and *p* values (where available). Where results pertain to all 3 orthogonal axes, only statistically significant results are presented. Abbreviations include F-test (*F*), effect size (ES), anteroposterior (AP), mediolateral (ML), craniocaudal (CC), root mean square (RMS), centre of mass (CoM), centre of pressure (CoP), diplegia (Di.), hemiplegia (Hemi.), mid-stance (MS), pre-swing (PS), early swing (ES), late swing (LS), step width (SW), step length (SL).

Measure of Dynamic Stability	Study	Results	Spatiotemporal Parameters (CP compared to TD)
	Dixon et al. (2016)	No significant difference	Speed and stride length reduced Step width increased
	Rethwilm et al. (2021)	Increased, CP 0.103 ±0.031*, TD 0.071 ±0.016* (p <0.001, Eta² 0.19) *N.B. dimensionless values	Step width increased, cadence not significantly different Speed and step length reduced
ML - Average in single support (mm)	Dixon et al. (2016)	No significant difference	Speed, and stride length reduced Step width increased
	Sharifmoradi et al. (2018)	Increased, CP 3.43 ±1.80, TD 1.71 ±0.59 ($p = 0.02$)	Speed and step length reduced Cadence not significantly different
	Rethwilm et al. (2021)	Increased, CP 0.139 ±0.037*, TD 0.084 ±0.017* (p <0.001, Eta² 0.27) *N.B. dimensionless	Step width increased, cadence not significantly different Speed and step length reduced
Foot placement estimator (m)	Bruijn et al. (2013)	Higher in AP (i.e. less stable, $p < 0.01$) No significant difference in ML at preferred speed N.B. Reduced at faster speeds ($p < 0.01$)	Speed and step width increased Double support and stride time not significantly different
Maximum Floquet Multipler	Kurz et al. (2012)	Increased (i.e. less stable, $p = 0.03$) N.B. Positively correlated with step width ($P = 0.86$, $p = 0.0001$) and negative correlation with functional balance index (GMFM Section E, $P = -0.6$, $p = 0.05$)	Speed and step length not significantly different Step width increased

GLOSSARY

2D	Two-dimensional	
3D	Three-dimensional	
3DGA	Three-dimensional gait analysis	A clinical tool involving the instrumented measurement and analysis of gait (walking or locomotion) using 3D kinematics, kinetics, and other data.
	Attenuation coefficients	Segmental analysis of tri-axial accelerations in which a lower coefficient is reflective of poorer attenuation from lower to higher segments, and thus indicative of instability (where this is defined as the task of isolating the upper body - particularly the head - from more distal movement and perturbations).
AP	Anteroposterior	Referring to forward or backward movement along the Cartesian *y* axis.
BoS	Base of support	The area beneath the body as defined by the point (or points) of contact with the floor.
CoM	Centre of mass	The notional point of a body at which the mass of the whole is averaged and through which the gravitational vector acts.
CoM-CoP divergence	Centre of mass to centre of pressure divergence	The distance been the CoM and the CoP in the transverse plane, where a greater distance is indicative of a greater CoM/CoP separation and hence a larger gravitational moment arm requiring greater postural control to control or counter-act it.
CoM-CoP inclination	Centre of mass to centre of pressure inclination	The angle created by a line bisecting the CoM and the CoP, where a greater angle is indicative of a greater CoM/CoP separation and hence a larger gravitational moment arm requiring greater postural control to control or counter-act it.
CoP	Centre of pressure	The point at which pressure on a contact point is averaged and thus through which the ground reaction force originates.
CP	Cerebral palsy	A lifelong condition affecting movement and co-ordination occurring due to injury or malformation of the developing brain.
Di.	Diplegic	Predominately bilateral lower limb involvement.
	Dynamic balance index	The distance in the transverse plane of the CoM from a position half way between the feet during the gait cycle (irrespective of contact with the floor), normalised by half the length of the foot.
	Dynamic stability	The inherent ability of an individual to maintain upright stance through attenuation of - or recovery from - perturbations of varying magnitude (internal or external) and avoid falls.
	Foot placement estimator	A distance calculated in different planes of the actual foot placement from the hypothetical balancing step (i.e. the step required to stop based on pendular movement). A greater distance is therefore indicative of a more unstable step.
GMFCS	Gross Motor Function Classification System	A functional, disease-specific five point scale (I-V), where I indicates the mildest functional impairment and V the most severe.
Hemi.	Hemiplegic	Unilateral involvement (typically upper and lower limb on the same side).
	Maximum floquet multiplier	The cycle-by-cycle rate of return to the equilibrium given a small perturbation, where a value closer to one indicates that more steps are required to return to a theoretical limit cycle.
ML	Mediolateral	Referring to sideways or lateral movement occurring along the Cartesian *x* (horizontal) axis.
MoS	Margin of stability	An outcome measure designed to indicate the degree of stability at any given time based on the distance between the velocity adjusted CoM and the border of the BoS in the transverse plane (in the AP or ML direction).
TD	Typically developing	
YP	Young people (children and adolescents)	

Appendix 4. Glossary