LIVERPOOL JOHN MOORES UNIVERSITY

LJMU Research Online

Bailey, HGB, O'Brien, TD, Barton, GJ, Bass, A, Wright, D, Pinzone, O, Greaves, H and Foster, RJ

Exploratory Investigation of Head Stability in Children with Cerebral Palsy and Typically Developing Children during a Targeted Stepping Task

http://researchonline.ljmu.ac.uk/id/eprint/24688/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Bailey, HGB, O'Brien, TD, Barton, GJ, Bass, A, Wright, D, Pinzone, O, Greaves, H and Foster, RJ (2024) Exploratory Investigation of Head Stability in Children with Cerebral Palsy and Typically Developing Children during a Targeted Stepping Task. Applied Sciences, 14 (19).

LJMU has developed **LJMU Research Online** for users to access the research output of the University more effectively. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LJMU Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain.

The version presented here may differ from the published version or from the version of the record. Please see the repository URL above for details on accessing the published version and note that access may require a subscription.

For more information please contact researchonline@ljmu.ac.uk

http://researchonline.ljmu.ac.uk/

applied sciences

MDPI

Article

Exploratory Investigation of Head Stability in Children with Cerebral Palsy and Typically Developing Children during a Targeted Stepping Task

Harry G. B. Bailey [1], Thomas D. O'Brien [1], Gabor J. Barton [1], Alf Bass [2], David Wright [2], Ornella Pinzone [2], Henrike Greaves [1,2] and Richard J. Foster [1,*]

1 Research Institute for Sport and Exercise Science, Tom Reilly Building, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, UK; h.g.bailey@2016.ljmu.ac.uk (H.G.B.B.); t.d.obrien@ljmu.ac.uk (T.D.O.); g.j.barton@ljmu.ac.uk (G.J.B.); henrike.greaves@alderhey.nhs.uk (H.G.)

2 Alder Hey Children's Hospital, Alder Hey Children's NHS Foundation Trust, Liverpool L12 2AP, UK; alf.bass@alderhey.nhs.uk (A.B.); david.m.wright@alderhey.nhs.uk (D.W.); ornella.pinzone@alderhey.nhs.uk (O.P.)

* Correspondence: r.j.foster@ljmu.ac.uk

Abstract: Children with cerebral palsy (CP) exhibit head instability during simple overground walking, which may comprise sensory input and reduce stepping accuracy. Investigations of head stability during more challenging tasks, where fall risk may be increased, are limited. This study explored differences in head stability between ambulatory children with hemiplegic CP (N = 9) and diplegia (N = 9) (GMFCS I and II) and typically developing (TD) children (N = 8) during a targeted stepping task. All children completed five trials stepping into two successive rectangular floor-based targets whilst walking along an 8 m walkway. Three-dimensional motion capture enabled calculation of head stability and foot placement within and before each target. A two-way mixed-design ANOVA compared differences between all groups and target approach. Children with diplegic CP showed greater sagittal, frontal, and resultant head-to-laboratory and head-to-trunk head instability compared to children with hemiplegic CP and TD children. Anteroposterior foot placement error was significantly greater in children with hemiplegic CP (8.5 ± 5.0 cm) compared to TD children (3.8 ± 1.5 cm). Group differences in head instability were not consistent with group differences in foot placement error. To better understand how head instability might affect fall risk in children with CP, more challenging environments should be tested in future.

Keywords: cerebral palsy; ambulatory; head stability; foot placement; postural control

check for updates

Citation: Bailey, H.G.B.; O'Brien, T.D.; Barton, G.J.; Bass, A.; Wright, D.; Pinzone, O.; Greaves, H.; Foster, R.J. Exploratory Investigation of Head Stability in Children with Cerebral Palsy and Typically Developing Children during a Targeted Stepping Task. *Appl. Sci.* **2024**, *14*, 9008. https://doi.org/10.3390/app14199008

Academic Editors: Arkady Voloshin and Vladislav Toronov

Received: 18 July 2024
Revised: 18 September 2024
Accepted: 25 September 2024
Published: 6 October 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Many treatment strategies for ambulatory children with cerebral palsy (CP) focus on developing better control of the lower limbs [1–3] to improve mobility and independence. The achievement of these outcomes requires the maintenance of postural stability, for which effective control of the head segment is critical [4]. Despite this, head stability is rarely considered when determining the causes and planning treatment of gait impairments for these children.

There is growing evidence that the head is unstable in children with CP [5–11]. In comparison to typically developing (TD) children, children with CP exhibit differences in several discrete measures of head stability, such as greater sagittal and frontal plane head displacement during quiet sitting [9] and reaching [12], excessive flexion and extension of the head during squatting and standing movements [10], and increased angular amplitudes of the head in the frontal, sagittal, and transverse planes during straight line overground gait [6–8,11] and turning gait [13]. When responding to balance perturbations, children with CP are more likely to stabilize their head to the trunk segment (e.g., use an 'en bloc' strategy) when task difficulty increases [5], suggesting the ability to independently control the head may be compromised in challenging scenarios. Head stability can also change depending on the visual condition. Previous research highlights the differential effects that focusing on a target in front of them during overground gait can have on children with CP; while children with CP GMFCS I reduced their head movements in all planes of motion in a similar manner to TD children indicating increased visual attention, children with CP GMFCS II remained unchanged [6]. Though it is currently unclear, it is likely that head instability could further compromise existing visual, vestibular, and proprioceptive sensory deficits that are common in children with CP [14–17] due to the organs of the visual and vestibular systems being located within the head [18]. These sensory systems are critical for controlling spatial orientation of the head and trunk, stabilizing vision during rotational movements and accelerations of the head, and gauging the relative alignment of neighboring body segments within the environment.

There is limited consensus on the most appropriate ways to measure head instability in children with CP, and whether this should differ between diagnosis. Previous research has investigated head instability in small numbers of children with only diplegic CP or hemiplegic CP compared to TD children [10,11], or the combined group effects of children with varying diagnosis of CP [5,9,12]. This ignores potential group differences between children with hemiplegic and diplegic CP, which is particularly important since both groups demonstrate different development rates [19] and impairment characteristics [20] in their gait. It is unknown, for example, whether children with bilateral lower limb impairment (diplegic CP) are less able to attenuate accelerations of the head compared to children with unilateral lower limb impairment (hemiplegic CP). Impaired attenuation of accelerations between the trunk and head segments was previously reported in a CP cohort combining children with hemiplegia, diplegia, and dystonia compared to TD children [21]. Reporting these groups separately could better inform future tailored treatment strategies.

Understanding of head instability is limited to typical level straight-line gait [6–8] with little focus on the interaction between instability of the head and how this might affect functional performance of the child, except for basic spatiotemporal parameters (e.g., gait speed, cadence, or step length). To increase the complexity of typical gait, the current study used a targeted stepping task (stepping into two successive floor-based targets) to replicate the functional challenges of navigating a cluttered or busy environment. In this way, we hope to elucidate more functionally relevant links between head stability and accurate movement control. The aim of this study was to explore the differences in head stability between children with diplegic and hemiplegic CP and TD children when completing the stepping task. It was hypothesized that children with diplegic and hemiplegic CP show greater head instability compared to TD children when stepping into both targets.

2. Materials and Methods

2.1. Participants

Eighteen children diagnosed with hemiplegic or diplegic CP (Table 1) took part in this study. Children with confirmed diagnosis of spastic CP, aged 7–16 years, and independently mobile without walking aids (GMFCS I–II) who were referred for routine clinical gait assessment were included in this study. Children who had received orthopedic surgical intervention or botulinum toxin injections within the previous year, with a history of orthopedic or neurological conditions (other than CP), having an equinus contracture greater than 10°, and corrected binocular visual acuity worse (greater) than 0.5 LogMar, assessed via FrACT [22,23], were excluded. Eight TD children aged 7–16 years were recruited as a control group.

Table 1. Participant characteristics (mean (1SD)).

	Diplegic CP Group (*n* = 9)	**Hemiplegic CP Group (*n* = 9)**	**TD Group (*n* = 8)**
Sex (m/f)	6/3	5/4	5/3
Age (yrs)	10.2 (2.5)	10.6 (2.8)	10.9 (2.4)
Height (m)	1.43 (0.13)	1.43 (0.15)	1.31 (0.48)
Mass (kg)	40.02 (15.02)	38.00 (10.01)	35.86 (13.65)
GMFCS level (I/II)	6/3	8/0 *	-
Affected side (L/R)	-	4/5	-
Visual acuity (LogMAR)	0.10 (0.19) †	−0.04 (0.22)	−0.21 (0.09) †
Contrast sensitivity (LogCS)	1.82 (0.34)	1.59 (0.80)	1.96 (0.08)
TMT part A (s)	55.3 (24.7)	60.0 (38.5)	27.4 (7.9)
TMT part B (s)	138.2 (86.3)	174.4 (102.4)	89.8 (70.5)
Executive function (TMT B–TMT A) (s)	82.9 (64.6)	114.4 (71.3)	62.4 (64.5)
Foot length (cm)	22.4 (2.5)	21.4 (1.7)	21.6 (2.6)
Foot width (cm)	8.5 (1.1)	8.0 (0.6)	8.2 (1.1)

NB: * One patient had no formal documentation confirming GMFCS level. † There was a significant main effect of group on visual acuity (TD v CP DI; $p = 0.01$). There were no significant main effects of group on age ($p = 0.87$), height ($p = 0.62$), mass ($p = 0.81$), contrast sensitivity ($p = 0.36$), TMT part A ($p = 0.052$), TMT part B ($p = 0.17$), executive function ($p = 0.30$), foot length ($p = 0.52$), or foot width ($p = 0.68$), as determined via a one-way between group ANOVA.

This study was conducted in accordance with the Declaration of Helsinki. Written informed assent and consent was gained from children and their parents or guardians, respectively.

Visual and Executive Function Tests

Visual and executive function tests were carried out to examine the group differences of factors that may influence stepping performance. Visual acuity and contrast sensitivity were assessed using the FrACT [22,23]. Executive function was assessed with the Trail Making Test (TMT, parts A and B) and was calculated as the time taken to complete TMT part B minus that taken to complete TMT part A [24].

2.2. Procedure

Testing took place following each child's prescribed clinical gait assessment. Children were asked to walk at a self-selected (preferred) speed along an 8 m walkway, stepping into two successive targets on the floor (Figure 1). Targets were created using black electrical tape affixed flush to the floor. Target position for each participant was determined during three practice overground gait trials, so that the participant's 4th step landed in target 1 and 7th step landed in target 2. No other guidance was provided. The targets were rectangular with dimensions normalized to 150% of participant's foot length and foot width. Therefore, the position of targets on the ground, the relative distance between targets, and the size of targets changed between participants. Target size was chosen to reflect scenarios in activities of daily living where precise foot placement is required to navigate the environment. Participants walked to a cone beyond target 2 to ensure steady walking speed through the targets. Five trials were captured, and all children successfully stepped in to both targets during each trial. Children with CP did not wear any orthotics or use any form of walking aid, and 11 children (3 TD children, 5 children with diplegic CP, and 3 children with hemiplegic CP) wore glasses when completing the trials.

Participants wore tight-fitting clothing (e.g., Lycra or swimsuit). Twenty-nine retroreflective markers were placed according to a modified Davis model [25], with additional markers placed on both acromion processes, xyphoid process, T10, and a headband comprising four markers. Children completed this study in bare feet with one additional marker placed centrally on the dorsum of each foot (determined as 50% of measured foot length and width), representing the foot center. A four-marker cluster positioned on the laboratory floor was used to define virtual landmarks for each corner of both targets using a digitizing wand (C-Motion, Germantown, MD, USA). Kinematic data were captured at 340 Hz using 12 Smart DX cameras (BTS Bioengineering, Milan, Italy).

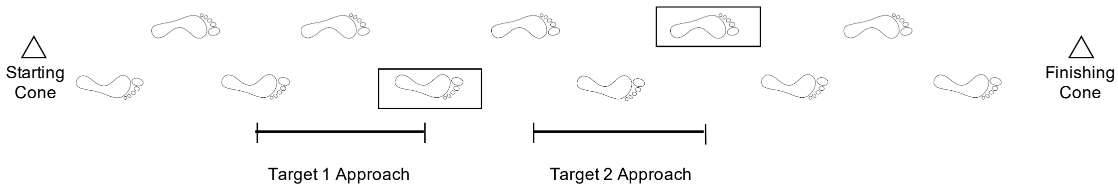

Figure 1. A schematic of the experimental setup. Black electrical tape was used to create two high-contrast targets normalized to 150% of participant foot length and width, measured whilst lying prone. Approach to the targets (Target 1 Approach and Target 2 Approach) was defined from touch-down of penultimate foot placement of the targeting foot prior to the target up to touch-down within the target.

2.3. Data Analysis

Kinematic data were labelled and gap-filled in BTS SMART Analyzer (BTS Bioengineering, Milan, Italy), then exported as c3d files for further analysis in Visual3D (C-Motion, Germantown, MD, USA). All gaps in trajectories were interpolated with a 3rd-order polynomial fit and a maximum gap size of 34 frames (10% of the 340 Hz capture rate, that is, 0.1 s) and then all trajectories were filtered using a 4th-order Butterworth low-pass digital filter at 8 Hz. Kinematic-based overground gait events (touch-down and foot-off) were determined by calculating the local maxima and minima distance of the foot relative to the pelvis segment in the anteroposterior direction [26].

2.3.1. Head Stability Variables

Angular velocity was calculated for the head-to-lab (head angle relative to the global laboratory coordinate system), representing overall movement of the head, and head-to-trunk (head angle relative to the trunk segment), representing movement of the head on top of the trunk unit. A resultant (square root of the sum of the squares) angular velocity of all three orthogonal components combined was calculated, to determine the net effect of the task on head instability, along with the angular velocity in the separate planes of movement (sagittal, flexion/extension; frontal, obliquity; transverse, rotation). Head stability was then defined to determine magnitude and direction of head movements during the approach to both target 1 and target 2. Approach to the targets (Target 1 Approach and Target 2 Approach) was defined from touch-down of penultimate foot placement of the targeting foot prior to the target up to touch-down within the target:

1. Peak maxima and peak minima of angular velocity: peak vector of resultant (all three planes) and the individual planes of head-to-lab and head-to-trunk angular velocity, reflecting peak values of instability in the direction (±) of head movements.
2. Variability: standard deviation of head-to-lab and head-to-trunk angular velocity amplitude, calculated over each approach phase (within-trial variability).
3. Angular velocity inflection count: the number of zero crossings of head-to-lab and head-to-trunk angular acceleration (first-order derivative of angular velocity), reflecting the overall frequency of head movements.

2.3.2. Foot Placement Variables

Foot placement error within the target was determined as the relative distance between the foot center and target center when the foot was flat within the target. Target centers were calculated as the mean of the four virtual landmarks digitized on each corner of the respective target. Foot placement bias, accuracy, and precision were calculated in the anteroposterior and mediolateral directions separately for both target 1 (right foot strike) and target 2 (left foot strike):

1. Foot placement bias: displacement (magnitude and direction) of the foot center relative to the target center; positive anteroposterior and mediolateral foot placement bias indicates the foot was placed anterior and lateral to the target center, respectively.

2. Foot placement accuracy: the sum of foot placement bias in the AP and ML direction, reflecting the overall absolute magnitude of the foot center relative to the target center.
3. Foot placement precision: the standard deviation of foot placement bias across trial repetitions [27–29].
4. Approach duration: the time taken to complete two steps prior to touch-down within each target.

2.4. Statistical Analysis

For each participant, the average of 5 trials for each condition were used for statistical analysis. Differences between groups (children with hemiplegic CP, children with diplegic CP and TD children) and approach to target (target 1 and target 2) in head stability and foot placement variables were assessed using two-way mixed-design ANOVAs. Multiple post-hoc comparisons were adjusted for using a Bonferroni correction and effect sizes (partial eta squared) were calculated for each statistical comparison, common indicative thresholds for which are small (0.01), medium (0.06), and large (0.14) [30].

Considering the small study sample size, exploratory nature of our analysis (i.e., high number of variables reported), and use of multiple Bonferroni-corrected ANOVA models, a studywide false discovery rate method was implemented for all main effects and interactions to mitigate the potential for high false-positives that could lead to false or misleading conclusions. An appropriate approach to do this is the Benjamini–Hochberg procedure, with a threshold of 20% for all p-values produced from all ANOVA models [31] being used to rank all ANOVA main effects. Statistical calculations were computed in SPSS (version 25.0) (Chicago, IL, USA).

3. Results

3.1. Visual and Executive Function Tests

There was a significant main effect of group on visual acuity (TD children = −0.21 (0.09) versus children with diplegic CP = 0.10 (0.19); $p = 0.01$). There were no significant main effects of group on contrast sensitivity ($p = 0.36$), TMT part A ($p = 0.052$), TMT part B ($p = 0.17$), or executive function ($p = 0.30$), as determined via a one-way between-group ANOVA.

3.2. Head Stability Measures

All outcome measures separated by approach to target 1 and target 2 (mean and 1SD) are reported in Supplementary Table S1. All statistical comparisons and Benjamini–Hochberg outcomes are reported in Supplementary Table S2.

3.2.1. Head-to-Lab Angular Velocity

Resultant and frontal maximum head-to-lab angular velocity were significantly greater in children with diplegic CP ($p = 0.006$) compared to children with hemiplegic CP and TD children (Figure 2). Sagittal and frontal minimum head-to-lab angular velocity were significantly greater in children with diplegic CP compared to children with hemiplegic CP (sagittal $p = 0.028$, frontal $p = 0.002$) and TD children (sagittal $p = 0.002$, frontal $p = 0.003$). Resultant, sagittal, and frontal head-to-lab angular velocity variability were significantly greater for children with diplegic CP compared to children with hemiplegic CP (resultant only, $p = 0.023$) and TD children (resultant $p = 0.024$, sagittal $p = 0.011$, frontal $p = 0.023$).

A significant group-by-approach interaction was present for resultant, sagittal, and frontal head-to-lab angular velocity inflection count. In each case, children with diplegic CP had a greater number of inflections than children with hemiplegic CP and TD children during approach to target 2 compared to target 1 approach, but children with hemiplegic CP and TD children had similar head-to-lab inflections across both approach phases (Figure 3).

3.2.2. Head-to-Trunk Velocity

Frontal maximum head-to-trunk angular velocity was significantly greater for children with diplegic CP compared to children with hemiplegic CP (p = 0.003) and TD children (p = 0.001) (Figure 4). Transverse maximum head-to-trunk angular velocity was greater for all three groups during target 2 approach compared to target 1 approach (p = 0.003).

A significant group-by-approach interaction indicated that transverse minimum head-to-trunk angular velocity increased during the approach to target 2 compared to target 1 for children with both diplegic and hemiplegic CP but decreased for TD children. Sagittal and frontal minimum head-to-trunk angular velocity was significantly greater for children with diplegic CP compared to children with hemiplegic CP (sagittal only; p = 0.007) and TD children (frontal only; p = 0.032). Resultant, sagittal, and frontal head-to-lab angular velocity variability was significantly greater for children with diplegic CP compared to children with hemiplegic CP (resultant p = 0.012, sagittal p = 0.022, frontal p = 0.009) and TD children (frontal only, p = 0.003).

A significant group-by-approach interaction was present in resultant, sagittal, and frontal head-to-trunk angular velocity inflection count. In general, the interaction was described by children with diplegic CP having a greater number of inflections during the approach to target 2 compared to target 1 approach across all planes and the resultant, but children with hemiplegic CP and TD children having a greater number of inflections during approach to target 1 compared to target 2 (Figure 3).

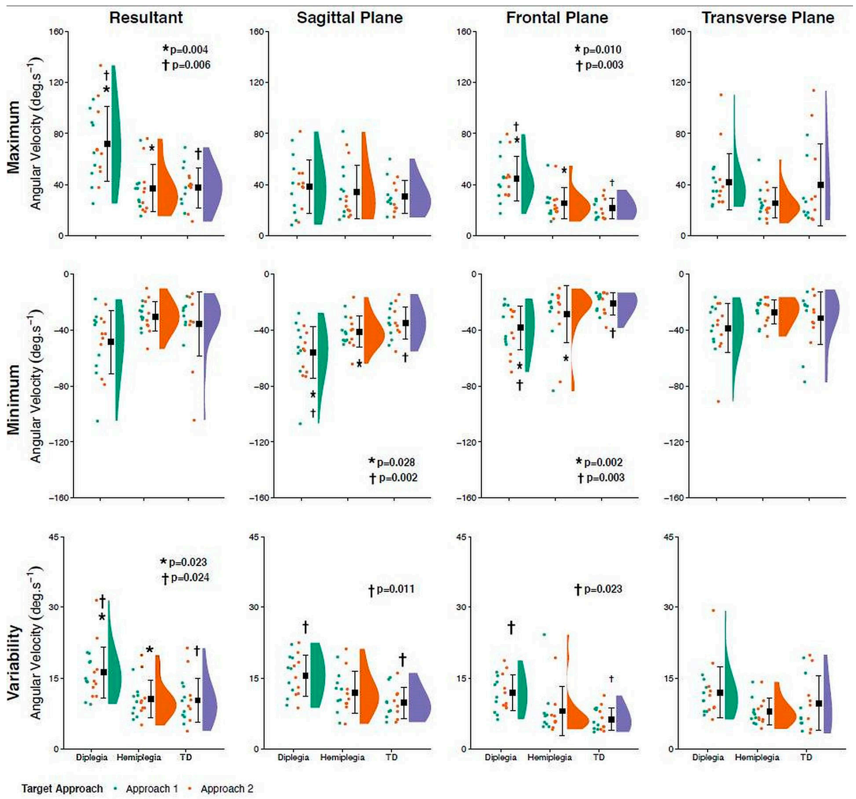

Figure 2. Raincloud plots [32,33] displaying the central tendency (mean ± 1SD), probability distribution (split-half violin), and jittered dot plots (individual participant means) for both target approaches combined for the maximum (**top row**), minimum (**middle row**), and variability (**bottom row**) of head-to-lab resultant, sagittal, frontal, and transverse plane angular velocity.* = significant main effect of group between children with diplegic CP and children with hemiplegic CP. † = significant main effect of group between children with diplegic CP and TD children. NB: Bonferroni p-values represent significant post-hoc pairwise comparisons.

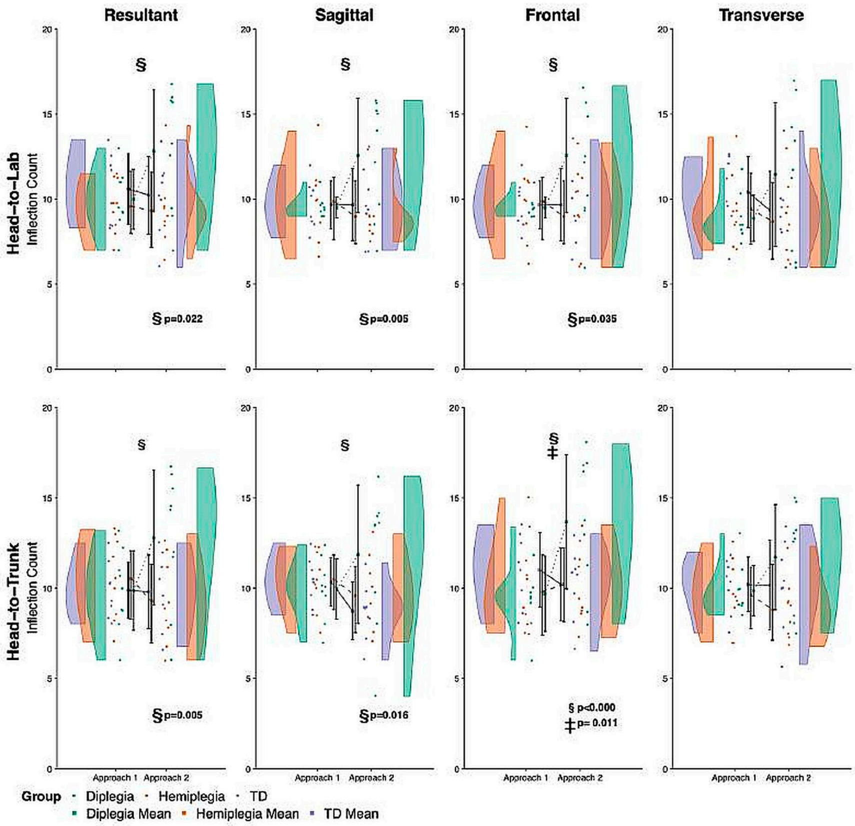

Figure 3. Raincloud plots [32,33] displaying the central tendency (mean ± 1SD), probability distribution (split-half violin), and jittered dot plots (individual participant means) for each of the two target approaches for head-to-trunk (**top row**) and head-to-lab (**bottom row**) velocity inflection counts. ‡ = a significant main effect of approach. § = a significant group-by-approach interaction.

3.3. Foot Placement Variables

A significant group-by-approach interaction for mediolateral foot placement bias, representing different foot placement preferences between groups revealed that children with diplegic CP placed their foot lateral to the target center in target 1 (1.2 ± 2.2 cm) and target 2 (0.5 ± 3.0 cm), and TD children placed their foot medial to the target center in target 1 (−1.3 ± 1.8 cm) and target 2 (−0.4 ± 2.3 cm) (Figure 5). In comparison, children with hemiplegic CP placed their foot medial to the target center of target 1 (−1.2 ± 3.7 cm) but lateral to the target center of target 2 (2.3 ± 3.7 cm). Anteroposterior foot placement accuracy was significantly greater in children with hemiplegic CP (8.5 ± 5.0 cm) compared to TD children (3.8 ± 1.5 cm, p = 0.014).

3.4. Approach Duration

There was a significant group-by-approach phase interaction for approach duration. All groups had a similar approach duration during the approach to target 1 (diplegic CP; 1.03 ± 0.16 s, hemiplegic CP; 1.08 ± 0.12 s, TD children; 1.10 ± 0.12 s), but approach duration to target 2 increased in children with diplegic CP (1.31 ±0.33 s) whilst decreasing in children with hemiplegic CP (1.04 ± 0.12 s) and TD children (1.03 ± 0.11 s).

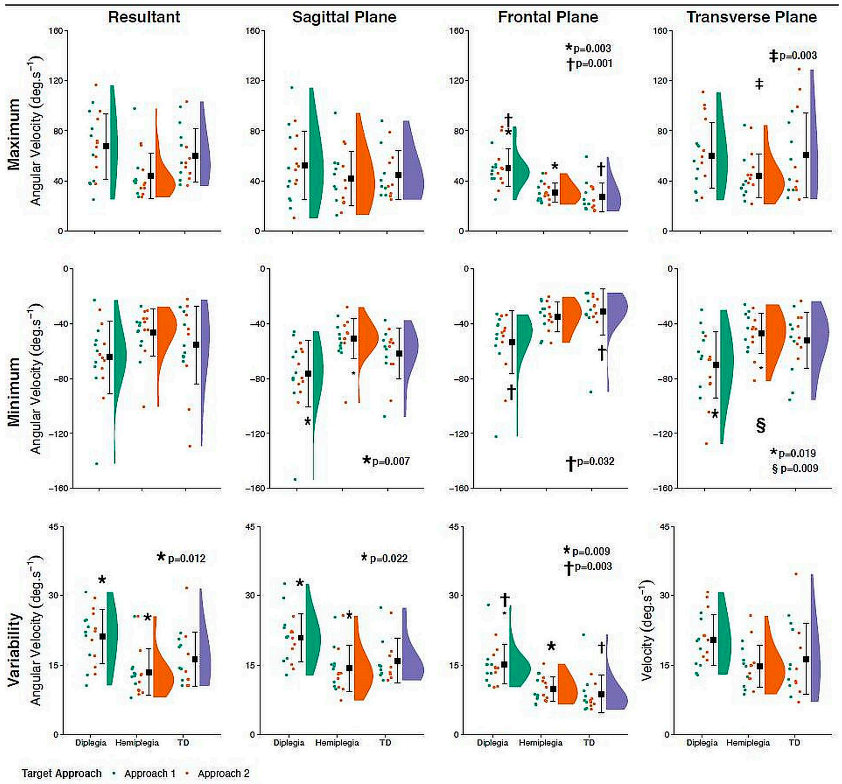

Figure 4. Raincloud plots [32,33] displaying the central tendency (mean ± 1SD), probability distribution (split-half violin), and jittered dot plots (individual participant means) for both target approaches combined for the maximum (**top row**), minimum (**middle row**), and variability (**bottom row**) of head-to-trunk resultant, sagittal, frontal, and transverse plane angular velocity. * = significant main effect of group between children with diplegic CP and children with hemiplegic CP. † = a significant main effect of group between children with diplegic CP and TD children. ‡ = a significant main effect of approach. § = a significant group-by-approach interaction. NB: Bonferroni-corrected *p*-values represent significant post-hoc pairwise comparisons.

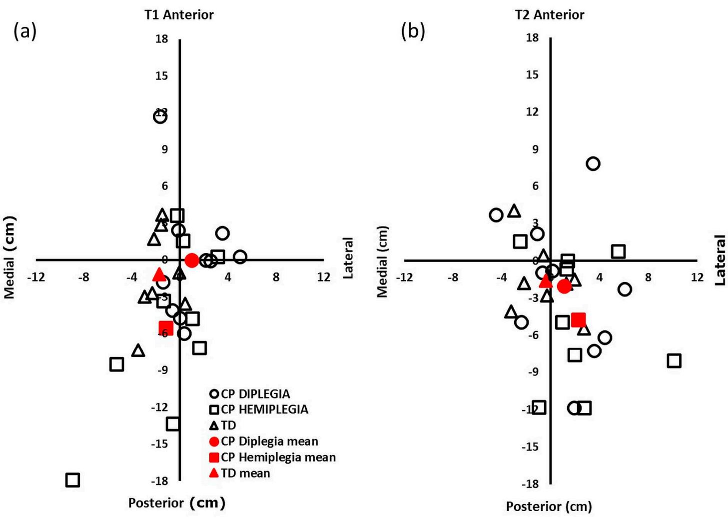

Figure 5. Location of the foot center for all participant groups, relative to the center of the target in (**a**) target 1 and (**b**) target 2, representing both the mean (filled shapes) and dispersion of foot placement bias (unfilled shapes). Positive anteroposterior and mediolateral values indicate the foot was placed anterior and lateral to the target center, respectively.

4. Discussion

This is the first study to measure head stability in children with CP when completing a targeted stepping task. Children with diplegic CP exhibited greater head instability than children with hemiplegic CP and TD children during the task, but similar foot placement error to TD children. Children with hemiplegic CP exhibited similar head stability to TD children but greater absolute anteroposterior foot placement error.

Children with diplegic CP showed greater head-to-lab and head-to-trunk instability than other groups, whilst children with hemiplegic CP behaved similarly to TD children. One explanation of this global instability may be the challenge for children with diplegic CP to attenuate accelerations travelling up the body to the head via active or passive methods when impaired by reduced bilateral lower limb control and differing gait patterns compared to unilateral impairment in children with hemiplegic CP. This is consistent with previous findings [21,32].

Children with diplegic CP exhibited a significantly greater downward (sagittal) angular velocity of the head relative to the lab and trunk, compared to children with hemiplegic CP and TD children. This may be because children with diplegic CP tilt their head to look down at the ground more to gather additional information about the target location in an attempt to reduce foot placement errors [15,33,34]. Children with diplegic CP may also look down at the ground more due to their reduced visual acuity, which could make it more difficult to see the target clearly on the floor, although their visual acuity still fell within typical ranges for children [35]. Capturing gaze behavior with an eye-tracker alongside head segment kinematics may provide further insight into whether children with diplegic CP utilize movement of the head to maintain visual focus at the expense of previewing what is in front of them, though this could lead to an increased fall risk due to reduced detection of upcoming obstacles along their travel path.

Children with CP have previously exhibited an 'en-bloc' stabilization strategy by locking (i.e., reducing the degrees of freedom between) neighboring segments together under challenging circumstances [5,36]. In contrast during the current stepping task, children with diplegic CP showed greater head-to-trunk angular velocity. This suggests that the task may not have produced a significant threat to postural control and future gait studies could focus on higher risk activities such as obstacle clearance or stair descent.

Children with hemiplegic CP exhibited greater anteroposterior foot placement error despite no differences in head instability, suggesting the inaccuracies in foot placement are driven by factors other than the impaired gathering of accurate sensory information because of head instability. One possible explanation may relate to asymmetry between the affected and unaffected limb. The previous literature has reported step length differences between limbs in children with hemiplegic CP [37,38]. However, since targets were positioned within the regular footfall of each child during familiarization trials, this is unlikely to be the case. Instead, the difference is likely to be caused by the low difficulty/demand of the task and verbal instructions provided by the investigator. Due to the construction of the targets, the task presented no significant consequence if the child failed to place their foot within the target, and no specific instructions were provided to the participants regarding placement of the foot within the target, as long as the foot was inside the rectangle. No instruction was given to limit potential visual targeting by participants, but may this have resulted in participants simply placing the foot within the borders of the target. More complex and unpredictable travel paths are required to determine how accuracy of movement control changes when there are greater consequences for fall risk.

Whilst head-to-lab and head-to-trunk angular velocity remained similar between approach phases for all participant groups, children with diplegic CP increased the number of head accelerations during the approach to target 2 compared to target 1, evidenced by an increase in velocity inflection count. A corresponding increase in time taken to approach target 2 was responsible for this change for children with diplegic CP, as rate of inflection did not significantly increase (head-to-lab resultant rate of inflection: target 1 = 9.7; target 2 = 9.8).

Limitations

All children stepped into targets with the same limb (i.e., the right foot in target 1 and left foot in target 2), meaning the unilateral nature of hemiplegia gait may impact on current findings, although visual inspection of the data shows no clear impact of targeting with the affected versus unaffected limb. Future studies may choose to assess stepping into targets with children's affected versus unaffected side to ensure a standardized approach, an approach previously taken when assessing stepping accuracy in unilateral amputees [27]. Children with diplegic CP varied across GMFCS I and II, but children with hemiplegic CP were all GMFCS I, suggesting group outcome measures may have been influenced by the child's level of motor involvement. Although preliminary in nature, this study reports head instability, with large effect sizes, during a functionally relevant task in a cohort where this was previously thought not to be the case. This study can be used to inform future research design and the development of methodologies to target this issue further. Future test protocols should aim to challenge head stability in all three planes of movement, which may provide more comprehensive differences in the resultant 3D movement of the head.

5. Conclusions

In this exploratory study, group differences in head instability were not consistent with group differences in foot placement error. More detailed and insightful methodological approaches are required to understand the cause and environmental factors underpinning fall risk for children with CP.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14199008/s1, Table S1: Mean (1 SD) of all outcome measures. Results of post-hoc testing ($p \leq 0.05$) and above the stated false discovery rate threshold (20%) are represented in the significant differences column. Table S2: Statistical output for all dependent outcome measures. F statistic, p value and effect size (partial eta squared (ηp2) are reported for main effect comparisons of approach, group, and group-by-approach interaction. Outcome measures with $p \leq 0.05$ and above the stated false discovery rate threshold (20%; indicating statistical significance) are shaded in grey.

Author Contributions: Conceptualization, H.G.B.B., T.D.O., G.J.B., A.B., D.W., O.P., H.G. and R.J.F.; methodology, H.G.B.B., T.D.O., G.J.B., O.P., H.G. and R.J.F.; software, H.G.B.B.; formal analysis, H.G.B.B.; investigation, H.G.B.B., O.P., H.G. and R.J.F.; data curation, H.G.B.B.; writing—original draft preparation, H.G.B.B.; writing—review and editing, H.G.B.B., T.D.O., G.J.B., A.B., D.W., O.P., H.G. and R.J.F.; visualization, H.G.B.B.; supervision, T.D.O., G.J.B. and R.J.F.; project administration, H.G.B.B. and R.J.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study was conducted in accordance with the Declaration of Helsinki and approved by the NHS Research Ethics Committee and Health Research Authority (UK) (reference number: 18/EM/0278) on 23 October 2018.

Informed Consent Statement: Informed consent was obtained from all subjects involved in this study.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Anttila, H.; Autti-Rämö, I.; Suoranta, J.; Mäkelä, M.; Malmivaara, A. Effectiveness of physical therapy interventions for children with cerebral palsy: A systematic review. *BMC Pediatr.* **2008**, *8*, 14. [CrossRef] [PubMed]
2. Lee, J.H.; Sung, I.Y.; Yoo, J.Y. Therapeutic effects of strengthening exercise on gait function of cerebral palsy. *Disabil. Rehabil.* **2008**, *30*, 1439–1444. [CrossRef] [PubMed]
3. Dodd, K.J.; Taylor, N.F.; Damiano, D.L. A systematic review of the effectiveness of strength-training programs for people with cerebral palsy. *Arch. Phys. Med. Rehabil.* **2002**, *83*, 1157–1164. [CrossRef]

4. Assaiante, C.; Amblard, B. An ontogenetic model for the sensorimotor organization of balance control in humans. *Hum. Mov. Sci.* **1995**, *14*, 13–43. [CrossRef]
5. Mills, R.; Levac, D.; Sveistrup, H. Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy. *Gait Posture* **2018**, *66*, 13–20. [CrossRef]
6. Bartonek, A.; Lidbeck, C.M.; Gutierrez-Farewik, E.M. Influence of External Visual Focus on Gait in Children With Bilateral Cerebral Palsy. *Pediatr. Phys. Ther.* **2016**, *28*, 393–399. [CrossRef] [PubMed]
7. Heyrman, L.; Feys, H.; Molenaers, G.; Jaspers, E.; Monari, D.; Meyns, P.; Desloovere, K. Three-dimensional head and trunk movement characteristics during gait in children with spastic diplegia. *Gait Posture* **2013**, *38*, 770–776. [CrossRef] [PubMed]
8. Wallard, L.; Bril, B.; Dietrich, G.; Kerlirzin, Y.; Bredin, J. The role of head stabilization in locomotion in children with cerebral palsy. *Ann. Phys. Rehabil. Med.* **2012**, *55*, 590–600. [CrossRef]
9. Saavedra, S.; Woollacott, M.; van Donkelaar, P. Head stability during quiet sitting in children with cerebral palsy: Effect of vision and trunk support. *Exp. Brain Res.* **2009**, *201*, 13–23. [CrossRef] [PubMed]
10. Dan, B.; Bouillot, E.; Bengoetxea, A.; Noël, P.; Kahn, A.; Cheron, G. Head stability during whole body movements in spastic diplegia. *Brain Dev.* **2000**, *22*, 99–101. [CrossRef] [PubMed]
11. Holt, K.G.; Ratcliffe, R.; Jeng, S.-F. Head stability in walking in children with cerebral palsy and in children and adults without neurological impairment. *Phys. Ther.* **1999**, *79*, 1153–1162. [CrossRef]
12. Saavedra, S.; Joshi, A.; Woollacott, M.; van Donkelaar, P. Eye hand coordination in children with cerebral palsy. *Exp. Brain Res.* **2009**, *192*, 155–165. [CrossRef] [PubMed]
13. Bartonek, A.; Lidbeck, C.; Hellgren, K.; Gutierrez-Farewik, E. Head and Trunk Movements During Turning Gait in Children with Cerebral Palsy. *J. Mot. Behav.* **2019**, *51*, 362–370. [CrossRef]
14. Almutairi, A.; Cochrane, G.; Christy, J. Vestibular and oculomotor function in children with CP: Descriptive study. *Int. J. Pediatr. Otorhinolaryngol.* **2019**, *119*, 15–21. [CrossRef]
15. Fazzi, E.; Signorini, S.G.; La Piana, R.; Bertone, C.; Misefari, W.; Galli, J.; Balottin, U.; Bianchi, P.E. Neuro-ophthalmological disorders in cerebral palsy: Ophthalmological, oculomotor, and visual aspects. *Dev. Med. Child Neurol.* **2012**, *54*, 730–736. [CrossRef] [PubMed]
16. Wingert, J.R.; Burton, H.; Sinclair, R.J.; Brunstrom, J.E.; Damiano, D.L. Joint-Position Sense and Kinesthesia in Cerebral Palsy. *Arch. Phys. Med. Rehabil.* **2009**, *90*, 447–453. [CrossRef] [PubMed]
17. Ghasia, F.; Brunstrom, J.; Gordon, M.; Tychsen, L. Frequency and severity of visual sensory and motor deficits in children with cerebral palsy: Gross motor function classification scale. *Investig. Opthalmology Vis. Sci.* **2008**, *49*, 572–580. [CrossRef]
18. Pozzo, T.; Berthoz, A.; Lefort, L. Head stabilization during various locomotor tasks in humans. I. Normal subjects. *Exp. Brain Res.* **1990**, *82*, 97–106. [CrossRef]
19. Farmer, S.E. Key factors in the development of lower limb co-ordination: Implications for the acquisition of walking in children with cerebral palsy. *Disabil. Rehabil.* **2003**, *25*, 807–816. [CrossRef] [PubMed]
20. Rodda, J.; Graham, H.K. Classification of gait patterns in spastic hemiplegia and spastic diplegia: A basis for a management algorithm. *Eur. J. Neurol.* **2001**, *8* (Suppl. S5), 98–108. [CrossRef] [PubMed]
21. Summa, A.; Vannozzi, G.; Bergamini, E.; Iosa, M.; Morelli, D.; Cappozzo, A. Multilevel Upper Body Movement Control during Gait in Children with Cerebral Palsy. *PLoS ONE* **2016**, *11*, e0151792. [CrossRef] [PubMed]
22. Bach, M. The Freiburg Visual Acuity Test-Variability unchanged by post-hoc re-analysis. *Graefe's Arch. Clin. Exp. Ophthalmol.* **2007**, *245*, 965–971. [CrossRef]
23. Bach, M. The freiburg visual acuity test—Automatic measurement of visual acuity. *Optom. Vis. Sci.* **1996**, *73*, 49–53. [CrossRef]
24. Partington, J.E.; Leiter, R.G. Partington's Pathways Test. *Psychol. Serv. Cent. J.* **1949**, *1*, 11–20.
25. Davis, R.B.; Õunpuu, S.; Tyburski, D.; Gage, J.R. A gait analysis data collection and reduction technique. *Hum. Mov. Sci.* **1991**, *10*, 575–587. [CrossRef]
26. Zeni, J.A., Jr.; Richards, J.G.; Higginson, J.S. Two simple methods for determining gait events during treadmill and over-ground walking using kinematic data. *Gait Posture* **2008**, *27*, 710–714. [CrossRef] [PubMed]
27. Foster, R.; Haley, M.; Talbot, I.; De Asha, A.; Barnett, C. Individuals with unilateral transtibial amputation exhibit reduced accuracy and precision during a targeted stepping task. *J. Biomech.* **2020**, *105*, 109785. [CrossRef]
28. Chapman, G.J.; Scally, A.; Buckley, J.G. Importance of binocular vision in foot placement accuracy when stepping onto a floor-based target during gait initiation. *Exp. Brain Res.* **2011**, *216*, 71–80. [CrossRef]
29. Reynolds, R.F.; Day, B.L. Visual guidance of the human foot during a step. *J. Physiol.* **2005**, *569 Pt 2*, 677–684. [CrossRef] [PubMed]
30. Field, A. *Discovering Statistics Using IBM SPSS Statistics*; Sage: New York, NY, USA, 2013.
31. Benjamini, Y.; Hochberg, Y. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J. R. Stat. Soc. Ser. B Methodol.* **1995**, *57*, 289–300. [CrossRef]
32. Armand, S.; Decoulon, G.; Bonnefoy-Mazure, A. Gait analysis in children with cerebral palsy. *EFORT Open Rev.* **2016**, *1*, 448–460. [CrossRef]
33. Matthis, J.S.; Yates, J.L.; Hayhoe, M.M. Gaze and the Control of Foot Placement When Walking in Natural Terrain. *Curr. Biol.* **2018**, *28*, 1224–1233.e5. [CrossRef]
34. Patla, A.E.; Vickers, J.N. Where and when do we look as we approach and step over an obstacle in the travel path? *Neuroreport* **1997**, *8*, 3661–3665. [CrossRef] [PubMed]

35. Anstice, N.S.; Thompson, B. The measurement of visual acuity in children: An evidence-based update. *Clin. Exp. Optom.* **2014**, *97*, 3–11. [CrossRef] [PubMed]
36. Barton, G.J.; Hawken, M.B.; Foster, R.J.; Holmes, G.; Butler, P.B. The effects of virtual reality game training on trunk to pelvis coupling in a child with cerebral palsy. *J. Neuroeng. Rehabil.* **2013**, *10*, 15. [CrossRef] [PubMed]
37. Zonta, M.B.; Júnior, A.R.; Camargo, R.M.R.; Dias, F.H.; dos Santos, L.H.C. Two-dimensional analysis of gait asymmetry in spastic hemiplegia. *Einstein* **2010**, *8*, 343–349. [CrossRef]
38. Norlin, R.M.; Odenrick, P. Development of gait in spastic children with cerebral palsy. *J. Pediatr. Orthop.* **1986**, *6*, 674–680. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.